FIBER REINFORCED CEMENT COMPOSITES: MULTI-CRACK LINEAR FRACTURE MECHANICS COMPUTER MODELING

By

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ABSTRACT

FIBER REINFORCED CEMENT COMPOSITES: MULTI-CRACK LINEAR FRACTURE MECHANICS COMPUTER MODELING

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The first part of this research presents a computer-based model for predicting the tensile stress-strain behavior of fiber reinforced cement composites. The structure of the material is modelled by stochastically generating the multiple cracks and other material attributes. The analysis is based on linear elastic fracture mechanics, with due consideration given to the crack-arrest action of fibers as well as the multiple cracking effects on the stress field.

The tensile mechanical behavior is described through the stress-strain curve of the material, which is described in three stages: linear, pre-peak, and post-peak.

The unique characteristic of the model is its ability to use multiple cracks and stochastically generate the structure of the material.

Validation of the model was successfully accomplished by comparing eight actual experimental stress-strain curves to the ones produced by the model. Also, the model was validated by carrying out a parametric study of the effects of the material properties on its mechanical performance in tension.

The importance and usefulness of the model as a research tool was also demonstrated, partly through deriving optimum fiber reinforcement variables for some key categories of fiber reinforced cement composites.

Although the developed algorithm requires much computational time, the model was successfully used without access to a super computer. Also, computer processing time is getting more accessible and cheaper every day, which further makes the model a practical research tool.

The second part of this research was an independent experimental approach to the optimization of carbon fiber reinforced cement composites through latex modification of the matrix. Latex modification is used to enhance the fracture toughness of the matrix and the fiber-to-matrix bond strength as well as the composite material impermeability, durability and adhesion capacity. A comprehensive experimental study concluded that the overall mechanical, physical and durability characteristics of carbon fiber reinforced cement composites can be improved through latex modification. Repair applications of the developed latex modified carbon fiber reinforced cement composites were also investigated.

In memory of my father, Ali Aouadi.

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LIST OF SYMBOLS AND ABBREVIATIONS

LEFM: Linear Elastic Fracture Mechanics

FRC (or frc): Fiber Reinforced Cement

X1, X2, X3: Cartesian coordinate system

x, y, r, θ: Polar coordinates system

σ_{ij}: Stress components

ε_{ij}: Strain components

u_i: Displacement components

E: Modulus of elasticity (in general)

ν: Poisson's ratio

Z: Complex number identifying a point of plane coordinates x1, and x2; (Z=x1+ix2)

$\phi(z)$; $\Phi(z)$; $\Omega(z)$; X(z); G(z): Complex functions used in the solution of LEFM Problems

Real(); Re(): Real part of a complex number or function

Im(): Imaginary part of a complex number or function

$\overline{(\,)}$: Conjugate of a complex number or function

A; a: half crack length

K1; KI: Mode 1 stress intensity factor

K1c; KIC; TKI; Kc: Mode 1 fracture toughness, (or the critical mode 1 stress intensity factor)

G: Strain energy release rate

Gc: Critical strain energy release rate

SEM: Scanning Electronic Microscope

HCP; hcp: Hydrate Cement Paste

W/C; w/c: Water to cement ratio

psi: Pounds per square inches

ksi: Kips per square inches

lb: Pounds

in: inches

MN: Mega Newtons

Pa: Pascals (metric stress unit)

MPa: Mega Pascals

m: meter

cm: centimeter

mm: millimeter

μm: micrometer

COD; COD(x); w: Crack opening displacement

ASTM: American Society of Testing of Materials

C-S-H; (CSH): Calcium Silicate Hydrate

C-H; CH: Calcium Hydroxide

A*: Point on stress-strain curve: starting point of the model; corresponds to an elastic matrix. No cracks have yet started propagating into the matrix.

A1: Point on the stress-strain curve; (aggregate bond cracks propagated to their maximum possible length within the interfacial zone)

P; P(x); FBRIDGE: Axial force along a fiber (bridging force)

S(x); SIGF: Axial stress along a fiber

t(x): Shear stress along a fiber

TAU: Fiber to matrix bond strength

TAUF: Frictional shear strength

ALTAU: Ratio of TAUF to TAU

X: Stretched fiber length

S: Slippage of fiber end

DEL: Fiber elastic elongation

L: Fiber embedded length

Lf, FBL: Fiber length

Df: Fiber diameter

Ef, MODF: Fiber modulus of elasticity

SIGULT: Fiber ultimate strength

Af: Cross sectional area of fiber

SQRT(): Square root of ()

f_{nn}, f_{nt}, f_{tn}, f_{tt}: Elementary solutions (or kernels)

SIF: Stress Intensity Factor (in general)

T-TEST: Statistical Student's-T Test Method

ANOVA: Analysis of variance statistical method

MOD0: Modulus of elasticity of matrix

MOD: Modulus of elasticity of composite

Vf; F: Fiber volume fraction

α: Parameter (4TAU/(Ef*Df))

SIG: Average composite stress

X1, X2,...: Variables labels

R1, R2, ...: Response variables labels

R1_LO, R2_LO, ...: Lower constraint limits on response variables

R1_HI, R2_HI, ...: Upper constraint limits on response variables

NC: Number of cracks

SPSS: Commercial statistical software

Design-Expert: Commercial data analysis and optimization software

CHAPTER 1

Introduction and Background

1.1 Objectives And Scope

The objective of this study is to develop a computer-based model that simulates the tensile mechanical behavior of cement-based fiber-reinforced composite materials. Tensile behavior is described through the stress-strain curve of the material.

The structure of the material is modelled by stochastically generating multiple cracks and other attributes of the material such as the fibers. Consideration of multiple cracking and stochastic methods in modeling are the key contributions of this research to the state of knowledge in fracture mechanics and modeling of fiber reinforced cement composites.

The model is based on the theory of linear elastic fracture mechanics (LEFM), which is briefly introduced in this Chapter. Also, Chapter 1 presents a thorough review of the literature related to this study.

Modeling of fiber reinforced cement composites is accomplished, in this investigation, by considering the following steps:

- Analysis stage: This stage sets up all the basic theories and ideas into equations and procedures to be used by the model. This analysis is presented in Chapters 2, 3, and 4.

- Synthesis stage: This stage is basically the translation of the results of the previous stage into flow charts, and then into FORTRAN subroutines. Details of this stage are presented in Chapter 5.

- Verification and Validation stages: These last stages insure that the model is a realistic representation of the real system, and that the model does what it was designed for. This is accomplished through a rigorous statistical

comparison of the results predicted by the model to actual experimental results. The validation process is presented in Chapter 7.

The model was successfully validated, and it was concluded that the approach considered in this study could realistically predict the tensile stress-strain curves of fiber reinforced cement-based composites.

Examples of simulations using the model are demonstrated in Chapter 8.

Finally, it is recommended that the model be further improved and refined. Also, it is recommended that similar models could be developed for flexural, compressive, and combined types of loading using similar approaches.

1.2 Introduction To Linear Fracture Mechanics

1.2.1 General

The objective of Fracture Mechanics analysis is to determine the crack effects on the behavior of a structural member.

A crack (or cut) is characterized by a discontinuity in displacements across its surfaces. Figure 1.1 presents the essential features of a crack.

If a structural member containing a crack is loaded, the tip of the crack will undergo a combination of three loading modes, which are characterized by the direction of relative displacements of the crack surfaces in the vicinity of the tip, as shown in Figure 1.2.

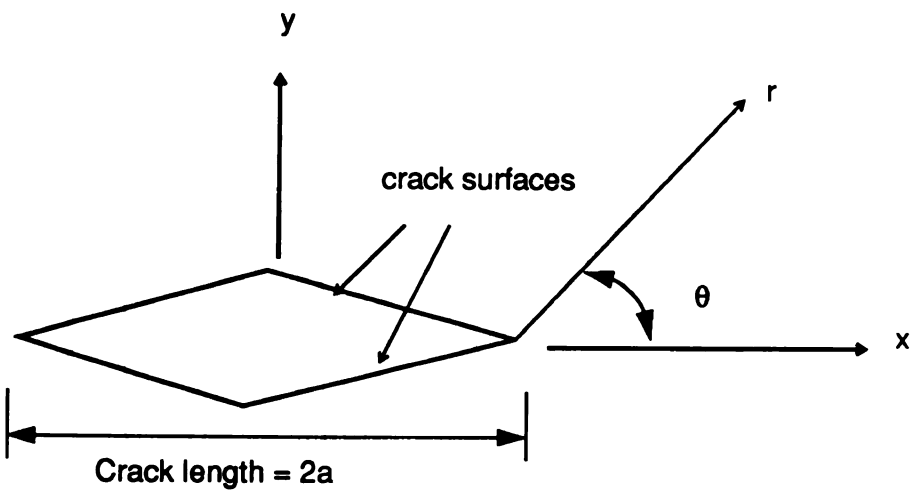
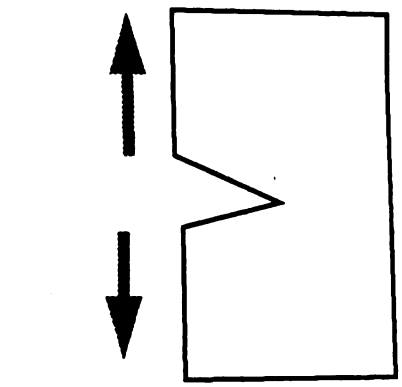
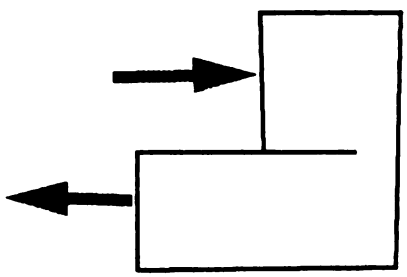


FIGURE 1.1 Typical Crack Geometry

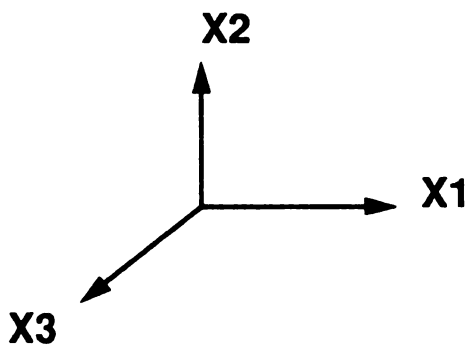


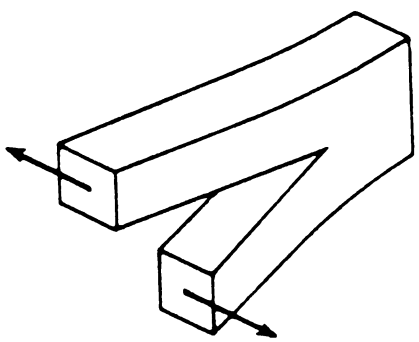
OPENING MODE OR MODE I

MOST MATERIAL TESTS AND ACTUAL FAILURES ARE IN THIS MODE.



SLIDING MODE OR MODE II





TEARING MODE OR MODE III

FIGURE 1.2 Modes Of Loading Of a Crack

At a certain load level, the crack will start propagating. This propagation may evolve quasi-statically (i.e. slowly, in a stable or controlled manner) or dynamically (unstable). Depending on the material, fracture may be described as "ductile" or "brittle". On the micro scale, ductile fracture proceeds by the growth and coalescence of voids ahead of the crack tip. Such fracture consumes a high level of energy and leads to "fibrous" crack surfaces. Brittle fracture at the micro scale proceeds by grain cleavage or separation along grain boundaries. A low level of energy is required and the resulting crack surfaces may be characterized as "granular". On the macro scale, ductile behavior is associated with large permanent deformations (i.e. after complete fracture, the two parts no longer fit together), whereas brittle fracture involves little or no permanent deformation (Reference 1.3).

1.2.2 Stress Intensity Factor And Computational Techniques

Linear fracture mechanics problems are basically special problems of linear elasticity. The main objective of this introductory section is to show the derivation of the basic linear elastic fracture mechanics (LEFM) equations and definitions, using the usual plane linear elasticity notations.

The plane linear elasticity equations of equilibrium, strain-displacement, compatibility, and stress-strain relations are shown in Equations 1.1 through 1.4, respectively.

$$\frac{\partial \sigma_{11}}{\partial x_1} + \frac{\partial \sigma_{21}}{\partial x_2} = 0 \qquad \text{and} \qquad \frac{\partial \sigma_{12}}{\partial x_1} + \frac{\partial \sigma_{22}}{\partial x_2} = 0 \qquad (1.1)$$

$$\varepsilon_{11} = \frac{\partial u_1}{\partial x_1} \qquad \varepsilon_{22} = \frac{\partial u_2}{\partial x_2} \qquad \varepsilon_{12} = \left(\frac{\partial u_1}{\partial x_1} + \frac{\partial u_2}{\partial x_1}\right)/2 \qquad (1.2)$$

$$\frac{\partial^2 \varepsilon_{22}}{\partial x_1^2} - 2\frac{\partial^2 \varepsilon_{12}}{\partial x_1 \partial x_2} + \frac{\partial^2 \varepsilon_{11}}{\partial x_2^2} = 0 \qquad (1.3)$$

$$E\varepsilon_{11} = \sigma_{11} - \nu(\sigma_{22} + \sigma_{33})$$

$$E\varepsilon_{22} = \sigma_{22} - \nu(\sigma_{11} + \sigma_{33}) \quad \text{.....(1.4)}$$

$$E\varepsilon_{12} = (1+\nu)\sigma_{12}$$

where;

$\sigma_{33} = 0$ for plane stress, $\sigma_{33} = \upsilon(\sigma_{11} + \sigma_{22})$ for plane strain, and ν is the poisson's ratio.

Many LEFM problems can be solved using the following approach:

Westergaard [1.1] introduced a harmonic function $\phi'(z)$, where $z = x_1 + ix_2$, such that;

$$\sigma_{11} = Real\phi' - x_2 Im\phi''$$

$$\sigma_{22} = Real\phi' + x_2 Im\phi'' \quad \text{.....(1.5)}$$

$$\sigma_{12} = -x_2 Real\phi''$$

$$u_1 = \frac{1+\upsilon}{E}\left(\frac{\kappa-1}{2} Real\phi - x_2 Im\phi'\right)$$

$$\text{.....(1.6)}$$

$$u_2 = \frac{1+\upsilon}{E}\left(\frac{\kappa+1}{2} Im\phi - x_2 Real\phi'\right)$$

where $\phi' = \frac{d\phi}{dz}$ and $\kappa = \frac{3-\upsilon}{1+\upsilon}$ for plane stress

$\kappa = 3 - 4\upsilon$ for plane strain

The expressions of Equations (1.5) and (1.6) satisfy Equations (1.1)-(1.4) as can be shown using the Cauchy-Riemann equalities:

$$Real\phi' = \frac{\partial}{\partial x_1} Real\phi = \frac{\partial}{\partial x_2} Im\phi$$

$$Im\phi' = \frac{\partial}{\partial x_1} Im\phi = -\frac{\partial}{\partial x_2} Real\phi$$

Based on the above formulations of the theory of linear elasticity in the complex form, many crack problems were solved by choosing a suitable complex function ϕ, and enforcing the correct boundary conditions.

For example, consider an infinite plate with a through-crack, as shown in Figure 1.3. It can be shown (Reference 1.1) that the solution is:

$$\phi'(z) = \frac{\sigma_\infty}{\sqrt{1-\left(\frac{a}{z}\right)^2}}$$

so that $\phi(z) = \sigma_\infty\sqrt{z^2-a^2}$ and $\phi''(z) = -\dfrac{\sigma_\infty a^2}{(z^2-a^2)^{3/2}}$

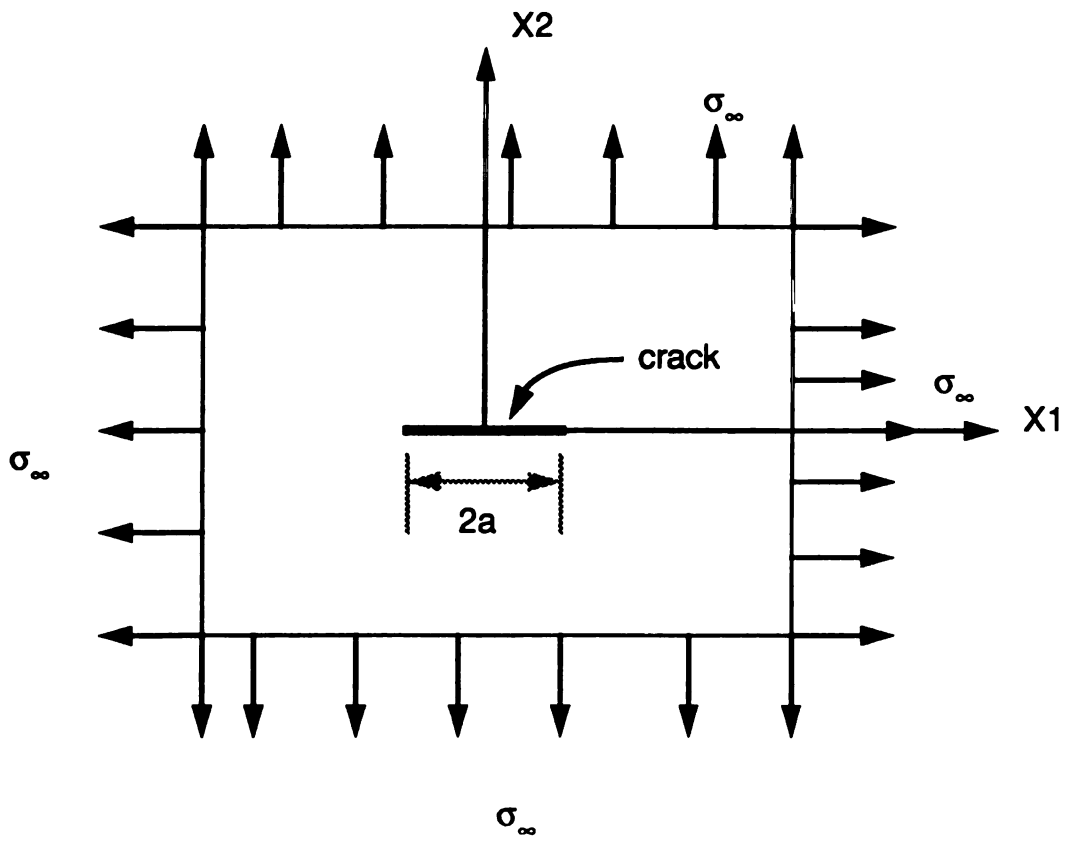


FIGURE 1.3 Crack problem example

Irwin [1.2] inspected this solution near the crack front (tip) by introducing the variables shown in Figure 1.4.

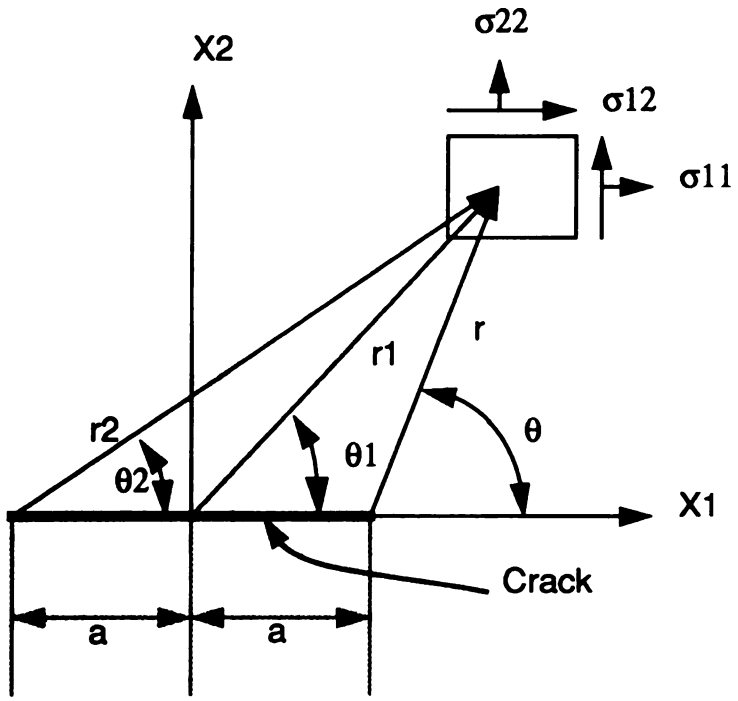


FIGURE 1.4 Configuration Used By the Irwin Solution

where;

$$z = r_1 e^{i\theta} = a + re^{i\theta} = -a + r_2 e^{i\theta_2}$$

so that

$$z - a = re^{i\theta} \quad \text{and} \quad z + a = r_2 e^{i\theta_2}$$

and

$$\phi = \sigma_\infty \sqrt{r r_2}\, e^{i((\theta+\theta_2)/2)}$$

$$\phi' = \frac{\sigma_\infty r_1}{\sqrt{r r_2}} e^{i(\theta_1 - \frac{\theta+\theta_2}{2})}$$

$$\phi'' = -\frac{\sigma_\infty a^2}{(r r_2)^{3/2}} e^{-i(3/2)(\theta+\theta_2)}$$

where the angles are restricted to the range $-\pi$ to π

To obtain the solution in the vicinity of the crack tip, i.e. r<<a, we let

$r_1 = a, r_2 = 2a, \theta_1 = 0, \theta_2 = 0$

and substitute $\phi, \phi', and \phi''$ into Equations (1.5) and (1.6) to get

$$\sigma_{11} = \frac{\sigma_\infty \sqrt{\pi a}}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left(1 - \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right)$$

$$\sigma_{22} = \frac{\sigma_\infty \sqrt{\pi a}}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left(1 + \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right)$$

$$\sigma_{12} = \frac{\sigma_\infty \sqrt{\pi a}}{\sqrt{2\pi r}} \sin\frac{\theta}{2}\cos\frac{\theta}{2}\cos\frac{3\theta}{2}$$

and

$$u_1 = \frac{(1+\upsilon)\,\sigma_\infty \sqrt{\pi a}}{E} \sqrt{\frac{r}{2\pi}}\,(\kappa - \cos\theta)\cos\frac{\theta}{2}$$

$$u_2 = \frac{(1+\upsilon)\,\sigma_\infty\sqrt{\pi a}}{E}\sqrt{\frac{r}{2\pi}}\,(\kappa-\cos\theta)\sin\frac{\theta}{2}$$

It can be shown that the distribution of stress and displacement in the vicinity of the crack tip is the same for all plane mode I problems. Thus we can write the general mode I crack-tip solution as:

$$\sigma_{11} = \frac{K_1}{\sqrt{2\pi r}}\cos\frac{\theta}{2}\,(1-\sin\frac{\theta}{2}\sin\frac{3\theta}{2})$$

$$\sigma_{22} = \frac{K_1}{\sqrt{2\pi r}}\cos\frac{\theta}{2}\,(1+\sin\frac{\theta}{2}\sin\frac{3\theta}{2})$$

$$\sigma_{12} = \frac{K_1}{\sqrt{2\pi r}}\sin\frac{\theta}{2}\cos\frac{\theta}{2}\cos\frac{3\theta}{2}$$

$$u_1 = \frac{(1+\upsilon)K_1}{E}\sqrt{\frac{r}{2\pi}}\,(\kappa-\cos\theta)\cos\frac{\theta}{2}$$

$$u_2 = \frac{(1+\upsilon)K_1}{E}\sqrt{\frac{r}{2\pi}}\,(\kappa-\cos\theta)\sin\frac{\theta}{2}$$

Where K1 is called the "stress intensity factor". This factor depends on: (a) the problem geometry including the crack geometry, and (b) the magnitude of the applied load.

K1 is defined as $\lim_{r-0}(\sqrt{2\pi r}\sigma_{22}(r,0))$ or

$$K1 = \lim_{r-0}\sqrt{2\pi}\,(\sqrt{r}\phi'(a+r))$$

There are other methods used in determining the stress intensity factors of fracture mechanics problems (Reference 1.1):

- Mapping Techniques
- Laurent Series Expansion Method
- Asymptotic Approximations
- Alternating Method
- Integral Transform Methods
- Singular Integral Equations
- Conventional Finite Elements
- Special Finite Elements
- Boundary Element Method

A large number of solutions, obtained using these and other techniques, have been tabulated in various texts and handbooks.

The analysis used in this research is based on singular integral equations methods, and the details of this method will be presented in Chapter 4.

1.2.3 Fracture Criteria; Crack Initiation And Growth

Crack propagation (or growth) can be initiated under some stress conditions. These conditions are usually referred to as the fracture criteria.

Crack growth can be either stable or unstable. The crack initiation and growth criteria in mode 1 can be stated analytically as follows (Reference 1.1):

$K_1 = K_{1c}$

with $\frac{\partial K_1}{\partial a} < 0$ For stable growth,

and $\frac{\partial K_1}{\partial a} > 0$ For unstable growth.

Where K_{1c} is called the fracture toughness (or the critical stress intensity factor), which is a material property, and a is the half crack length.

The above criteria will be used in this study, and they will be explored further in the next chapter. However, it is important to mention that the above criteria may also be expressed using an energy approach by replacing K_1 with G, and K_{1c} with G_c. G is called the strain energy release rate, and G_c is called the critical strain energy release rate. G is related to the stress intensity factor K_1 as follows:

$$G = \frac{K_1^2}{E}.$$

Another energy based parameter that is often used in solving linear fracture mechanics problems is known as the J-integral, which can also be related to the stress intensity factors. These energy based parameters are briefly mentioned here because they appear in the literature review. Details regarding these energy based parameters are beyond the scope of this study. The approach used in this study is based on the stress intensity factors.

1.3 Review Of The Literature; Aspects Of Linear Fracture Mechanics Application To Cement-Based Materials

1.3.1 The structure of cement based materials

The first recognition that substantial microcracking occurrs before the stresses and strains become large enough to cause tensile failure under compressive load appeared as early as 1928 (Reference 1.4). The authors confirmed that compressive failure of concrete starts with bond failure at

aggregate-paste interface; then lateral splitting begins.

Blakey (Reference 1.5) provided a summary of the then current state of knowledge on fracture of concrete. The conclusions reached were: i) failure is related to the volumetric strain and to the shear strain energy absorbed in volumetric strain; and ii) cracking may start by: (a) fracture of the paste; (b) fracture of the aggregate; and (c) bond failure.

In Reference 1.6, the internal cracking of concrete was observed using microscopic and x-ray techniques as concrete was loaded axially to strains of up to 0.003. It was observed that very little cracking occurs through the aggregates. Bond cracks at aggregate-paste interfaces exist before any load is applied. The bond strength is less than the mortar strength. Bond cracks increase in size and number with increasing strain, but the increase is negligible below about 30% of the ultimate stress (strain=0.0006). Bond cracks occur first around the larger aggregate particles. Cracks in the mortar begin to increase and form continuous crack patterns at strains of about 0.0012 to 0.0018 (70-90% of ultimate stress). These mortar cracks appear always to bridge between nearby bond cracks. On the descending branch of the stress- strain curve, the concrete is extensively cracked. It was concluded that bond cracking alone does not cause failure. Concrete was noted to have a very redundant structure, and considerable interconnection between bond cracks is needed before failure occurs.

Shah and Winter (Reference 1.7) showed that the heterogeneity introduced by the aggregates in concrete leads to inelastic behavior. Evidence was presented that the bond between aggregates and mortar is the weak link in concrete.

In Reference 1.8, cracking characteristics of hcp (hydrated cement paste) and concrete in both tension and compression were studied using an optical microscope. It was found that cracks tend to form either at the cement-aggregate interface (bond failure) or as internal cracks in the aggregate which then propagate into the matrix.

The failure criteria for concrete are discussed in Reference 1.9. It has been found that crack initiation is due to the elastic incompatibility of the hcp and aggregates upon drying; these cracks will then propagate under tensile stress. Their formation relieves stress concentrations, and equilibrium is restored. As the load increases, the initially stable cracks begin to grow, till the system becomes unstable.

Shah (Reference 1.10) studied the cracking of plain and fiber reinforced concrete (FRC). In plain concrete, the non-linear behavior was assumed to be due to the composite action between the hcp and aggregates; volume changes were related to internal microcrack propagation. For steel FRC, fracture toughness was taken to be the area under the load-deflection curve. It was found that this toughness increases with increasing fibre volume, fibre aspect ratio, and fibre ductility.

The forces binding the cement and aggregate phases, and the effect of aggregates on the failure and strain distribution in hcp, mortar and concrete were discussed in Reference 1.11. It was stated that cracks at the interface exist even before loading; discrete microcracking occurs as cracks grow and are arrested by different phases. It was concluded that aggregate particles behave as stress-raising discontinuities. The steep stress gradients and strain concentrations within the material are due to the differential stiffness of the matrix and aggregates, and also due to the inherent imperfections in the interfacial region.

In Reference 1.12, a conceptual model was formulated to describe

progressive crack growth in plain concrete under compressive loading. At the macroscopic level, cracking was observed in prisms under compressive loads. In addition, fracture mechanics concepts were used to analyze the behavior of isolated cracks under compressive loading. It was concluded that below about 85 percent of the ultimate stress, the cracking is concentrated at the cement-aggregate interfaces and at voids. At higher stress levels, cracks extend into the mortar.

Swamy (Reference 1.13) discussed the basic features of cracking, fracture and deformation of concrete, and a theoretical model was developed which correlates size effects, stiffness, and ductility with the behavior of concrete under load. The model is based on concrete as a two-phase material, one phase being microcracks, and predicts the non-linear stress-strain behavior, size-dependent strength, and size effects on stiffness and ductility.

In Reference 1.14, cylindrical concrete specimens with a gauge length of 200 mm and diameter of 100 mm were tested under sustained axial tension. Ultrasonic pulse velocity and strain distribution measurements were made. It was found that interfacial cracks form in concrete at an early stage of loading, but failure was governed by the growth of cracks into the cement matrix. Under sustained loading, strength decreased to about 70% of the ultimate stress.

Both Portland cement and mortar were cast against glass microscope slides. After curing, the hcp was allowed to dry, causing separation due to shrinkage between the hcp and glass; the mortar specimens were fractured (Reference 1.15). Three boundary zones were observed using scanning electron microscope (SEM): i) An aggregate - "duplex film" boundary zone occurring at the original aggregate interface; and ii) A "duplex film" secondary lime boundary zone; the secondary lime layer served to join the duplex film to the paste.

In Reference 1.16, it was postulated that, under complex stress states, the fracture mechanism of concrete is that of crack initiation, followed by stable crack growth which eventually becomes unstable. These different stages can be identified. Both upper and lower bound failure criteria were proposed.

The structure of concrete has been generally described in three levels: (i) "microlevel", consisting of the porous matrix of hcp; (ii) "mezzo-level", consisting of mortar, including sand inclusions, microcracks, and capillary pores; and (iii) "macro-level", consisting of the concrete structure, including coarse aggregates, air voids, and interfacial cracks (Reference 1.17).

1.3.2 Fracture mechanics applicability to cement-based materials

Kaplan (Reference 1.18) did the first experimental work on the applicability of fracture mechanics to concrete. Three different mixes were tested at different notch depths. In the analysis, it was assumed that there was no crack growth before fracture. Kaplan found that:

i) Gc was approximately constant for different notch depths.

ii) Gc for smaller beams was about 38% less than for larger beams.

iii) Gc was about 12 times as large as that estimated from the surface energy of concrete. Nonetheless, Kaplan concluded the LEFM provided an appropriate fracture criterion for concrete.

In Reference 1.19, concrete plates, 132 in. long, 24 in. wide and 2.5 in. thick, with centrally located slots ranging from 2 to 12 inches in length, were tested in tension, and Gc was computed. It was found that Gc increases with increasing crack length. Up to 7% by volume of continuous, aligned fibres were then added, in order to examine their crack arrest mechanisms. It was found that with appropriate wire spacings, flaws could be prevented from propagating.

Lott and Kesler (Reference 1.20) described the fracture of concrete using linear elastic fracture mechanics (LEFM). The authors defined Kc as the pseudo-fracture toughness, since they included in this term some modifications of the elastic field near a crack tip due to aggregates. Kc (0.3 ksi$(in)^{1/2}$) was approximately independent of w/c ratio, but increased with coarse aggregate content. The fracture process was modelled as the growth of a zone of micro-cracking to a critical size at which fracture occurs.

Naus (Reference 1.21) concluded the following:

i) Kc decreases with increasing w/c ratio for hcp and mortar, but there is no effect in concrete.

ii) Kc decreases with increasing air content.

iii) Kc increases with age.

iv) Kc increases with increasing maximum aggregate size.

v) Kc increases with increasing gravel/cement ratio.

vi) Kc increases with increasing sand/cement ratio in mortars; it decreases with increasing sand to cement ratio in concrete.

In Reference 1.22, It has been found that the addition of aggregates increases Kc, and also results in a progressive increase in toughness with crack growth. Toughness increases with aggregate content. For hcp, toughness increases with decreasing w/c ratio, almost irrespective of age. In hcp, the unhydrated clinker acts in a similar manner to aggregates in mortar.

The applicability of LEFM to hcp, mortar and concrete has been investigated by testing plate specimens with a precast flaw. The dimensions of the specimens were 2x12xW in., where W ranged from 18 to 36 in. The results indicated that, at least for these test conditions, LEFM did not apply to the materials tested. It was found that large localized strains occurred near flaws (Reference 1.23).

Radgy and Hansen (Reference 1.24) presented a review of the literature in the field of fracture mechanics of cement and concrete, with 44 references cited. The application of fracture theory is discussed, and various fracture parameters from the literature are tabulated. Cracking and fracture are also discussed from a phenomenological point of view.

Higgins (Reference 1.25) reached the following conclusions relating to the fracture toughness of cement paste (hcp):

i) the material is notch sensitive;

ii) Kc appears to be independent of notch depth;

iii) Kc increases with age to about 20 days, and then remains constant;

iv) Kc increases with decreasing w/c ratio;

v) Kc increases somewhat with increasing rate of loading;

vi) Kc increases with increasing notch width, but remains constant at notch widths below 0.5 mm;

vii) Kc increases with increasing beam depth, but appears to be independent of changes in beam width or length.

The fracture parameters of hcp, aggregate, and the cement-aggregate interface have been studied using wedge-loaded compact tension specimens (Reference 1.26). It was found that:

i) hcp is notch sensitive.

ii) in hcp, Kc decreases with increasing crack length; a characteristic Kc occurs only after the crack has propagated a certain distance. The decrease of Kc with crack growth may be due to the formation of microcracks around the initial notch.

iii) Kc of the cement-quartz interface decreases very steeply with crack length, and levels off at a value of Kc about 1/3 that for hcp.

iv) behavior of concrete in bending depends largely on the Kc of the interface.

A review of the structure and mechanical properties of cement and concrete was presented in Reference 1.27. As part of this, a brief review of fracture mechanics applications to cement-based materials was presented.

Reference 1.28 concluded the following about the fracture of cement-based materials;

i) Fracture toughness increases with increasing aggregate size.

ii) Matrix cracks are initiated by aggregate particles.

iii) Different aggregates give different Kc values.

iv) Fracture toughness increases with increasing specimen size.

In Reference 1.29, fracture studies were carried out on mortar beams of two different sizes: 3 in. wide x 3 in. deep x 11.5 in. long, and 3 in. wide by 1.5 in. deep x 11.5 in. long. Ratios of notch depth to specimen depth (a/w) varied from 0.04 to 0.69. The results were:

i) For both beam sizes, nominal flexural strengths of the notched beams were about 75% of those of the unnotched beams.

ii) Kc showed a high variability, but appeared to be independent of a/w.

iii) The initial Kc was higher for the 3 in. deep specimens (476 psi $(in.)^{1/2}$ vs. 353 psi$(in.)^{1/2}$).

iv) After slow crack growth during loading was estimated by compliance techniques, the recalculated Kc values were 651 psi$(in.)^{1/2}$ for the 3 in. deep beams, and 450 psi$(in.)^{1/2}$ for the 1.5 in. deep beams, with a larger scatter in results than for the Kc values based on the initial crack depth.

The authors therefore concluded that:

i) The compliance method for estimating slow crack growth is inaccurate.

ii) Notch effects can be measured even in shallow beams.

iii) The existence of a true Kc for concrete is uncertain.

In Reference 1.30, the authors showed that Kc depends on:

i) beam dimensions;

ii) notch dimensions;

iii) concrete properties; and

iv) the method of analysis used.

Shah (Reference 1.31) found that the critical strain energy release rate (Gc) calculated conventionally did not accurately represent the fracture behavior of the

material. A modified definition of Gc was therefore developed, which included both the elastic and the inelastic strain energy absorbed during crack extension. For the double torsion specimens studied, unstable crack propagation occurred at a crack length of about 305-380 mm, at a value of Gc = 0.56 lb/in.

A "model law" for the notch sensitivity of cementitious materials is presented in Reference 1.32 assuming that LEFM is applicable to these materials. It indicates that the notch sensitivity of the specimen is a necessary but not sufficient condition for the applicability of LEFM. The "model law" predicts:

i) Maximum notch sensitivity will occur at a relative crack length of 0.246 (with respect to specimen width).

ii) Notch sensitivity will increase with increasing size.

iii) Notch sensitivity will decrease as the ratio of fracture toughness to tensile strength (Kc/St) increases.

The "model law" was then used to analyze data from the literature, as well as some data obtained by the authors.

Bazant (Reference 1.33) presents a fracture theory of heterogeneous materials for which the fracture zone is not small compared to structural dimensions, and which exhibit gradual strain-softening due to microcracking. The material fracture properties are characterized by only three parameters: fracture energy, uniaxial strength, and the width of the crack band (i.e. the fracture process zone). A method of determining the fracture energy from measured complete stress-strain relations is also given. It is concluded that the fracture of concrete must be analyzed in terms of both strength criteria and fracture energy criteria. A simple formula is derived to predict from the tensile strength and aggregate size the fracture energy for a fully developed fracture process zone; the width of this process zone in plain concrete is about 3 times the maximum aggregate size.

In Reference 1.34, the fracture toughness of concrete was investigated by testing about 3000 specimens, with varying types of cement, types of aggregate, maximum aggregate size, specimen age, specimen temperature, specimen size,

and type of test (beam in tension; prism with a central slit; compressive cylinder with a central notch). It was found that Kc increases with increasing crack length, and it depends on the maximum aggregate size, and also depends on the temperature. The critical crack length was also found to increase linearly with increasing maximum aggregate size.

1.3.3 Fracture mechanics application to fiber reinforced cement-based materials

Romualdi (Reference 1.35) performed four-point flexural tests on a series of beams reinforced with varying amounts of aligned steel fibres. The results were analyzed in terms of a fracture arrest concept; at some critical reinforcement spacing, cracks could be contained between adjacent reinforcing elements.

It has been found that steel fibres resist crack growth, and that the resistance to crack growth is proportional to the inverse square of the fibre spacing. Gc increased with fibre content, because of the energy required to cause slippage of the short fibres ahead of the crack tip. It was also found that fibres increase both the impact resistance and fatigue life of concrete (Reference 1.36).

The work of fracture and Kc for FRC samples made with glass, mild steel and high carbon steel fibres were determined in 3-point bending. The work of fracture was determined from the area under the load-deflection curve. The work could be increased by 2 orders of magnitude with 2% by volume of fibres, while Kc increased by only a factor of 2. It was found that (Reference 1.37):

i) The work decreases with increasing notch/depth ratio; it was approximately equal to 10 Joules/meter^2.

ii) Kc was not significantly different in wet or dry specimens.

iii) Kc decreased with long-term storage in a dry environment, perhaps due to shrinkage cracks. Mild steel gave the highest Kc values after long term storage.

Glass FRC beams (250x38x38 mm) were tested in 4-point loading (Reference 1.54). The notch depth was about 14 mm and a compliance technique

was used to determine crack length. It was found that for the unreinforced matrix Kc was approximately constant, at about 0.4 MN $m^{-3/2}$. However, the apparent Kc for the glass FRC increased with crack growth. Kc also increased with increasing fibre content. It was approximately independent of age.

Polymer impregnated concrete specimens (impregnated with various polymers) were cast in the form of 40x40x460 mm beams. It was found that strength could be predicted reasonably well using linear fracture theory (Reference 1.38).

Polymer impregnated cement beams (76x13x13 mm) were tested in 3-point bending, and the results were analyzed to provide a measure of the effective surface energy (or fracture energy) (Reference 1.39). The fracture energy of the impregnated material was considerably higher than that of the unimpregnated hcp ($735x10^4$ vs. $0.91x10^4$ ergs/cm^2). The increase appeared to be entirely due to the polymer contribution.

It was found that the fracture toughness of latex modified concrete was about 17% higher than that of ordinary air-entrained concrete (Reference 1.40).

Compact tension single edge cracked specimens were mode using high alumina cement reinforced with E-glass fibres, with a glass content of about 15% by weight (Reference 1.41). Using a quasi-static approach, the work to extend the crack was calculated. It was found that for air cured specimens, Kc increased with age up to about 5 weeks; for water cured specimens, Kc increased with age for about 3 weeks and then decreased, due to the effect of water on the fibres and on the bond. A large zone of fine cracks was noted around the principal crack when the specimens were the crack tip. Kc appeared to be independent of specimen size.

Polymer impregnated (PMMA) hcp and mortar specimens were prepared, and compared with regard to their strength and fracture parameters (Reference 1.42). Fracture tests were carried out on double torsion specimens, 105x57x6.3 mm. It was found that impregnation greatly increased the measured Kc values, and the strength under sustained load appeared also to be increased. In terms of

fracture characteristics, the unimpregnated mortars failed by fracture through the hcp, with the sand grains still covered by a layer of hcp. The fracture surface of the impregnated mortars passed through both the hcp and the sand grains.

Acoustic emission was used to study the fracture of plain and polymer impregnated mortars (Reference 1.43). It was found that:

i) Fracture mechanics parameters such as Kc were independent of crack length beyond a crack length of 20 mm.

ii) Kc was not particularly affected by w/c ratio and curing time.

iii) Polymer impregnation increased Kc.

iv) From the acoustic emission results, it was found that extensive microcracking occurred in both materials. However, impregnation suppressed the onset of microcracking, leading to an enhanced fracture stress.

v) Microcracking appeared to occur within a zone around the macrocrack tip, and contributed to crack propagation resistance.

In Reference 1.44, the post-cracking behavior of FRC was studied in flexure. Steel, polypropylene and glass fibers were used. Three stages in the stress-strain behavior were defined:

i) A linear region, in which the energy goes in part into initiating cracking;

ii) In the second region, up to the maximum load, energy is used up in sub-critical crack growth;

iii) The descending branch, in which there is energy absorbed in unstable crack growth.

A method of analysis was suggested to evaluate the energy absorption capacity of concrete in terms of the maximum load, specimen compliance, and deflection. The total energy absorption capacity increased with increasing fibre content. The order of effectiveness of different fibres was steel > glass > polypropylene.

The cracking stress and the fracture toughness of steel FRC were measured (Reference 1.45). The fracture surface energy and work of fracture were also determined. The work of fracture was explained in terms of the work done in overcoming friction during fibre pull-out. The greater toughness of PMMA concrete was due to an increase in interfacial frictional shear stress.

The fracture toughness of polymer concrete was measured (Reference 1.46). It was found that premix polymer additives reduced Kc, while polymer impregnation increased Kc by a factor of about three. Compliance techniques for monitoring crack length were found to be useful. Cast notches gave somewhat different results from natural cracks.

The fracture toughness of steel FRC was evaluated (Reference 1.47). Fibre volumes ranged from 0-2%. The crack opening displacement (COD) measurements were made. Kc was determined on the basis of maximum load, neglecting slow crack growth. It was concluded that the ASTM method for fracture testing of metals is also suitable for concrete. Kc of FRC was 2-3 times greater than Kc for plain concrete.

The CNRBB test (circumferentially notched round bar under bending) was used to determine the fracture toughness of cylinders 200 mm long, 100 mm in diameter, with notches of different depths. Both steel and polypropylene fibres were used. It was found that cracks at the cement-aggregate interface existed even before the specimens were loaded. Both Kc and Gc were found to increase with increasing notch depth. Both parameters increased with increasing fibre content; steel fibres were about twice as effective as polypropylene fibres (Reference 1.48).

After a review of the attempted applications of LEFM to fibre reinforced cementitious materials, three series of tests on steel FRC were reported (Reference 1.49). It was found that, depending on the specimen dimensions and type of test, brittle failure might not occur. A pseudo-plastic zone occurred in front of the crack tip, due to the action of fibres. It was concluded that experimental techniques to measure fracture properties must still be developed for FRC.

Reference 1.50 has suggested that the stress intensity factor for FRC be

separated into two components in order to account for the effects of fibers.

Mindess (Reference 1.51) reviewed about 37 References on the application of fracture mechanics to fibre reinforced concrete, polymer concrete, and polymer impregnated concrete. The difficulties of applying fracture mechanics principles to these systems were discussed, as were some of the models that have been proposed for the way in which polymers or fibres improve the fracture toughness of cementitious systems. It was concluded that a non-linear fracture mechanics criterion would be more suitable for describing the fracture of these materials.

Fibre concrete beams (using steel, glass or polypropylene fibres) were tested in 4-point bending (Reference 1.52). Crack extension as observed using optical microscopy was shown to be complex. It was shown that the fracture toughness vs. crack growth curves give a clear characterization of the influence of slow crack growth on the fracture behavior of fibre concretes, and that slow crack growth cannot be neglected in fracture toughness tests. Considerable branch cracking was observed during the tests, and even low fibre volumes imparted some stable crack growth to the system. The apparent Kc increased, first linearly, and then much more rapidly, with crack growth.

The fracture toughness of polypropylene fibre concrete was measured using both cubes with two slits in eccentric compression, and also compact tension specimens (Reference1.53). It was found that the introduction of polypropylene fibres did not particularly change the fracture toughness. It was concluded that LEFM could be applied to these materials.

1.3.4 CONCLUSION

From the literature review it seems clear that LEFM may be applied to hardened cement paste specimens of sufficient dimensions provided that the special properties of these materials are taken into account.

The phenomenological descriptions of the fracture process of concrete and FRC have delivered valuable information. But many fundamental problems are still unsolved. Therefore, direct applicability of LEFM to concrete and FRC is not certain.

Also, it seems clear that a great deal of further research, both experimental and theoretical, into the fracture of hcp and concrete is warranted. The physical process of cracking needs further study; the simplistic models of crack propagation are not sufficient to represent the fracture process.

CHAPTER 2

Modeling Of The Mechanical Behavior Of Fiber Reinforced Cement Based Composites: The Analysis Stage

2.1 INTRODUCTION:

This chapter presents the general procedure of the modeling process, with emphasis on the first stage, the analysis stage. The purpose of the model is to predict analytically the tensile behavior of fiber reinforced cement composites based on: (1) stochastic simulation; (2) theory of linear elasticity; (3) theory of linear elastic fracture mechanics (LEFM); and (4) the state-of-the-art on the mechanics of the tensile behavior of fiber reinforced cement-based composites (the real system).

A real system or simply a system is defined as a set or collection of related, interdependent, and interactive elements (components or entities) that act together to accomplish a certain task. The elements of a system have attributes (or characteristics) that have logical or numerical values. There are a number of internal relations (or activities) that exist between the elements which imply the interactions between these elements. A system has a boundary. All the elements of the system are within its boundary. Whatever is outside the boundary is labeled as the system environment. External relationships are held between the elements of the system and its environment. The attributes of the system elements define its state. A system receives input from its environment (Reference 2.1). Figure 2.1 schematically presents the above concepts.

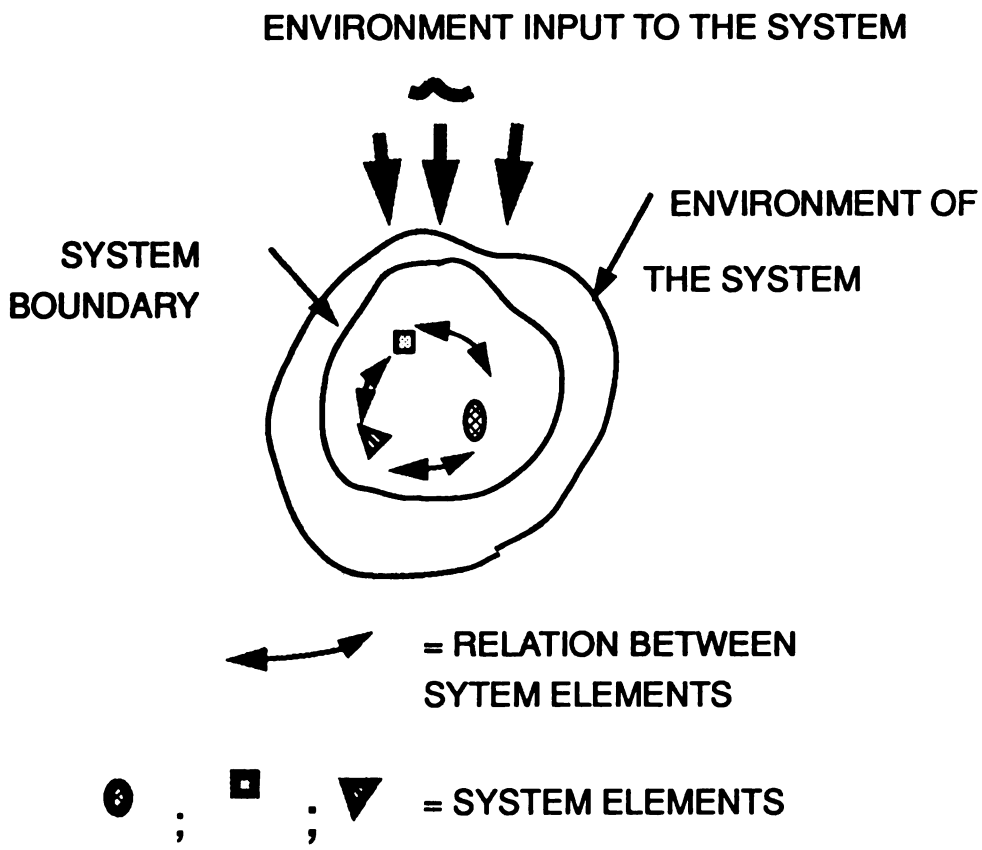


FIGURE 2•1 Graphical Presentation of a System

A model is defined as an abstraction of a real system. There are, however, many classes of models; a symbolic model is to be used for the problem at hand. A symbolic model requires mathematical or logical operations and most of the time it is implemented as a computer algorithm. There are many advantages of using symbolic models (Reference 2.1):

- They enable the researcher to systematically organize his or her theory and empirical observations about a real system and to deduce logical conclusions.

- They help the researcher to learn more about the real system.

- Symbolic models cost less than experimenting with the real system.

- Results can be obtained faster than experimenting with the real system.

- It is usually easier to use a model than the real system. Also, a model is more flexible to work with.

However, there are few disadvantages regarding the construction and use of models (Reference 2.1):

- It is not guaranteed, ahead of time, that the model will produce beneficial results regarding the real system. Therefore, a formal stage of model construction is its validation.

- Some researchers tend to treat, erroneously, their particular models as the best and only representation of the real system.

- Models may erroneously be used outside the range of their applicability.

Symbolic models can be classified as static or dynamic depending on whether they take time variation. Most models are dynamic, even though the time variable may not be explicit in the model; it suffices that one variable is time dependant. Another classification of models is deterministic versus stochastic models. In deterministic models all relationships between the elements are prefixed. In a stochastic model, at least one variable is random. It is not necessary for the model to approximate the exact behavior of the system to be effective; it suffices that there is a high correlation between the behavior of the model and that of the real system.

The structure of cement-based materials is highly heterogenous and random; therefore, in our case, a stochastic model would be more representative of the actual system.

After constructing and checking or validating a mathematical (or symbolic model), conclusions and solutions to problems related to the real system can be established. An important tool in establishing these results using a valid model is simulation. Simulation may be defined as conducting experiments using a valid model in order to establish conclusions and solutions to problems related to the real system. Due to rapid advances in computer

technology, simulation (being a numerical technique) is one of the most widely used and accepted tools in operation research.

If the model ia a stochastic model, the process of simulation is called stochastic simulation or the Monte Carlo Method. There seems to be a wide range of definitions for the term Monte Carlo Method; however, in general it refers to any technique that uses random numbers for solution of a model (References 2.1, 2.2, and 2.3).

Because our study concerns stochastic symbolic models and for convenience, the words simulation and Monte Carlo Method will be used interchangeably to mean stochastic simulation as defined above. However, in some contexts the terms simulation and Monte Carlo Method may have differences (Reference 2.1).

The system investigated in this study is fiber reinforced cement-based composites subjected to static tensile stresses. The model to be constructed is described in the following sections.

2.2 Stages of the model development:

Before beginning to construct a model, the researcher should answer the following questions (Reference 2.3):

(1) What are the problems the model expected to help solve?

(2) If the model is built, what kind of comparison would be made with the real (or actual) system in order to determine the validity of the model?

(3) Assuming that the model has been constructed and its validation checked, what experiments with the model will help answer questions related to the actual system? In other words, what kind of simulations are to be run on the model?

After establishing the need and the necessity of the model by answering the above questions, the first stage of model development is the study of the actual system:

- identify the elements of the system.

- identify the attributes of each element.

- identify the type of values of the attributes (numerical or logical).

- identify the range of values of the attributes.

- identify the relationship between the attributes and between the elements (internal relations).

- identify external relations between elements and environment.

- identify those aspects of the system that require stochastic description.

This first stage is termed "System Analysis" which is centered around the organization of the theory and the analytical procedures for studying the system.

The second stage organizes the diverse results as established in the first stage (system analysis) into a logical structure. This stage provides the flow charts, computer codes and data files. In this stage the selection of hardware (computer) and software (programing language) is made. This second stage is termed "Model Synthesis". This stage ends when the computer program which represents the symbolic model of the system is completed.

The third stage of modeling is the "Model Verification" stage. This stage makes sure that the computer program works as was intended.

The fourth stage is the "Model Validation" stage. This stage establishes the degree of correlation between the model and the system.

The fifth and final stage of model development is termed "Model Analysis". This is the most important stage since it provides the results, conclusions and the answers to problems related to the real system, which were the reasons the model was needed to be constructed in the first place. In this stage, the verified and validated model is used to make inferences regarding the behavior of the real system.

Therefore, the five stages of model construction are, in order of execution:

(1) System Analysis

(2) Model synthesis

(3) Model Verification

(4) Model Validation

(5) Model Analysis

A compact description of these stages is shown in Table 2.1.

TABLE 2•1 Description Of the Modeling Stages

STAGE	TASKS
	JUSTIFY THE NEED AND FEASIBILIY OF THE MODEL
SYSTEM ANALYSIS	-- DEFINE THE REAL SYSTEM -- IDENTIFY SYSTEM ELEMENTS -- IDENTIFY PROPERTIES OF THE ELEMENTS -- IDENTIFY THE RANGES OF THE ABOVE VALUES -- IDENTIFY SYSTEM BOUNDARY -- IDENTIFY ENVIRONMENT INPUT -- IDENTIFY ALL TYPES OF RELATIONSHIPS -- IDENTIFY STOCHASTIC ASPECTS OF THE SYSTEM
MODEL SYN-THESIS	-- ORGANIZE THE INFORMATION OF STAGE 1 INTO A LOGICAL STRUCTURE. -- CHOOSE HARDWARE AND SOFTWARE, THAT IS: COMPUTER AND PROGRAMMING LANGUAGE
MODEL VERIFICA-TION	--CHECK AND DEBUG THE PROGRAM OF STAGE 2 --MAKE SURE THE PROGRAM GIVES THE INTENDED CORRECT RESULTS.
MODEL VALIDA-TION	--ESTABLISH THE DEGREE OF CORRELATION BETWEEN THE MODEL AND THE SYSTEM BY COMPARING AVAILABLE SYSTEM DATA WITH RESULS PRODUCED BY THE MODEL.
MODEL ANALYSIS	--EXPERIMENT WITH THE VERIFIED AND VALIDATED MODEL, TO ESTABLISH RESULTS, CONCLUSIONS, AND SOLUTIONS TO UNANSWERED PROBLEMS REGARDING THE REAL SYSTEM

In carrying out the final stages of modeling, decisions may be made to revise an earlier stage if any one of the stages proves to be invalid. The revision can be made in accordance with Figure 2.2 (Reference 2.3).

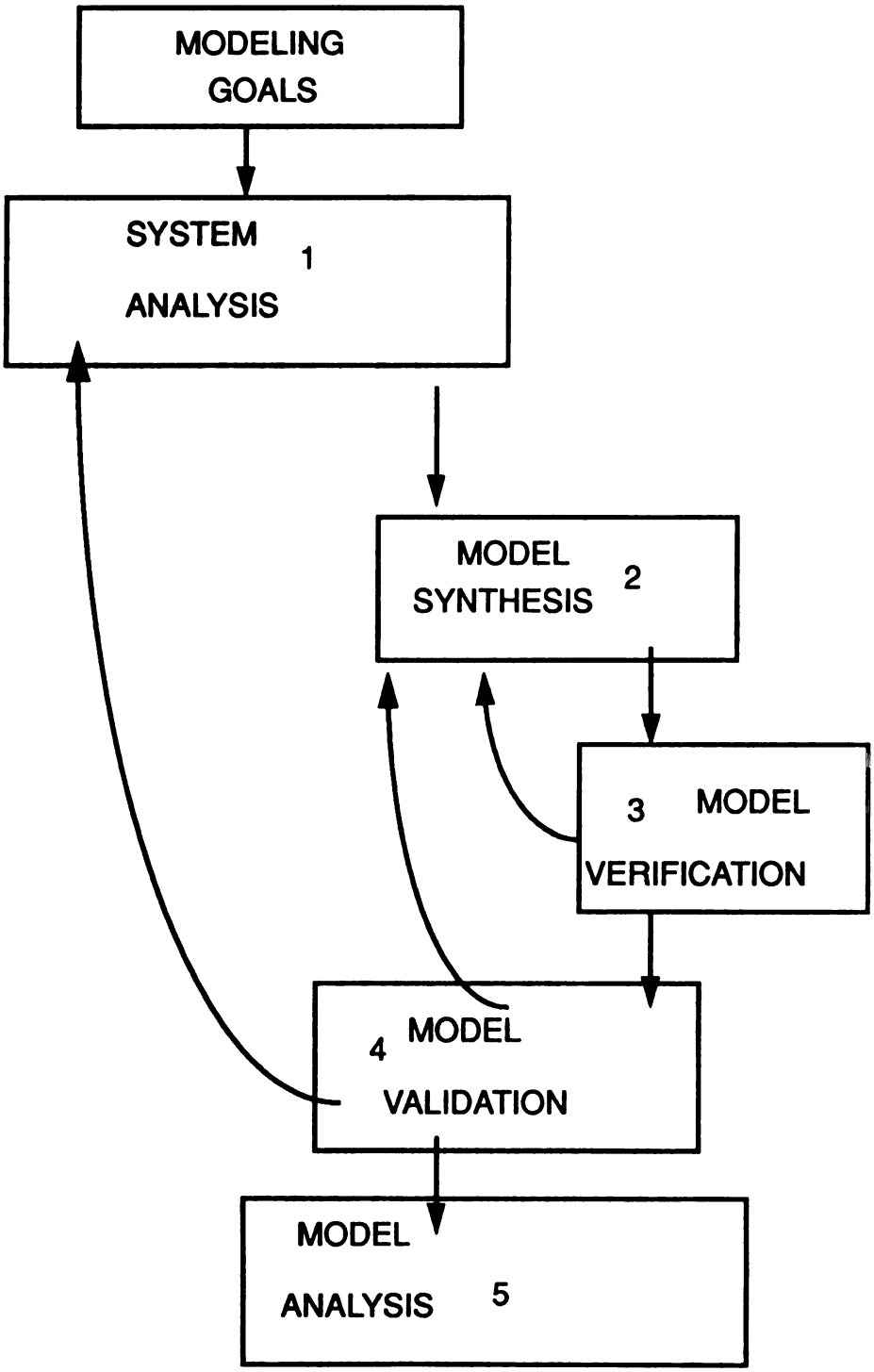


FIGURE 2.2 Revisions Of The Modeling Stage (Reference 2.3).

2.3 The need and feasibility of computer modeling of cement-based materials.

In this section we establish the need and feasibility of computer modeling of cement-based materials by answering the previously raised questions:

- Who may benefit from the model of cement-based materials?
- What types of problems (related to the tensile behavior of cement-based materials) will the model help solve?
- What kind of checking is feasible for validating the model?

Cement-based materials are the world's most commonly used building materials. In spite of this, when compared with many other materials, little is known about the mechanics of their behavior. This proposed model is to be used as a research tool to investigate the tensile behavior of cement-based materials.

New cement-based materials are evolving with advancements in composites technology. Fiber reinforced cement-based composites are now considered as low-cost and energy-efficient alternatives to metals and plastics; therefore, a model of fiber reinforced cement composites can help in the evaluation process of new cement based composite materials. Also, the model may help in the development of new advanced cement-based composites.

2.4 Analysis of fiber reinforced cement-based composite materials (system analysis stage)

2.4.1 Introduction:

This section defines specifically what is to be modeled (that is the real system). And presents the inputs and the outputs of the system. As mentioned earlier, the system is a specimen of fiber reinforced cement-based composite subjected to tensile loads. The input to the system is uniaxial displacement. The output of the system is mainly the material resistance in terms of load-deflection (or stress-strain) curves and the maximum load re-

sisted by the specimen. Also the output will include the development of cracks in the specimen under increasing tensile loads. This description is depicted in Figure 2.3.

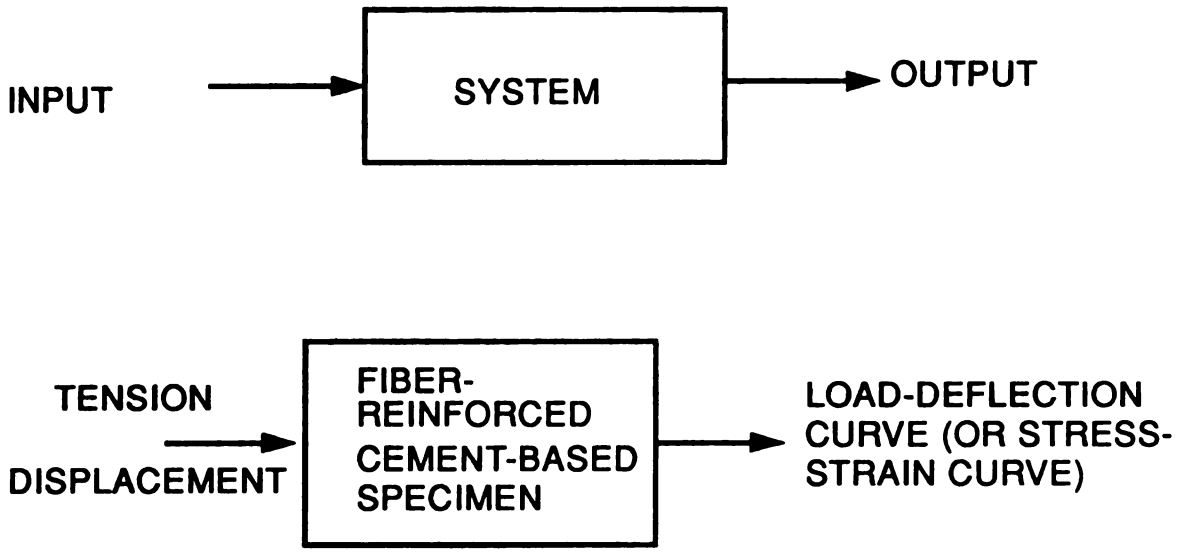


FIGURE 2•3 Formal Definition of the System.

The goal is to relate the inputs and the system to the outputs. In other words, if the system is described through some state variables and mechanisms of action which make the outputs predictable, then a theory describing the system behavior will be developed. For the system at hand, that is fiber-reinforced cement-based composite material, we need to know:

(i) The structure of the composite; and

(ii) A theory that best describes the material behavior as the applied displacement is increased; and relates changes in the material structure to changes in the output, mainly the crack pattern and load-deflection curve.

In order to achieve the above objectives, the state-of-the art knowledge about the subject was used together with personal ingenuity; were

used, also simplicity was kept in mind for ensuring the usefulness and practicality of the resulting model. In modeling the performance characteristics of fiber reinforced cement-based composite materials under tension, the following aspects of the material structure and behavior were considered separately.

The structure of the matrix is considered to be homogeneous and isotropic, with inclusions and defects distributed within it. The inclusions include the fibers and the aggregates. The defects include voids or pores and cracks. The interface between the inclusions and the matrix is considered as a separate component of the structure of the material. The cracks are of two kinds: cracks at the interfaces between matrix and inclusions, and those within the matrix. A general sketch of the structure of the material is presented in Figure 2.4.; more information regarding the origin and magnitude of defects and the material components will be presented in later sections.

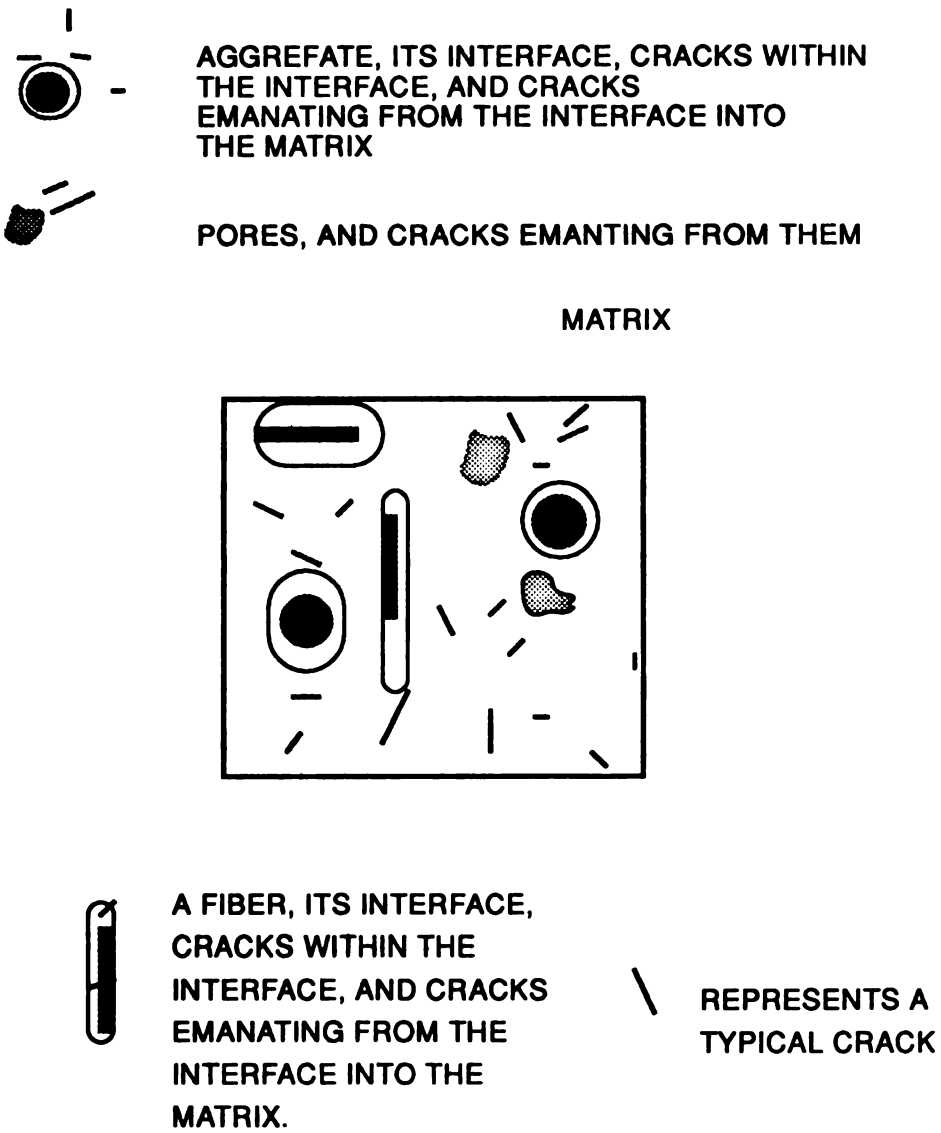


FIGURE 2•4 Meso-Level Structure of Fiber Reinforced Cement-Based Composite Materials

Since cracks are inherent parts of the structure of cement-based materials, fracture mechanics is the discipline that can describe the behavior of

the material when subjected to static loading. The stress-strain curves of most cement pastes (the matrix) is linear; linear fracture mechanics can thus be used to describe the behavior of cement composites if an indirect way can be found to incorporate the nonlinear effects of the inclusions (fibers and aggregates). In short, the system can be described in two steps:

(1) Use linear fracture mechanics to study the response of the specimen to displacement input.

(2) At the same time, indirectly, and in a way that is compatible with the theory of linear fracture mechanics, include the effects of aggregates and fibers.

The model should consider:

(1) The actual crack configuration prior to loading;

(2) Techniques to follow the development of cracks that mostly affect the material resistance;

(3) The aggregate effects on crack propagation, and its relation to the resistance of the material under load;

(4) The toughening effects of fibers and their interaction with the cracks; and

(5) Above all, the relation of (3) and (4) to the linear fracture mechanics problem.

The stress-strain curve is to be developed by considering the stages that the material undergoes as the input displacement is increased. The following stages are defined based on the internal changes occurring within the specimen as the testing proceeds:

- Stage 0: Preload
- Stage 1: Aggregate interfacial cracks propagate to their maximum length possible.
- Stage *: Starting point of the model; corresponds to an elastic matrix; no crack has yet started propagating into the matrix.

- Stage 2: Matrix has just reached its breaking limit; that is at least one crack has started propagating into the matrix.
- Stage 3: Pre-peak; fiber reinforcement enters into the picture by toughening the matrix and trying to arrest the propagating cracks; the Pre-peak region is characterized by the fact that the reinforcement effect of fibers is higher than the damaging effect of the propagating cracks. Hence, the material keeps on resisting more load. Also, in this region the rate of change of fiber reinforcement effects is higher than the rate of the crack damaging effects; this is due to the fact that the material keeps on resisting more load during this stage.
- Stage 4: Peak; at this stage the material has reached its maximum capacity, and its resistance cannot go beyond this point. At this point the fiber reinforcing effect and the crack damaging effect have the same rate of change.
- Stage 5: post-peak; in this stage the rate of the fiber reinforcing effect is lower than the rate of the damaging effect of cracks; therefore the material resistance has no way to go but to drop.

These general stages of material behavior at increasing levels of input displacement form the basis that the model uses to generate the stress-strain curve. Also, the crack propagation patterns will be monitored during these stages. More detailed presentations of the material behavior at different stages are presented in the following sections, which deal with:

(i) Linear Fracture Mechanics and the fracture criteria of isotropic materials and its applicability to cement-based materials in general and cement paste in particular.

(ii) The structure of cement-based materials.

(iii) Crack propagation in fiber reinforced cement-based composite materials.

. (iv) Fiber reinforcing mechanisms and their interactions with cracks; incorporation of these mechanisms into a linear fracture mechanics model.

(v) Strain or deformation computations.

(vi) Aggregates and their effects on the formation and propagation of crack; incorporation of these effects into a linear fracture mechanics model.

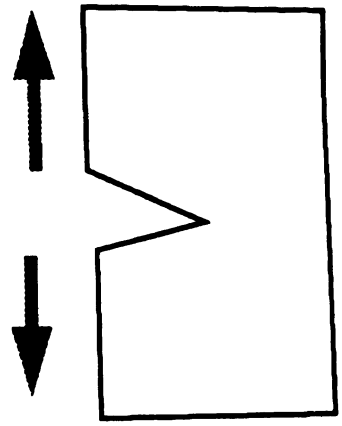
2.4.2 Linear Fracture Mechanics and the Fracture Criteria of Isotropic Homogeneous Materials; its Applicability to Cement-Based Materials in General and to Cement Paste in Particular.

An isotropic homogeneous material containing internal cracks (or cuts) is considered. Cracks are characterized by stress free surfaces and discontinuous displacements across their surfaces (Figure 1.1). There are three modes of loading that can be applied to a crack as shown in Figure 2.5. Fracture mechanics provides the concepts and equations used to determine how cracks grow and affect the strength of the material; in other words, fracture mechanics is the study of the effects of applied loads and the crack geometry on the Fracture process of the material. Fracture may be defined as a mode of structural failure characterized by the formation of new surfaces in the material, starting from an original crack. If the material is known to have a linear stress-strain relation then fracture mechanics is termed Linear Elastic Fracture Mechanics (LEFM). Hence, materials that do not yield upon failure can be analyzed using LEFM concepts. It can be shown also that LEFM problems may be converted into boundary value problems in linear elasticity. A fracture criteria may be defined as a theory that explains the phenomenon of fracture of a material. The concept of stress intensity factor, and the material fracture toughness Kc, were introduced and defined earlier in Chapter 1. A fracture criteria that can be used with LEFM, that is to decide whether a crack is propagating or not under a given condition, is a relation between the actual stress intensity factor K and the material toughness Kc: Fracture occurs if K = Kc.

Most cracks that develop under loading conditions follow mode 1 (see Figure 2.5), unless they are artificially forced into other modes (Reference 2.4). Hence tensile mechanical tests that are performed on cement-based materials will be of this category, that is mode 1. Therefore the failure criteria that the model uses is: K1=K1c

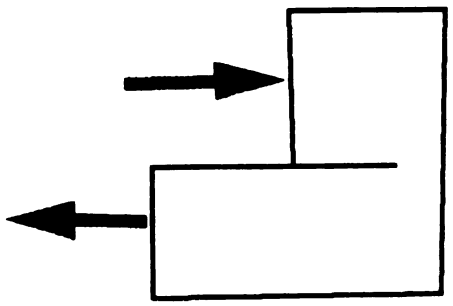
As discussed above, a prerequisite for the application of LEFM is a linear stress-strain behavior of the material. The general shapes of the

stress-strain curves for cement paste and for concrete are well established, and also the reasons for the shapes and differences are fairly well understood (concrete is produced by the addition of coarse aggregates to a mortar of fine aggregates and cement paste). Figures 2.6 presents these general shapes, and Figure 2.7 shows some crack related phenomena that takes place in concrete under compressive loads (Reference 2.5).

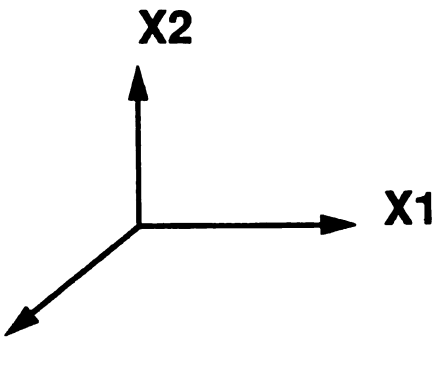


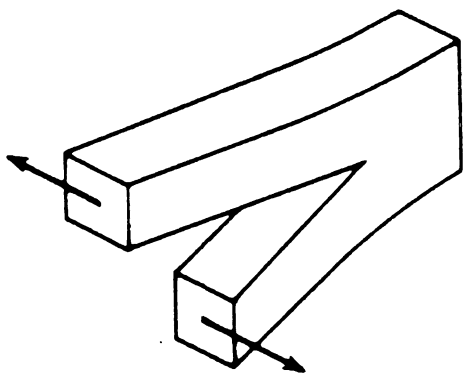
OPENING MODE OR MODE I

MOST MATERAILS TESTS IS IN THIS MODE, UNLESS ARTIFICIALLY FORCED OTHERWISE.



SLIDING MODE OR MODE II





TEARING MODE OR MODE III

FIGURE 2•5 Modes of Loading of a Crack.

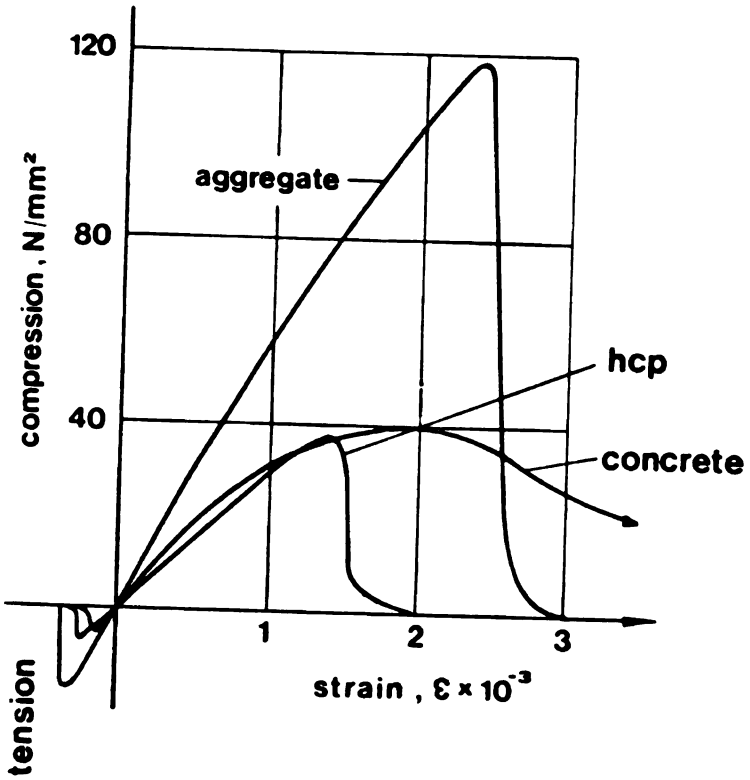


FIGURE 2•6 Stress-Strain Diagram Of Hardened Cement Paste, Aggregate And Concrete (reference 2.6)

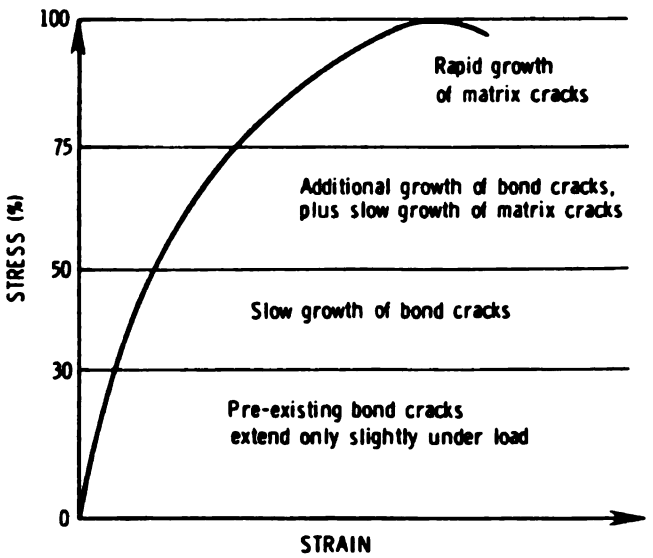


FIGURE 2•7 Stress-Strain curve for concrete.

The stress-strain curve for cement paste is observed in Figure 2.6 to be linear up to about 90 - 95% of its ultimate strength. The small nonlinear part in the stress-strain curve of cement paste is due to the fact that the paste contains some unhydrated cement grains which are dispersed in the cement hydrates (C-S-H). The bond between the hydrates and the non-hydrates is not perfect and uniform, this imperfect bond is the main cause of the nonlinear portion. In concrete, the interface between the paste and the aggregates is a major factor in the nonlinear behavior of concrete. The linear behavior of cement paste and its brittle nature of failure make LEFM applicable to the material. Also, relatively low ratio of tensile strength to compressive strength of cement paste, which is of the order of 1/10, agrees with LEFM predictions (Reference 2.5). Another point that makes LEFM applicable to cement paste is the fact that almost all investigators report that cement paste is notch-sensitive, that is, as an artificial cut is introduced into the specimen, the strength of the specimen varies with variation of notch length. Therefore, it can be confidently assumed that LEFM is applicable to cement paste, noting that cement paste is the matrix in fiber reinforced cement composites, which are the subject matter of this investigation.

The Fracture criterion in mode1 is: K1= K1c where K1 is the stress intensity factor at a certain point in time during the test; K1 should includes the effect of fibers at that time. K1c is the fracture toughness of the matrix taking into consideration the effects of aggregates.

2.4.3 Structure of Cement-based Materials With Respect to Crack Formation and Failure Process.

There are three different levels at which the structure of cement-based materials can be studied (Figure 2.8) (Reference 2.7). These three levels are interrelated, and in order to understand the structure of cement-based materials at a certain level, we need to use results from the previous levels. The three levels are labeled the micro-level, the meso level, and the macro-level.

The micro-level is concerned with the study of the structure of hardened cement paste by considering the chemical and mineralogical aspects as the hydration process occurs.

The meso-level is concerned with details related to pores, cracks and inclusions.

The macro-level uses the information produced by the previous two levels to describe the material behavior in a way that can be used in structural engineering design and analysis.

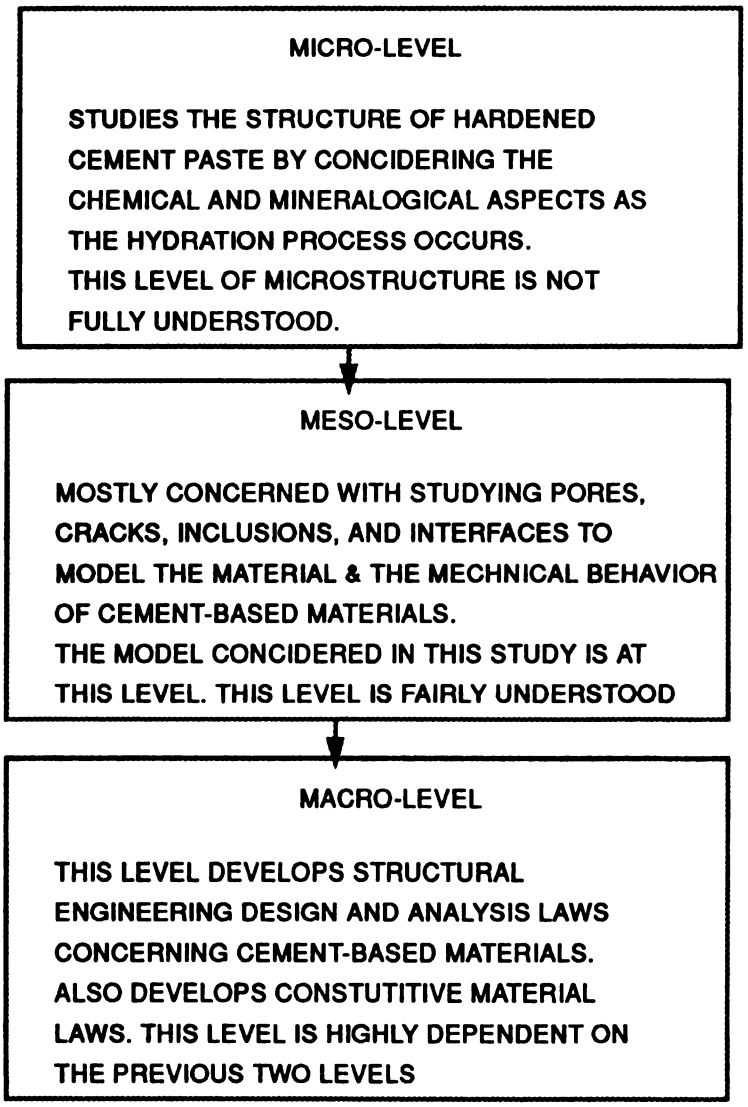


FIGURE 2•8 Levels of the Structure of Cement-Based Materials.

Our concern is to study the material behavior at the meso-level. Therefore, the main characteristics of the material structure that we will consider are pores, pre-existing cracks, inclusions and interfaces between inclusions and the matrix.

However, it is helpful to consider some micro-level aspects of the hydration process of cement-based materials (Reference 2.8):

- The early hydration processes include formation of a mostly C-S-H (calcium silicate hydrate; a colloidal and poorly crystalline material of variable composition) composition around each of the individual cement grains.

- Subsequently, the hydration process leads to the deposition of a thickening layer of dense C-S-H within the shell and progressive emptying out of the interior of the shell into the outside of the shell.

- The external environment to the shell, especially the local availability of solution-filled space for products to deposit in, strongly influences which mode of hydration would occur.

- As the hydration process continues a skeleton of hydration products ties the shells together into a three-dimensional network of hardened cement paste.

- Special structures, involving several different classes of C-H (calcium hydroxide or Ca(OH)2), occur near boundaries of cement paste with inclusions such as aggregates and fibers. This special structure is usually called the transition zone. The thickness of this zone is of the order of 50 micrometers.

- If fly ash is present, then shells similar to those around cement grains also form around fly ash particles. Products of the reaction of fly ash are deposited outside the shell.

This level of study is not, in any way, completely understood. However, past investigators have identified the types of constituents and their evolution as they form the hydrated cement paste. These constituents may be presented as follows:

[1] Hydration products far away from an inclusion interface: mainly aggregations of C-S-H and crystals of C-H.

[2] Hydration products at the transition zones, (very different in structure from [1]).

[3] Air voids: entrapped air voids and entrapped air bubbles.

[4] Other voids: capillary voids and interparticle voids.

The distribution of the above constituents depends on the mix proportions of cement-based materials. However, for a concrete mix, the overall structure of the hardened material may be quantitatively expressed as follows. The inclusions (aggregate, fibers,...) are held together through the transition zones (50 micrometer) by a mesh of three-dimensional cement paste hydrated products which are in the form of ribbons in the order of 150 micrometers or less in thickness. These ribbons are interrupted at frequent intervals (- 200 micrometer) by air voids (Reference 2.8).

In the following, the structure of cement-based materials will be considered at the meso-level, which investigates the material in relation to pores, pre-existing cracks and inclusions (fibers, aggregate,...).

The micro-level analysis of cement-based materials establishes the existence of pores and a transition zone between inclusions and the matrix. These pores directly affect the strength of the material.

Cracks exist in cement-based materials before any load is applied. These cracks are caused by the following mechanisms (Reference 2.7).

1. Incomplete compaction leads to the earliest type of cracks to form. This type of crack is due to localized high porosity areas.

2. The process of bleeding (caused by sedimentation) takes place immediately after pouring and before hardening. This process causes water-filled pockets to form under aggregates, hence producing horizontal cracks.

3. Heat of hydration produces thermal cracking. This type of cracking can be prevented with special curing conditions.

4. Shrinkage cracks occurs after demolding.

5. The thermal and shrinkage cracks form dominantly at the interfaces of inclusions and the matrix.

The above cracking phenomena are summarized in Table (2.2).

TABLE 2•2 Crack Formation In Cement Based Materials

Stage of life of the Material	Type of crack (surface discontinuity)
Pouring and compaction	Insufficient compaction pores
Fresh material	Bleeding cracks (cavities)
(after pouring & before Hardening)	
Hardening material	Thermal cracks
	Chemical and capillary
	Shrinkage cracks
Drying material (after demolding)	Shrinkage Cracks
	interfacial cracks
Loaded Material	Interfacial Cracks
	Matrix Crack growth

From the above description of the cracking phenomena in cement-based materials we can conclude that the strength performance of the material will depend on the curing conditions. For this reason we assume in what follows that the curing conditions are fixed.

The meso-level of studying cement-based materials recognizes that the transition zone is much weaker than the matrix and hence any crack propagation will initiate in the transition zone. The transition zone cracks (i.e. thermal and shrinkage cracks are influenced by the curing conditions.

2.4.4 Crack Propagation in Cement-Based Fiber Reinforced Materials.

Prior to any loading there are two types of cracks present in fibrous specimens:

(1) matrix cracks, and

(2) cracks at the interfaces between inclusions and the matrix.

It is well established that the interfaces are weaker than the matrix. Therefore, the interfacial cracks will propagate first to their maximum possible length within the interface. This maximum length is directly related to the size of the inclusions. The effects of matrix microcracks are assumed negligible when compared with those of the already propagated interfacial cracks that are comparable in size to aggregates. Hence, after a certain level of loading required to compute the propagation of microcracks at the interface zones (20% to 30% of maximum load), the specimen behavior is controlled by the further propagation into the matrix of interfacial cracks, the size of which is directly related to aggregate size. Therefore, after a certain amount of loading, the crack configuration is controlled by aggregate size. In the above discussion we restricted the interfacial cracks to aggregates and not fibers. In other words, we acknowledge that the interfacial cracks at fiber interfaces are more stable than those at the aggregates interfaces. We propose the following justifications, with the first one being the most sound reason.

(1) The transition zone (or interface) develops when the hydration products C-S-H and C-H get in contact with a relatively large and non-compatible boundary surface such as sand. That is the hydration products are very small compared to the boundary surface. This non-compatibility alters the hydration process, and creates the interface or the transition zone. The hydration products (aggregation of C-S-H particles and crystals of C-H) are of the order of 5 micrometers in size. Carbon fibers which are the key fiber types considered in this investigation, have diameters of the order of 10 micrometers, whereas the aggregate dimensions are more than 1 mm (or 1000 micrometers). Obviously, the difference in size is much greater in the case of aggregate than in the case of carbon fiber. Therefore, the fiber dimensions

are more compatible with those of the hydration products than the aggregate, and thus the alteration of hydration process by fibers is not as critical as that due to aggregate. In fact, since the fiber diameter is compatible to the size of hydration products, carbon fibers almost totally blend into the matrix and do not alter its original structure. However, this discussion may not fully apply to other fiber types with large diameters; these latter fibers have to have a transition zone just as the aggregates; the fiber transition zone may be stronger or weaker than that of the aggregate depending on the fiber diameter and its surface characteristics. This implies that the transition zone weakness is proportional to the size of the inclusion.

(2) The differences in elastic and chemical properties between fiber and aggregate make the crack propagation phenomenon at fiber interfaces different from that at aggregate interfaces.

The above reasonings indicate that, for the case of carbon fibers and after a certain load, major changes in the crack configuration (and hence the specimen response) may be noticed only when the aggregate interfacial cracks have been fully developed and start to propagating into the matrix.

From a linear fracture mechanics point of view the above analysis can be summarized as follows (Reference 2.10):

First, we consider a straight interfacial crack, that can be present at the interface of a polygon-shaped aggregate. We consider the case of a square aggregate (Figure 2.9a), where the crack can extend either at the interface or into the matrix. Figure 2.9b shows the relationship between the applied load at the onset of rapid unstable crack propagation and the crack length; the plotted curves are called "curves of instability". Curve 1 is the curve of instability for the interfacial crack and Curve 2 is the instability curve for a matrix crack having the same length. At point A the interfacial crack has reached a critical length, that is K1=K1c(Interface), where K1 is the stress intensity factor and K1c(interface) is the critical stress intensity factor of the interface. Therefore, the crack becomes unstable and will propagate rapidly within the interface until it reaches the end of the aggregate face (point B). At point B, the crack is arrested and cannot propagate into the matrix, because the stress intensity factor will be below the critical

stress intensity factor of the matrix. Therefore, the load has to be increased before the crack can propagate into the matrix. In other words, after the interfacial crack has reached point B, Curve 2 will control the crack propagation. Hence, the load has to be increased until it reaches point C before the crack can propagate into the matrix.

So far, we established that the final length of bond-cracks depends on the shape and size of the aggregate, and also on the fracture toughness of both the interface and the matrix. After full formation of the interface crack, the crack propagation is controlled mainly by the fracture toughness of the matrix and the fiber effect, which will be considered in the next subsection and in more details in the next chapter. From the above discussion it may be concluded that the specimen resistance can be determined (after a certain load) on the basis of a known crack distribution at interface zones. The length and orientation of these cracks depend on the aggregates and the direction of loading.

2.4.5 Fiber Reinforcing Mechanisms and their Interaction with Cracks.

In general, the most common energy absorption mechanisms provided by an inclusion to the composite are crack deflection and crack bridging. Crack deflection occurs when a crack runs into an inclusion, which causes the crack to change direction (figure 2.10). Crack bridging occurs, when a crack runs into an inclusion such as a fiber, which may not change the crack direction but may slow down or even stop crack propagation (figure 2.11).

In this subsection the mechanisms through which fibers interact with cracks are identified. Also, the bridging and pull-out mechanisms, that are more representative of carbon fibers in mortars are presented. A model that determines the fiber pull-out forces as it interacts with a propagating crack cracks is presented in the next chapter.

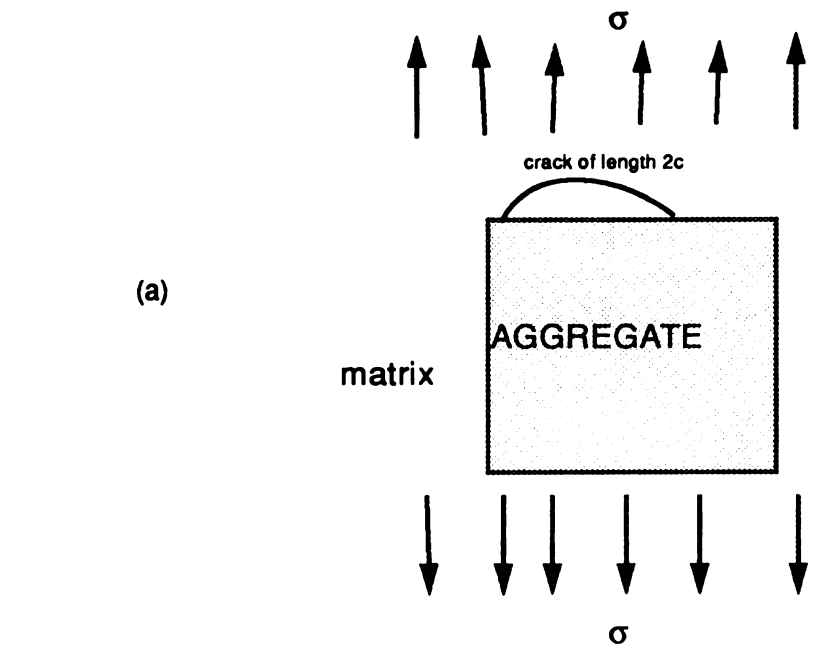
Toughening mechanisms due to the presence of fibers in mortar involves the cracking of the matrix followed by fiber resisting crack propagation until it fails at a subsequently higher composite stress. This mechanism

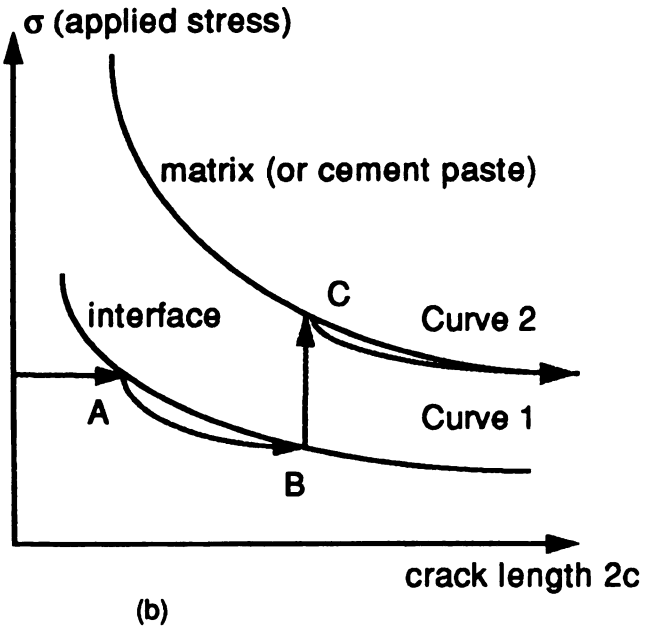
is strongly influenced by the strength of fiber and interface zone. The key toughening mechanisms, in the case of carbon fibers is the bridging and pull-out processes of the fibers; the fracture energy involved in pulling out the fibers against the interfacial bonding contributes to the toughness of the composite material. Full reviews of the relevant theoretical concepts and fracture mechanics approaches is presented in the next chapter: a new modeling approach of the fiber effects in cement-based materials is also presented in the next chapter.

2.4.6 Effects of Aggregates on the Fracture Toughness Of the Material

This investigation is concerned mainly with mortars. This restriction is due to the approach used as discussed previously.

Mortars, however, contain fine aggregates. Therefore, the effects of the fine aggregates on the material fracture toughness has to be included. An empirical relation is used for this purpose (Figure 2.12).





A: original interfacial crack has reached a critical length

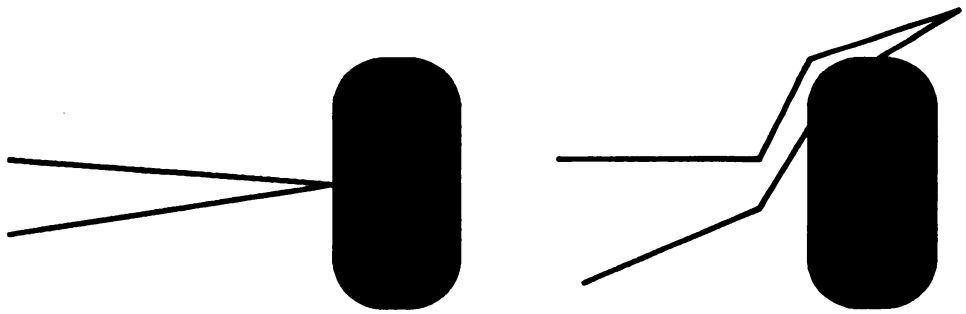
A--B: interfacial crack propagates within the interface

B: The crack reaches its maximum possible length within the interface

C: crack starts propagating into the matrix

B--C: load has to be increased so that the crack continue into the matrix

FIGURE 2•9 Aggregate Size Control of The Original Interfacial Cracks; Mechanism of Crack Extension for Square Shaped Aggregate.



A CRACK MAY DEFLECT IF THE INCLUSION IS NOT THE WEAKEST PATH

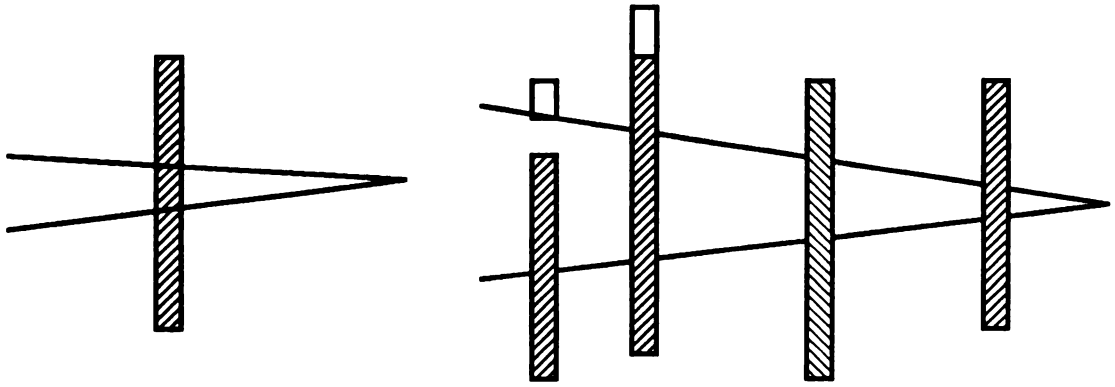
THE CRACK PROPAGATION PATH CAN BE FORMALLY SHOWN TO SELECT THE PATH THAT REQUIRES MININMUM ENERGY.

THEREFORE, THE CRACK USUALLY FOLLOWS THE INTERFACE OF THE AGGREGATE.

LIGHT-WEIGHT AGGREGATE USUALLY BREAKS UPON APPROACHED BY A RUNNING CRACK.

IN OUR CASE, DEFLECTION IS USED TO ASSIMULATE THE TOUGHENING EFFECTS OF AGGREGATES.

FIGURE 2.10 Deflection of a Crack By an Inclusion; a Toughening And Energy Absorption Mechanism.



FIBER
PULL-OUT

MATRIX CRACK MAY PROPAGATE PAST A FIBER, LEAVING IT UNBROKEN. THIS FIBER THUS ACTS AS A BRIDGE ACROSS THE CRACK. AS THE CRACK TENDS TO EXPAND INTO THE MATRIX, IT HAS TO DISSIPATE SOME ENERGY EITHER TO BREAK THE FIBER OR TO OVERCOME THE INTERFACIAL BOND OF THE FIBER. HENCE, THE UNBROKEN FIBER MAY BE THOUGHT OF AS EXERTING A CRACK CLOSING FORCE.

IN THE ABOVE BRIDGING PROCESS, FIBERS MAY PULL OUT DEPENDING ON THEIR LENGTH, THE INTERFACIAL BOND AND THEIR ELASTIC PROPERTIES.

FIGURE 2.11 Crack Bridging And Fiber Pull-Out; Mechanism of Action And Interaction of Fibers and Cracks.

FRACTURE TOUGHNESS INCREASE DUE TO AGGREGATE DEFLECTION OF RUNNING CRACKS:

$$\left(\frac{K_C}{K_{0C}}\right)^2 = \sum_0^7 A_n \left(\frac{r'}{c}\right)^n .$$

An 's: are empirical values

r' is related to the inclusion size Ro

c is the average distance between inclusions

Kc is fracture toughness of the matrix with aggregate.

K0c is toughness of matrix only.

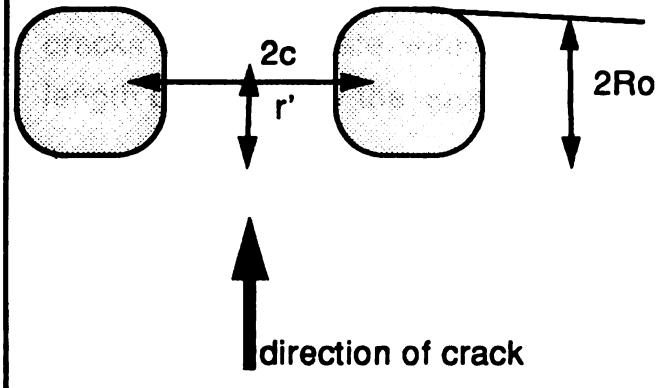


FIGURE 2.12 Empirical Model Used to Account for the Effects of Fine Aggregates on the Material Fracture Toughness.

CHAPTER 3

Fiber-Matrix Interaction Modeling

3.1 General description of the modeling approach

The general shape of the stress-strain curve can be predicted using the theory presented in Chapter 2. The following points summarize the approach.

- Cracks are inherently present in any cement-based material; therefore fracture mechanics is a very representative approach to the investigation of the mechanical behavior of cement-based materials.
- The structure of cement based materials is highly random, therefore stochastic modeling of the cracks and inclusions is appropriate.
- The matrix (i.e. cement paste) has to have a highly linear stress-strain curve, for linear elastic fracture mechanics to be applicable.
- The interfacial zones are weaker than the matrix; therefore the bond cracks will propagate within the interfacial zone first, to a maximum length controlled by the aggregate size.
- As the load is increased further, cracks will propagate into the matrix, where they will interact with the fibers.
- Fibers will bridge the cracks, allowing the material resistance to be increased to a peak value.
- In the post-peak region, The damaging effect of the propagating cracks exceeds the controlling effects of the bridging fibers; the material resistance drops thereafter, until failure (separation at a crack) occurs.
- From the above, one may postulate that the stress-strain curve will have a shape as shown in Figure 3.1.

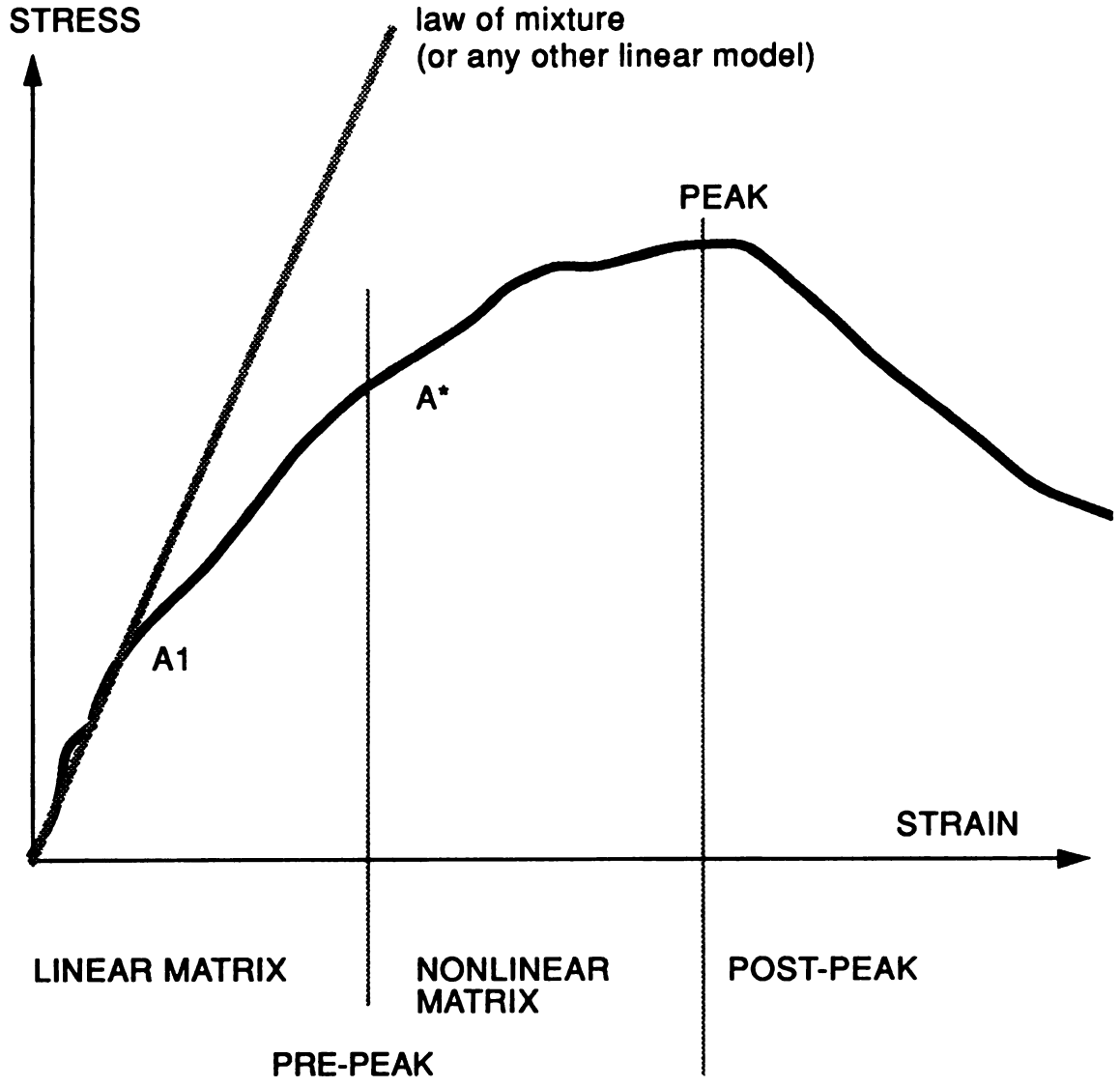


FIGURE 3.1 General Shape of The Stress-Strain Curve.

3.2 Fiber-Matrix Interaction; Stress Transfer, Crack Bridging, Bond and Pull-Out

Analytical treatment of fiber to matrix stress transfer and the crack-bridging action of fibers is usually accomplished by analyzing the shear stress that develops at the fiber-matrix interfaces. It is usually based on the configuration shown in Figure 3.2.

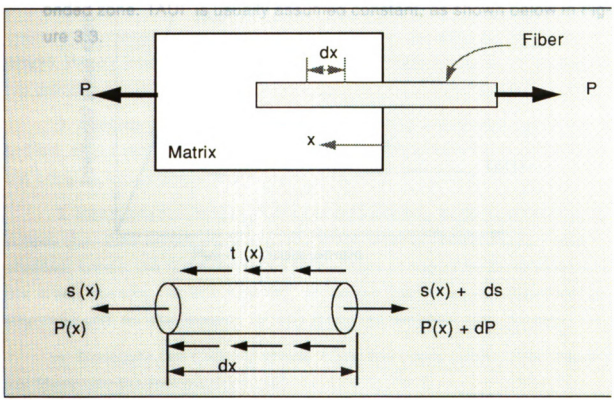


FIGURE 3.2 Stress Transfer at the Fiber-Matrix Interface

The mechanisms of stress transfer at the fiber interfaces can be described as follows:

- Originally, the stress transfer at the interface is elastic, that is the fiber and matrix deformations at the interface are compatible.
- The elastic shear stress at the interface is non-uniform. (Figure 3.3).
- At higher stress levels, debonding across the interface occurs, and friction takes over the mode. The frictional shear stress is usually assumed uniform along the fiber-matrix interface.
- The transition from elastic to frictional stress occurs when the interfacial shear stress exceeds the fiber to matrix bond strength (TAU). Thereafter, fiber debonding starts and frictional stress (TAUF) will act along the debonded zone. TAUF is usually assumed constant, as shown below in Figure 3.3.

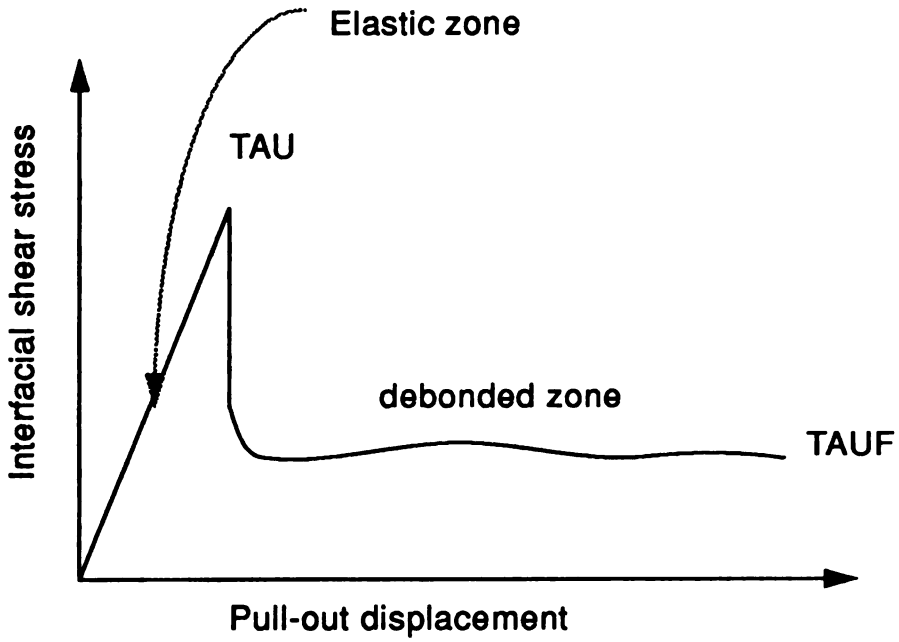


FIGURE 3.3 Theoretical Derivation of the Interfacial Elastic Shear Stress.

3.3 Commonly Used Fiber Pull-Out Models, and Derivations of the Equations For the Case of Constant Average Shear Along the Interface

3.3.1 Details Of the Pull-out Approach used:

The task is to compute the bridging forces exerted by each fiber that is bridging a currently propagating (active) crack. During each step (of load or crack length increment), the following subtasks are performed:

1. Add newly active fibers: as the crack propagates into the matrix, it interacts with new fibers; these fibers increase the bridging force on the crack. The current bridging forces may or may not stop (or stabilize the crack). Hence, keeping track of newly activated fibers is crucial in the modeling process.

2. Remove the bridging effects of fibers that are totally pulled out or broken; hence these fibers become inactive and they have no contribution to the bridging forces on the crack.

3. Revaluate the bridging forces of active fibers; since as a crack propagates (i.e. their length increase), the crack opening (width, COD) also increases; hence, the fibers have to either stretch or slip to be compatible with the crack opening. At any moment, an active crack can be described as: stretched with no end slipping, or fully stretched with one end slipping.

4. Distribute the bridging forces along the crack length. Also classify the fibers into the following groups:

Group A: Stretched with no end slip

Group B: Stretched with end slip

Group C: Broken or totally pulled out fibers (inactive fibers)

3.3.2 Evaluation of the Bridging Forces

The bridging forces can be computed using the following variables and the configuration shown in Figure 3.4.

X: stretched fiber length (primarily unknown)

S: slip of fiber end (primarily unknown)

COD: crack opening displacement at fiber location (known)

TAU: average fiber-matrix interfacial shear strength (known experimental value)

DEL: fiber elastic elongation=$2*TAU*X^2 / (Ef*Df)$

L: fiber embedment length (known, a random number between 0 and Lf/2)

lf: fiber length

Ef: Modulus of elasticity of the fiber

Df: Diameter of the fiber

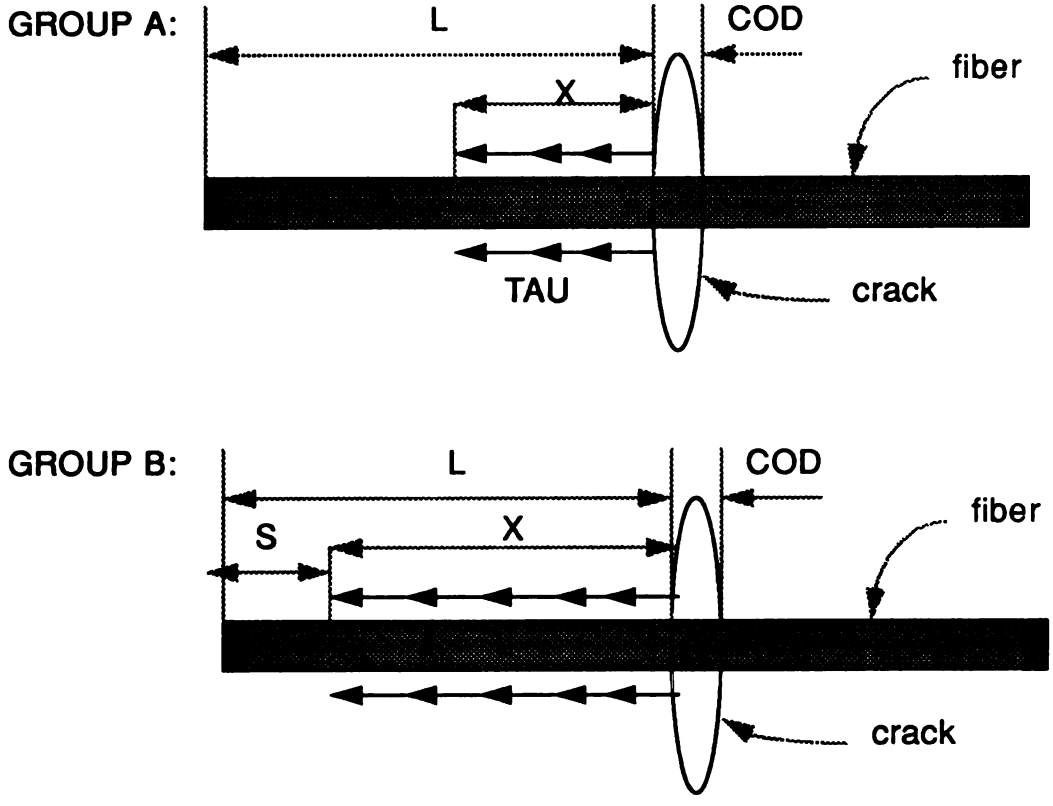


FIGURE 3.4 Configuration Used In the Computation of the Fiber Bridging Forces.

The fiber bridging force can be determined if the fiber stretched length X is known:

From the equilibrium the axial stress in the fiber is: SIGF=4*TAU*X/Df

Therefore, the bridging force is: FBRIDGE=Af*SIGF

X is determined from displacement compatibility at the crack opening:

2*DEL + S + SIGF*S/Ef = COD

where:

2*DEL: represents the total elastic deformation of the fiber segment embedded in both sides of the crack.

DEL is given by: $$DEL = \int_0^x \frac{SIGF(x)}{Ef} dx = \frac{2(TAU)x^2}{EfDf}$$

SIGF*S/Ef: represents the elastic deformation of the fiber segment which has slipped out from the matrix.

3.4 Techniques for Evaluating the Fiber Stretched Length X and the Slippage S

Let COD=w and a = 4 * TAU / (Ef * Df)

Therefore, the compatibility equation simplifies to:

$a*X^2 + a*X*S + (S - W) = 0$.....(3.1)

As a fiber becomes active for the first time, we assume S=0, that is no slippage. Therefore:

X = SQRT (W * Ef * Df / (4 * TAU))).....(3.2)

After the first time, when the effect of a fiber is being computed, we do not know whether S=0 or not. Hence, X and S are unknowns. However, if it is determined whether S=0 or S>0, then both X and S are determined from Equation(3.1) as follows:

IF S=0 then X is given by Equation (3.2)

If S>0, Then we know that X and S are related by: S=L-X, and then X can be obtained from equation (3.1), and is given by:

$$X = (w - L) / (a*L - 1) \quad \text{.....(3.3)}$$

Therefore, to solve for the bridging forces, we need to know whether the slippage S is zero or not.

3.5 Technique for Determining the Slippage: S

If during the previous classification of fibers, a fiber was classified in Group B, that is S>0, then this fiber will always remain in group B; that is X is given by Equation (3.3), and S=L-X.

If during the previous classification of fibers, the fiber was in group A, that is S=0, and the fiber had a stretched length X1, then first we assume that the fiber will remain in group A, and we compute the stretched length X2 using Equation (3.2).

If X2 is less then L, then the assumption is correct, that is the fiber end is not slipping, and the fiber remains in group A (X=X2).

If X2 is larger then L, then the assumption is wrong and we compute X using equation (3.3). The fiber is placed in group B, for the next step.

CHAPTER 4

PLANE ELASTIC ANALYSIS OF MULTI-CRACKED BODIES; COMPUTATION OF STRESS INTENSITY FACTORS (SIF) AT CRACK TIPS

4.1 Introduction:

In this study, we are concerned with the analysis of elastic bodies containing internal cracks (or cuts). In an isotropic homogeneous material; these cracks are characterized by stress free surfaces and discontinuous displacements across these surfaces. Figure 4.1 presents the essential features of a crack. A crack is usually flat, but may grow along a curved path, depending on the fracture criteria that are used.

A crack can be stressed in two different modes; the opening and sliding modes for plane problems such as our case.

Many problems of bodies with cracks have been solved with the aid of the linear theory of elasticity. A large selection of these solved problems can be found (References 4.1-4.3). Most of these solution, however, refer to solids with single cracks or with specially stacked cracks. In general, these solutions do not help in solving the problem at hand, namely plane elastic solids with arbitrarily located and oriented cracks.Alternative approaches to the solution of arbitrarily multi-cracked plane solids are discussed below:

Approach 1: References 4.4 and 4.5 present the solution for an infinite plate with arbitrary multiple cracks. This method uses the complex variable formulation of linear theory of elasticity, which reduces the multiple crack problem into solution of singular integral equations. This type of analysis is

defined in the infinite domain, and is approximate with an error of 3.4% (Reference 4.6) in application to finite bodies if the distance between cracks and the boundary is more than five times the crack length.

Approach 2: This method is called the "fictitious stress method" (or the virtual load method); it considers the interaction between the boundary and cracks. Using this method, multiple crack bodies with arbitrary boundary loads can be resolved, by superposition, into three basic parts:

(a) Analyze the uncracked body subjected to original boundary loads.

(b) Find stresses from part (a) at crack locations then set the solution for the infinite plate being loaded with stresses from part(a), and using approach 1.

(c) Divide the boundary of the body into discrete points, and assume there exist tangential and normal "fictitious stresses" applied at each boundary point. These fictitious stresses are unknowns to be solved for. Then set the solution of the uncracked body subject to the unknown fictitious stresses at the boundary.

By Superposing the solutions (a), (b), and (c) and by enforcing the boundary conditions at each crack point and boundary point, an integral equation is found for each crack point and each boundary point. Using numerical integration, the integral equations can be transformed into a set of linear equations, with the fictitious stresses being the unknowns. After the system of equations is solved, the solution parameters such as stresses and stress intensity factor smay be expressed as functions of the fictitious stresses, which were already solved for. A detailed explanation of this approach is given in Reference 4.6. This approach seems to give accurate results.

Approach 3. This approach presents an analytic fictitious boundary forces method for solution of multi-crack problems in finite bodies. The method is based on the following techniques: superposition, boundary element method, and analytical solution of elementary single crack problems. The general idea of this approach is described on Reference 4.7, and it has been proven to be highly accurate and reduces computation time. This approach was adopted for solving the multi-crack elastic problem.Detailed description of this approach is presented in the next sections, however, what follows is a brief and general description of the approach.

We adopt approach 1 for our analysis, which will be discussed in more details in the next section.

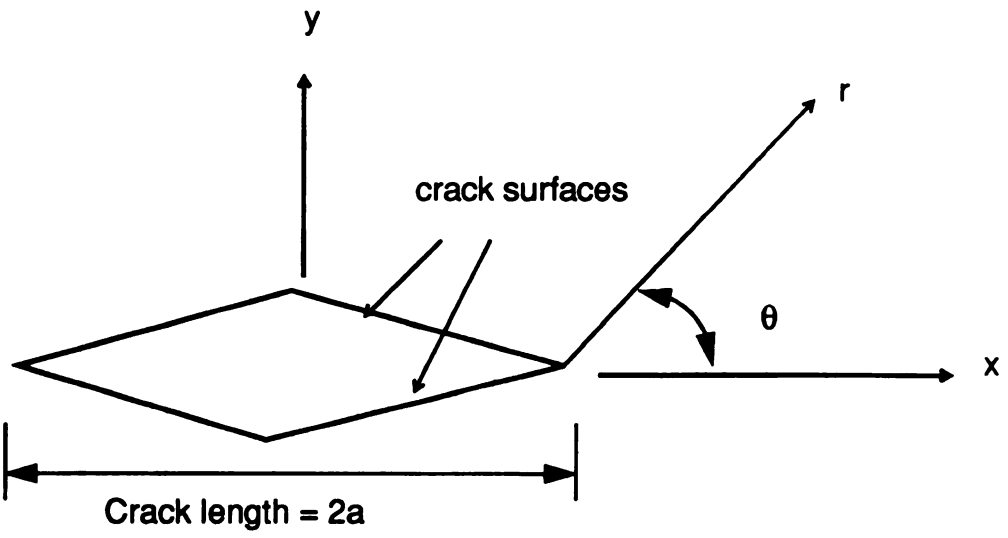


FIGURE 4.1 Crack Geometry.

4.2 Stress Intensity Factor Computation Technique for Multiple Crack Problem

4.2.1 Multiple Crack Problem in an Infinite Plane Plate; Description

We want a general approach to solving plane elastic problem for a solid weakened by a set of straight arbitrarily located cracks (Figure 4.2).

The boundary condition of the solid is applied at infinity and can be any type of displacements or stresses.

We are interested in determining the stress intensity factors at the tips of the cracks.

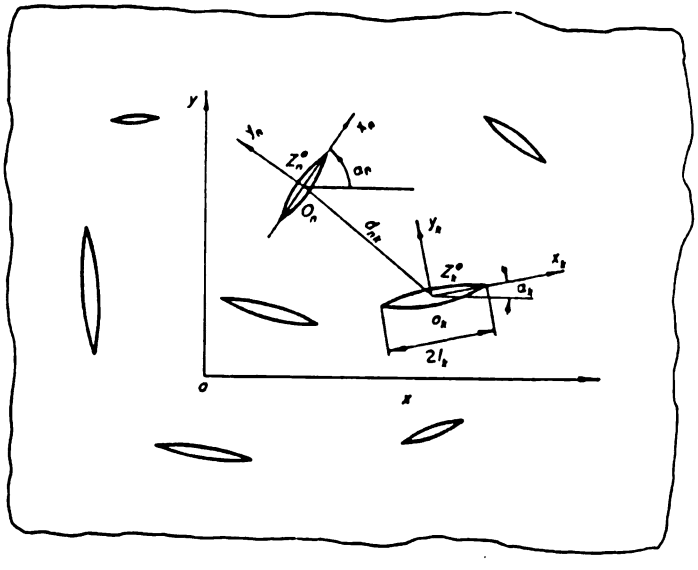
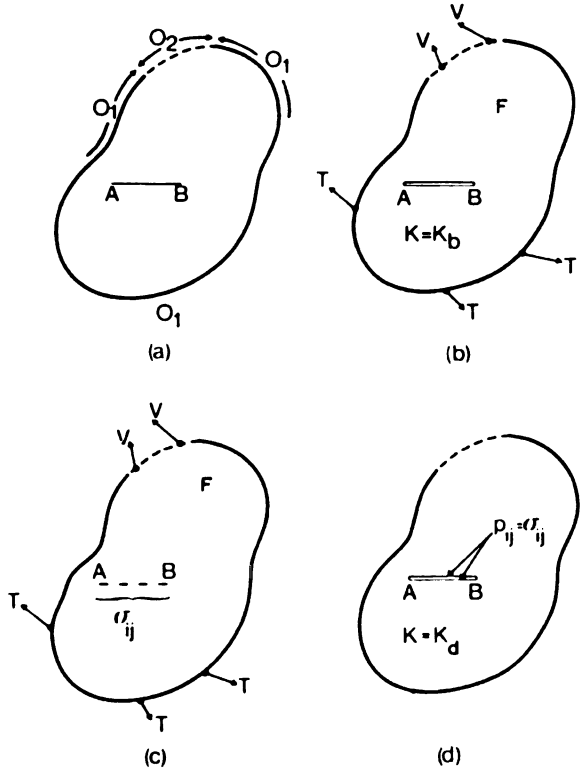


FIGURE 4.2 Infinite Plate With Multiple Cracks

4.2.2 The Bueckner's Principle

This principle allows the problem of determining the stress intensity factor of a crack in a loaded body to be changed to that of the same crack subjected to pressures on its surface in the same body. The crack surface pressures (or stresses) are simply determined as the stresses over the crack site in the uncracked body subjected to the originally applied boundary tractions and displacements. Therefore, this principle reduces any crack problem with complicated boundary conditions to a simple one with pressurized crack surfaces and zero displacement or tension boundary conditions. The Bueckneer Principle is illustrated in Figure 4.3 (Ref. 4.4, 4.5)



Elastic solid subjected to arbitrary tractions and displacements. ($K_b = K_d$). (a) Cracked region before loading. (b) Cracked region subjected boundary tractions and displacements. (c) Cracked region subjected to T and V with crack removed. (d) Cracked region with $T = V = 0$ and crack surfaces subjected to pressure distribution $p_{ij} = \sigma_{ij}$.

FIGURE 4.3 Description Of The Bueckner Principle

4.2.3 The Two Elementary Solutions

Plane elasticity stresses can be expressed using the basic complex analytical functions illustrated in Chapter 1, but in a different form as follows (Reference 4.4, 4.5):

$$\sigma_{xx} + \sigma_{yy} = 4Re\Phi(z),$$

$$\sigma_{yy} - i\sigma_{xy} = \Phi(z) + \Omega(\bar{z}) + (z - \bar{z})\overline{\Phi'(z)},$$

where z=x+iy refers to a point in the plane; and $\Phi(z)$, $\Omega(z)$, $\Phi'(z)$ are complex functions.

We Consider the Problem shown below (Figure 4.4); Two pairs of normal and tangential forces (P, and Q) are applied at a prescribed point (s,0) of both edges of a single crack in an infinite plate.

The solution to this problem is given by the following analytical complex functions (References 4.4, and 4.5). This solution is labeled elementary solution because it is basic to the solution of the overall problem. The concept in which the elementary solutions are used is similar to the concept of stiffness or flexibility coefficients in structural analysis.

$$\Phi(z) = \Omega(z) = -\frac{P - iQ}{2\pi i}\frac{X(s)}{X(z)(z - s)},$$

$$X(z) = \sqrt{(z^2 - a^2)}.$$

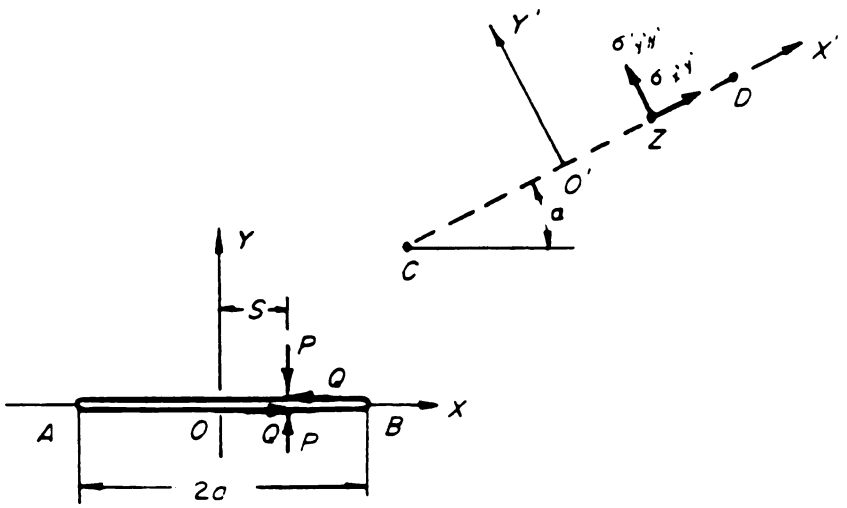


FIGURE 4.4 Loading Conditions for the Two Elementary Solutions; (i) P=1, Q=0 Corresponds to the First Elementary Solution; (ii) P=0, Q=1 Corresponds to the Second elementary Solution.

(i) the first elementary solution: P=1 Q=0

$$\sigma_{y'y'} - i\sigma_{x'y'} = f_{nn} - if_{nt} = -\frac{\sqrt{(a^2 - s^2)}}{2\pi}[G(z) + \overline{G(z)} + e^{-2i\alpha}(z - \bar{z})\overline{G'(z)}].$$

(ii) the second elementary solution: P=0 Q=1

$$\sigma_{y'y'} - i\sigma_{x'y'} = f_{tn} - if_{tt} = \frac{\sqrt{(a^2 - s^2)}}{2\pi i}[\overline{G(z)}(1 - 2e^{-2i\alpha}) - G(z) + e^{-2i\alpha}(z - \bar{z})\overline{G'(z)}],$$

where G(z), and G'(z) are given as follows:

$$G(z) = \frac{1}{X(z)(z - s)}, \qquad G'(z) = \frac{a^2 + sz - 2z^2}{(z - s)^2(X(z))^3}.$$

The above elementary solutions (i.e. f_{nn}, f_{nt}, f_{tn}, f_{tt}) are also known as the kernels.

4.2.4 The general solution

We consider an infinite plate with N cracks, with some type of boundary conditions at infinity.

1. The Bueckner's principle simplifies the problem to an infinite plate with N pressurized cracks and zero boundary conditions (see Figure 4.5 a). For example the applied normal and tangential forces on both edges of the k^{th} crack are pk (sk) and qk(sk) respectively.

2. The problem is then transformed into the superposition of N single cracks, with undetermined forces on both edges of each crack (Figure 4.5 b). For example the undetermined normal and tangential forces on both edges of the k^{th} crack are Pk(sk) and Qk(sk) respectively as shown below.

3. The superposition of the effects of all the cracks on each crack gives the following set of integral equations. Which, upon numerical integration is reduced to a set of linear equations with the undetermined crack forces as the unknowns.

$$P_k(s_k) + \sum_{l=1}^{N}{}' \int_{-a_l}^{a_l} P_l(s_l) f_{nn.lk}(s_l, s_k)\, ds_l + \sum_{l=1}^{N}{}' \int_{-a_l}^{a_l} Q_l(s_l) f_{tn.lk}(s_l, s_k)\, ds_l$$
$$= p_k(s_k), \quad (-a_k < s_k < a_k) \quad k = 1, 2, \ldots, N$$

$$Q_k(s_k) + \sum_{l=1}^{N}{}' \int_{-a_l}^{a_l} P_l(s_l) f_{nt.lk}(s_l, s_k)\, ds_l + \sum_{l=1}^{N}{}' \int_{-a_l}^{a_l} Q_l(s_l) f_{tt.lk}(s_l, s_k)\, ds_l$$
$$= q_k(s_k), \quad (-a_k < s_k < a_k) \quad k = 1, 2, \ldots, N$$

In the above equation, the summation is from 1 to N except k.

4. After the system of equations is solved for the undetermined forces Pk, and Qk. The mode1 stress intensity factors at crack tips (left, and right tips) are then computed from:

$$k_{1,l}^{\pm} = -\frac{1}{\sqrt{(\pi a_l)}} \int_{-a_l}^{a_l} P_l(s_l) \sqrt{\left(\frac{a_l \pm s_l}{a_l \mp s_l}\right)} \, ds_l,$$

The mode2 stress intensity factors at the crack tips can be computed from:

$$k_{2,l}^{\pm} = -\frac{1}{\sqrt{(\pi a_l)}} \int_{-a_l}^{a_l} Q_l(s_l) \sqrt{\left(\frac{a_l \pm s_l}{a_l \mp s_l}\right)} \, ds_l.$$

the above integrals can be easily numerically computed.

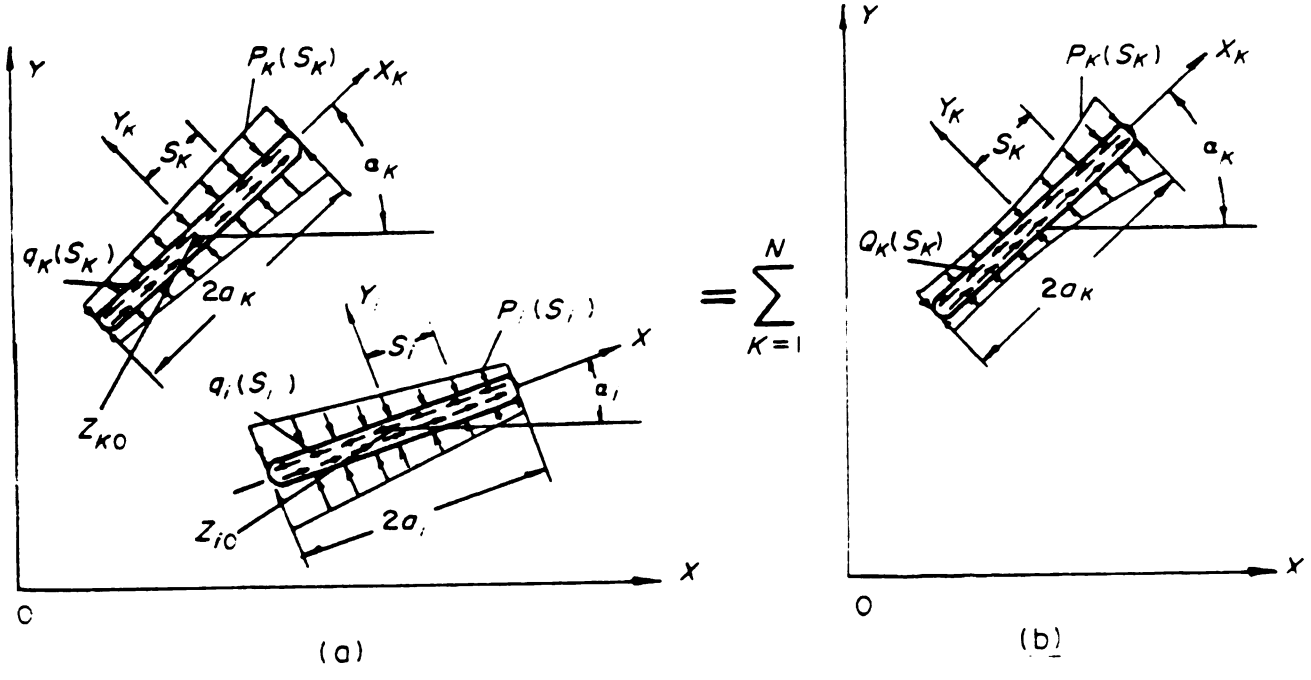


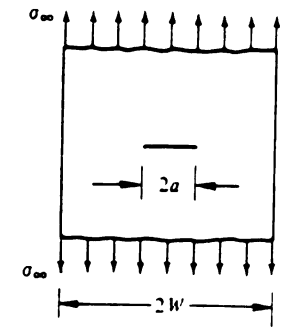
FIGURE 4.5 The Principle of Superposition for the Solution of the Multiple Crack Problem: (a) Infinite Plate Containing N Cracks; (b) Infinite Plate Containing a Single Crack.

4.2.5 Geometry Factor

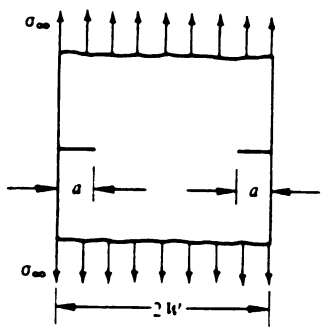
The factors used are shown below in Figure 4.6.

We consider only the factor of each crack as if it exists separately, because cement material failure is usually dominated by one major crack.

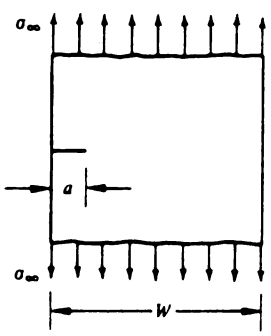
The Usage of the exact finite body solution is feasible and at least two procedures are available in the literature. However it is beyond the scope of this study and was not used in this model.



$$K_I = \sigma_\infty \sqrt{\pi a} \frac{1 - a/2W + 0.326\, a^2/W^2}{\sqrt{1 - a/W}}$$



$$K_I = \sigma_\infty \sqrt{\pi a} \frac{1.12 - 0.61a/W + 0.13a^3/W^3}{\sqrt{1 - a/W}}$$



$$K_I = \sigma_\infty \sqrt{\pi a} \left(1.12 - 0.23 \frac{a}{W} + 10.6 \frac{a^2}{W^2} - 21.7 \frac{a^3}{W^3} + 30.4 \frac{a^4}{W^4} \right)$$

FIGURE 4.6 Geometry Factors, Used to Account for Finite Bodies.

4.2.6 General Flow chart of subroutine SIF; Stress Intensity Factor Computation

1. Establish the current Cracks configuration: Position, length, inclination angle.

2. Compute the applied stress at the Location of each crack (Bueckner's principal)

3. Set up The matrix coefficients (kernels) from the integral equations.

4. Also set up the vector the unknowns (undetermined crack pressures)

5. Solve The set of linear equations

6. Compute numerically the left and right stress intensity factors

4.3 Computation of Strains

The strains are computed in two parts:

(1) EL is the linear component of the strains, which is based on the average stress, and the composite modulus of elasticity. EL is the contribution of the unfractured matrix and is given by:

EL = (Average Stress)/(Composite modulus of elasticity)

(2) The second component is due to the opening of cracks. This component is computed by assuming the cracks as smeared into the volume of the specimen. In the two-dimensional case, the cracks are smeared into the plane area of the specimen as illustrated in Figure 4.7.

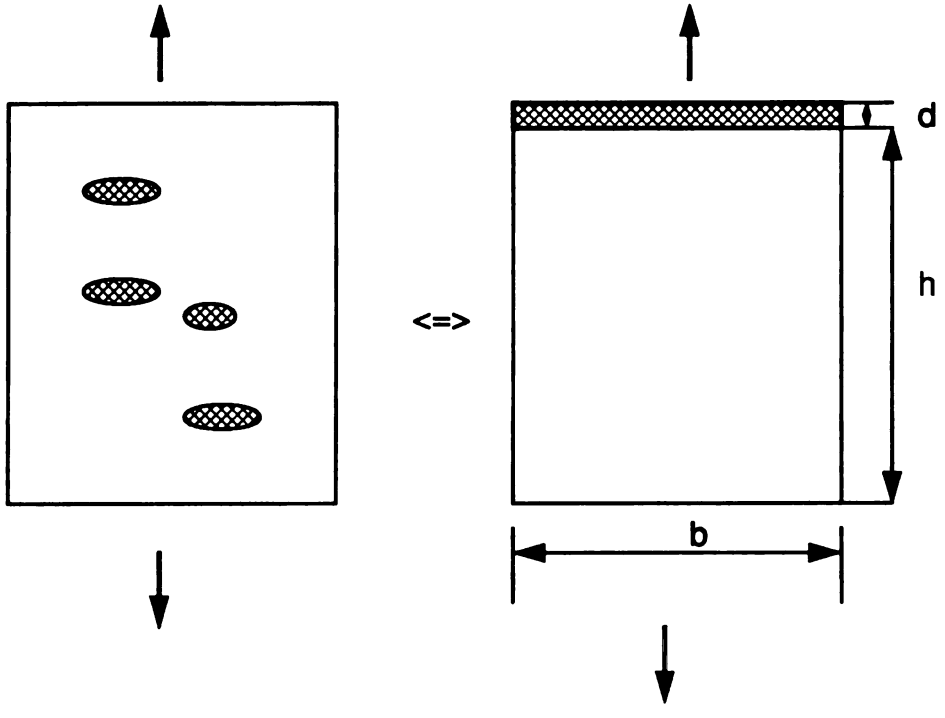


FIGURE 4.7 Configuration Used for Strain Computations

From the above configuration the strain component due to crack presence is computed as follows:

$$EF = \frac{d}{h} = \frac{db}{hb} = \frac{\sum_{allcracks} \int COD\,(x)\,dx}{hb}$$

where COD(x) represent the vertical crack opening displacement at a distance x along the crack; and the integration sign represent the total opening area of a crack.

In the above equation, the sum is of all the opened cracks in the specimen.

CHAPTER 5

Model Synthesis And Description Of Subroutines

5.1 Description of The Main Program

This program analytically predicts the maximum strength, the stress-strain curve, and the crack propagation patterns during tensile load application to a fiber reinforced cementitious specimen. The program randomly generates the crack positions and sizes. Linear elastic fracture mechanics applied to a finite body with multiple cracks is used to predict the fracture behavior. The prediction is based on the following known information: the mix proportions, the fiber properties, the fine aggregate content and average size, the matrix properties (especially the fracture toughness), and the fiber-matrix bond characteristics (mainly the average adhesion bond strength and a reduction factor to account for frictional shear in the post-peak region). Also, the program does a statistical parametric analysis of the effects of variation of a chosen variable (e.g. fiber content) on the composite material behavior. This analysis covers the following: (1) Multiple comparison of means using the statistical Student's-T test statistic (T-Test) for the peak stress, peak strain, and toughness; and (2) Analysis of variance (ANOVA) for the peak stress, peak strain, and toughness.

The unique characteristics of the model are:

1. The capability of considering multiple cracks

2. A built-in statistical parametric analysis module for any chosen variable.

The essential steps of the main program are described below. Full description of all the subroutines, variables, and the flow charts are presented in later sections. Also, the full FORTRAN source code is presented in Appendix A.

5.2 Basic Steps In The Main Program

- Read control data.
- Compute aggregate effects on increasing toughness, using subroutine KIAGG.
- Generate each specimen simulation, using subroutine SIM1
- Establish points A* and A1 of the stress-strain curve (see Figure 3.1); Compute the loads and strains corresponding to points A* and A1. The subroutine AS1 is used for this purpose.
- Compute points on the stress-strain curve between A* and A1, using subroutine FILLS1.
- Establish points in the prepeak region, between A1 and A2 (A2 is the peak point, see Figure 3.1). This is done using subroutine PREPEAK.
- Establish points in the postpeak region, using subroutines POST1, and POST2
- Do the statistical parametric analysis

5.3 Description of the subroutines

• SUBROUTINE SIM1

This subroutine computes the crack and aggregate position for tension specimens.

• REAL FUNCTION RANDOM(I)

This function returns a real random number between 0.0 and 1.0.

• SUBROUTINE KIAGG

This subroutine computes the toughness increase due to the presence of aggregate.

• SUBROUTINE AS1(P1)

This subroutine establishes points A* and A1 on the stress-strain curve.

----------list of variables-----(for subroutine AS1)---------

P: variable containing load values.

P1: initial load value input.

NACT: number of active cracks at a given load state.

IFLAG: integer flag takes the values of 0,1; controls the flow of computations (used internally by the subroutine).

PPLUS: variable that holds load values that are greater than the load corresponding to point A1, (cracks propagate into matrix at this load, NACT>0).

PMINUS: variable that holds a load value that is less than the load corresponding to point A1 (cracks do not propagate into matrix when this load is applied; NACT=0)

P11: variable that holds the value of the load at Point A1. P11 is within TOL1% (input variable) of the exact value. That is, any value of load above P11 will cause cracks to propagate into matrix. Any value below P11 will not cause crack propagation.

R1: variable that holds the relative ratio between PPLUS and PMINUS. R1 is given by the function:

$$2 \times (\text{PPLUS} - \text{PMINUS}) / (\text{PPLUS} + \text{PMINUS})$$

If R1 is within TOL1% then,

$$\text{P11} = (\text{PPLUS} + \text{PMINUS}) / 2$$

EL: The linear strain computed using linear stress strain equations and the effective modulus of elasticity of the composite. It is used in the initial part of the stress-strain curve, and during the search for point A*. EL is returned by subroutine ELIN.

EF: Strain computed by accounting for the effect of opened cracks (fractured specimen strain) returned by subroutine EFRAC.

PABOVE: a load value that is above point A* but below point A1.

PBELOW: a load value that is below point A*; at this load level the stress strain curve is linear.

PS: Value of load at point A*, this point is where the actual stress-strain curve deviates from linearity, that is when the preexisting interfacial cracks propagates within the interfaces of aggregates.

---LIST OF SUBROUTINES AND FUNCTIONS USED BY AS1--------

SIF: Subroutine that computes the stress intensity factors at crack tips.

CRIT: Subroutine that checks whether a crack is propagating or not. This subroutine returns NACT (the number of active cracks for a given load value).

RATIO1: Function that computes the relative ratio between PPLUS and PMINUS, used to decide on the location of point A1.

RATIOS: Function that returns the relative ratio between EL and EF, and it is used to decide on the location of point A*.

ELIN: Subroutine that computes the linear strain for a given load level

EFRAC: Subroutine that computes the fractured specimen strain at a given load level.

• FUNCTION RATIO1(PPLUS,PMINUS)

This function computes the relative ratio between PPLUS and PMINUS, used in deciding of the location of point A1. This function is computed as follows:

ABS(PPLUS-PMINUS)/ (PPLUS+PMINUS)/2.

• FUNCTION RATIOS(EL,EF)

This function returns the relative ratio between EL and EF, and it is used to decide on the position of point A*; It is computed as follows:

RATIOS= ABS(EL-EF)/ (EL+EF)/2.0

• SUBROUTINE ELIN(EL,P,A,MOD)

This subroutine computes the linear strain EL at a given load level.

-------List of variables for subroutine ELIN----------

MOD0 = Modulus of elasticity of the matrix

MODF = Modulus of elasticity of the fibers

MOD = Modulus of elasticity of the composite, when the law of mixture method is used, MOD is given by:

$$MOD = MODF \times F + (1 - F) \times MOD0$$

F = Volume fraction of fibers

METHD = Flag that refers to the method used to compute MOD. (METHD=1; Law of mixture method is used to compute MOD)

P= Load applied.

A= Specimen Area.

EL = Linear Strain.

• SUBROUTINE EFRAC(EF)

This subroutine computes the strain EF for a given load level, by accounting for the presence of cracks.

• SUBROUTINE PREPEAK(P11,...)

This subroutine computes the points on the stress-strain curve in the prepeak region when the cracks have started propagating into matrix and the fibers are interacting with the cracks (see main program flow charts for more details).

• SUBROUTINE OPTIM1

This subroutine optimizes the load increment between DPMAX and DPMIN.

• SUBROUTINE OPTIM2

This subroutine optimizes the active crack length increment between DELMAX and DELMIN.

• SUBROUTINE FIBER

This subroutine computes the bridging forces exerted by each of the fibers bridging the currently active cracks, at the current crack configuration. The subroutine performs the following tasks:

1. ADDS THE BRIDGING EFFECTS (FORCES) OF NEWLY ACTIVE FIBERS:

As each active crack propagates into the matrix, it interacts with new fibers; these fibers exert a bridging force on the crack. the bridging forces alter the stress intensity factor at the crack tip, and may or may not stabilize the crack depending on how large they are these. Hence, keeping track of the activated fibers is crucial in the modeling process.

2. REMOVES THE BRIDGING EFFECTS OF FIBERS THAT BECOME INACTIVE:

A fiber becomes inactive if it totally pulls out of the matrix or it is ruptured (broken). Hence, these inactive fibers have no contribution to the bridging forces of the crack.

3. REEVALUTES THE BRIDGING FORCES OF ACTIVE FIBERS (see Chapter 3, for more details):

As the crack propagates (crack length increases), the crack opening (width; COD) increases. Hence, the fibers that are in the path of the crack have to either elastically stretch, slip, or even break to be compatible with increased crack opening. At any moment, an active fiber may have any of the following states:

(a) Stretched with no end slip.

(b) Fully stretched and one end slips.

The stretching of the fiber is caused by the interfacial shear stress exerted on the fiber surface as the crack widens. The bridging force exerted by each fiber can be computed from the following variables, as presented in Chapter 3:

X: the stretched fiber length (unknown)

S: slippage distance of the fiber end (unknown)

COD: crack opening at fiber location (known)

TAU: fiber-matrix average shear strength (known)

DEL: fiber elastic elongation: $DEL = 2 \times TAU \times X^2 / (Ef \times Df)$

where Ef and Df are the modulus of elasticity and the diameter of the fiber, respectively.

L: fiber embedded length (known)

The fiber bridging forces of each crack are computed as follows:

Let's assume, without loss of generality, that for a given fiber we know the above two unknowns X (fiber stretched length) and S (slippage); also lets say that the fiber end is not slipping, $S = 0$,and $X \leq L$.

Equilibrium of the fiber forces gives the axial stress in the fiber as:

$$SIGF = 4 \times TAU \times X / (Df)$$

The bridging force is given by FBRIDGE=AF*SIGF, where AF is the cross-sectional area of the fiber. The above equations apply also if the fiber end is slipping. Notice that if the fiber end is slipping by an amount S, the fiber stretched length is X=L-S, where L is the shorter embedded fiber length. Hence the fiber bridging force is totally determined if the fiber stretched length X is known.

The fiber stretched length can be evaluated as follows:

The compatibility of fiber axial deformation at the crack requires that the following equation must be satisfied by each fiber that is bridging the crack (at a crack opening of COD):

$$S + 2 \times DEL + SIGF \times S / (Ef) = COD$$

By replacing DEL and SIGF with the expressions given above, we got:

$$4 \times TAU \times X^2 / (Ef \times Df) + S + 4 \times TAU \times X \times S / (Ef \times Df) = COD$$

Let $\alpha = 4 \times TAU / (Ef \times Df)$, then the above equation becomes:

$$\alpha \times X^2 + \alpha \times S \times X + (S - COD) = 0 \quad \text{.....(5.1)}$$

The following techniques are used to evaluate X and S from Equation 5.1:

Rule 1: As the fiber becomes active for the first time, there is no slippage S=0, therefore Equation (5.1) gives:

$$X = \sqrt{(COD \times Ef \times Df) / (4TAU)} \quad \text{.....(5.2)}$$

Rule 2: When the effect of a fiber is being computed not for the first time we do not know whether S=0 or S>0. Hence, both X and S are unknowns. If it is determined that S=0, then X is given by Equation (5.2). If it is determined that S>0, then we substitute S=L-X in Equation (5.1) and solve for X which gives the following expression for X:

$$X = (COD - L) / (\alpha L - 1) \quad \text{.....(5.3)}$$

Therefore, the problem is solved if we know whether the fiber end is slipping (S>0) or the fiber end is not slipping (S=0).

Rule 3: Depending on the current fiber status, the fibers are classified as follows:

GROUP A: S=0, ends of fibers are not slipping; fibers are stretched and X is given by Equation (5.2); and the bridging force is given by: BridgingForce = $4 \times Af \times TAU \times X / (Df)$.

GROUP B: S>0; One end slips by an amount S=L-X; The fiber is stretched over a length of X given by Equation (5.3); and the bridging force is given by: BridgingForce = $4 \times Af \times TAU \times X / (Df)$.

It is important to note that all newly activated fibers belong to group A, that is with S=0. However, for previously activated fibers, the following procedure is used to determine whether S=0 or S>0:

(1) If during the previous stage of fiber classification, a fiber was classified in group B (S>0), then this fiber will remain in group B till it is totally pulled out. X is always given by Equation (5.3). For this case, it is known that S>0.

(2) If during the previous classification a fiber was in group A that is S=0, and in the previous classification the fiber has a stretched length (note that W and COD are used interchangeably for convenience):

$$X_{i-1} = \frac{\sqrt{W_{i-1} \times Ef \times Df}}{4 \times TAU}.$$

Then we start the process by assuming that the fiber will remain in group A and compute the stretched length as follows:

$$XA_i = \frac{\sqrt{W_i \times Ef \times Df}}{4 \times TAU}$$

if $XA_i < L$ then the assumption is correct, that is the fiber end is not slipping and thus the fiber is still in group A; the bridging force is then computed using: $X=XA_i$

if $XA_i > L$, then the assumption is wrong, and the stretched length is computed as follows:

$$XB_i = \frac{W_i - L}{\alpha L - 1}.$$

The bridging force is then computed using $X=XB_i$, and the fiber is now in group B.

4. REDISTRIBUTION OF THE BRIDGING FORCES ALONG THE CRACK LENGTH:

The last task of this subroutine is the redistribution of the bridging forces along the crack length in a way that is compatible with the stress analysis and computation of the stress intensity factors in subroutine SIF.

----------LIST OF VARIABLES ----------

NACT: Number of active cracks at the current combination of load and crack configuration, returned by subroutine CRIT (input to subroutine FIBER).

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ACTNC(I); I=1,NACT: Array holding the crack numbers corresponding to the labels 1,2,...,NACT; returned by CRIT (input to FIBER)

NNC: Current number of active cracks; NNC=ACTNC(I)

NDELTA: Optimal current crack length increment, in multiples of fiber spacing (input to subroutine FIBER).

NFGRPA(NNC): Total number of group A fibers for crack number NNC; it is continuously updated and modified by subroutine FIBER, and originally initialized in the main program by subroutine FRCINIT.

FBL: Fiber length.

EMBDLA(NNC,J): Embedded length for fiber number J for crack number NNC of groupA computed by subroutine FIBER as a random number between 0 and FBL/2.0

The general procedure used by subroutine FIBER can be described as follows:

For every active crack, compute the bridging fiber forces. Add newly active fibers to group A and compute their corresponding embedded lengths; compute crack opening at the fibers position and distribute the bridging forces along the crack. Subsequently, reclassify fibers into their corresponding groups. Initialize the numbers of broken, pulled,... fibers, for the current crack. Update the total number of group A fibers for each active crack, compute the embedded length of the new fibers, and identify the type of each active crack NNC (internal or edge). For every fiber in group A compute the bridging forces and other related variables as well as the fiber behavior information. Compute crack opening at each fiber location of group A. Also compute the position of the fiber relative to the crack center (or edge), and compute the stretched lengths of fibers, and check whether each fiber is: (1) actually in group A; (2) has to be moved into group B; or (3) has been broken.

• SUBROUTINE CRKTYPE(NNC,XR,ITYPE)

this subroutine returns the type of the current crack, that is internal (ITYPE='IN'), left edge crack (ITYPE='EL'), or right edge-crack (ITYPE='ER')

• SUBROUTINE CRKOPEN(NNC,ITYPE,NFLBL,COD,SIG,E,ANEW)

This subroutine computes the crack opening of crack number NNC, at the position of fiber number NFLBL. The COD (crack opening displacement) is computed using the following formulas:

$$COD = 4 \times SIG \times (\sqrt{A^2 - X^2}) / E$$

where:

SIG: the average stress in the specimen = LOAD/AREA

A: halve the crack length, depends on whether an edge or internal crack

X: distance from crack center (or edge) to fiber position.

• SUBROUTINE DISTRB(NCRK,ITYPE,MM,LENGTH,FBRFRC)

This subroutine distributes the total force exerted by the fibers over the total length of the crack.

• SUBROUTINE CRIT

This subroutine establishes whether a crack is stable or propagating under the current crack configuration and stress condition.

• SUBROUTINE POST(...)

This subroutine establishes points in the stress-strain curve in the post peak region by reducing incrementally the material resistance from the peak value (PPEAK) to a minimum value of zero (ultimate failure). The following concepts are used:

- the load (material resistance) can only decrease since we passed the peak value.

- cracks size keep on growing.

- fibers are interacting with the crack propagation process.

-A combination of load and strain values (PPOST,EPOST) belongs to the stress-strain curve means that: for the current crack configuration, all cracks are stable under PPOST, however for any very small increase of the

previously active crack lengths, at least one crack becomes unstable. This combination represents an equilibrium condition between the applied loads and the material resistance PPOST in the post peak region.

----------LIST OF VARIABLES----------

PPEAK: peak load value

EPEAK: peak strain value

NP: number of post peak points desired

NC: total number of cracks

PPOST(*): this array holds post peak loads

EPOST(*): this array holds post peak strains

LP(*,*) this 2-D array holds the final half cracks length for a given crack number and a given post peak point.

DPP: load decrement in the post peak region

DLP: active crack length increment in the post peak region.

NACT: number of active cracks at a certain combination of load and crack configuration, returned by subroutine CRIT

NACT0: the value of NACT at peak conditions.

NNACT(*): array holding the values of NACT at the final stages of each step of the post peak region.

ACTNC(*): array holding the crack numbers corresponding to NNACT(*)

PFAIL: failure load (material resistance), computed as the material resistance value at the step immediately preceding the occurrence of the following conditions: (1) at least one crack has extended totally thru the width of the specimen; or (2) the load value is equal to zero; or (3) the predetermined strain level is reached. Failure is reached whenever conditions (1), (2), or (3) occurs which ever occur first.

EFAIL: failure strain corresponding to conditions similar to PFAIL.

L0(1:NC): array that holds the crack lengths at the end of one step

L1(1:NC): array that holds the varying crack lengths within one step.

• SUBROUTINE SIF

This subroutine computes the stress intensity factor at the tip of each crack. Details of the theory was presented in Chapter 4.

5.4 Model Flow Chart

A general and a detailed flow charts of the program are presented in Figures 5.1 and 5.2, respectively.

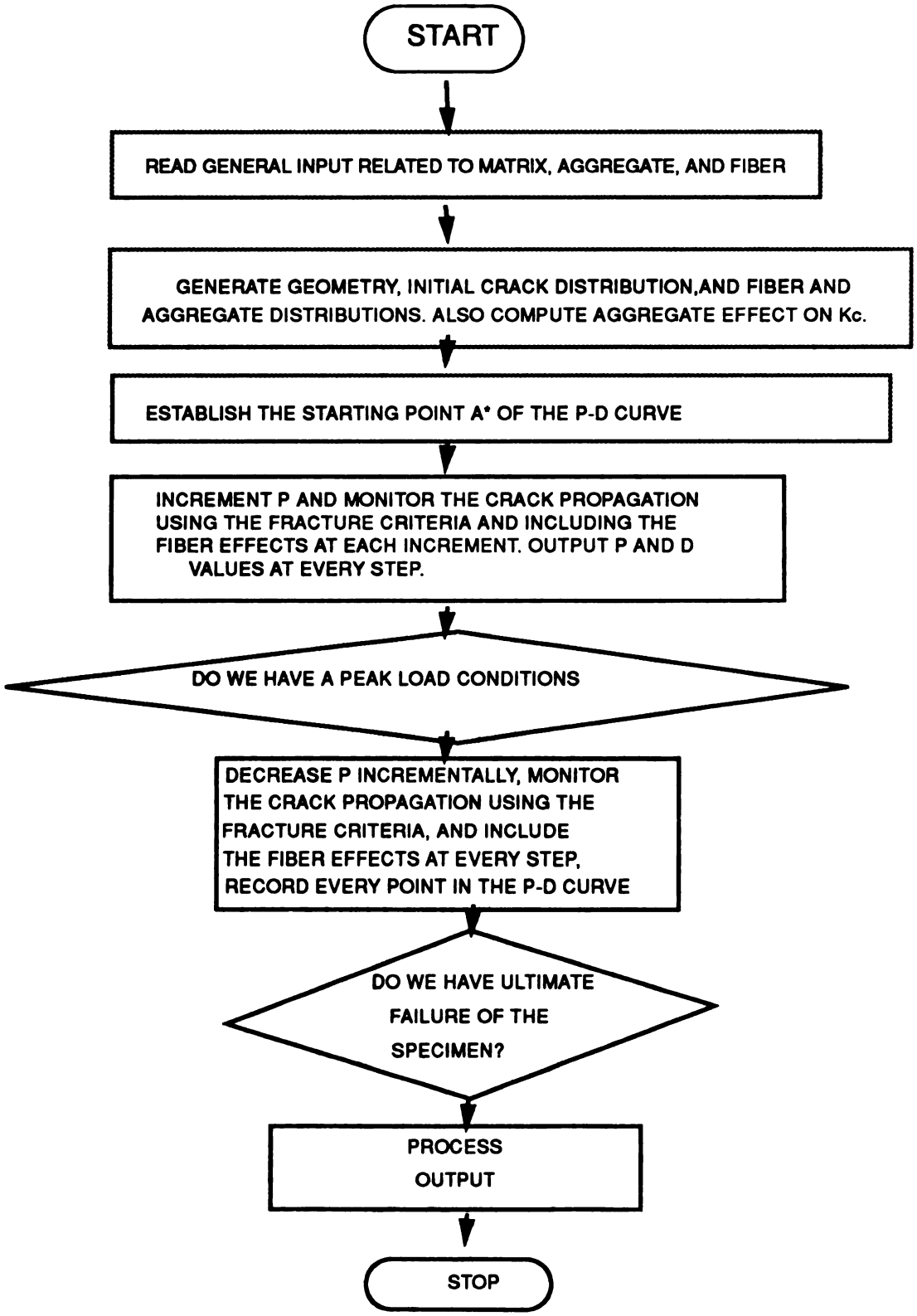


FIGURE 5•1 Main Program, General Flow Chart.

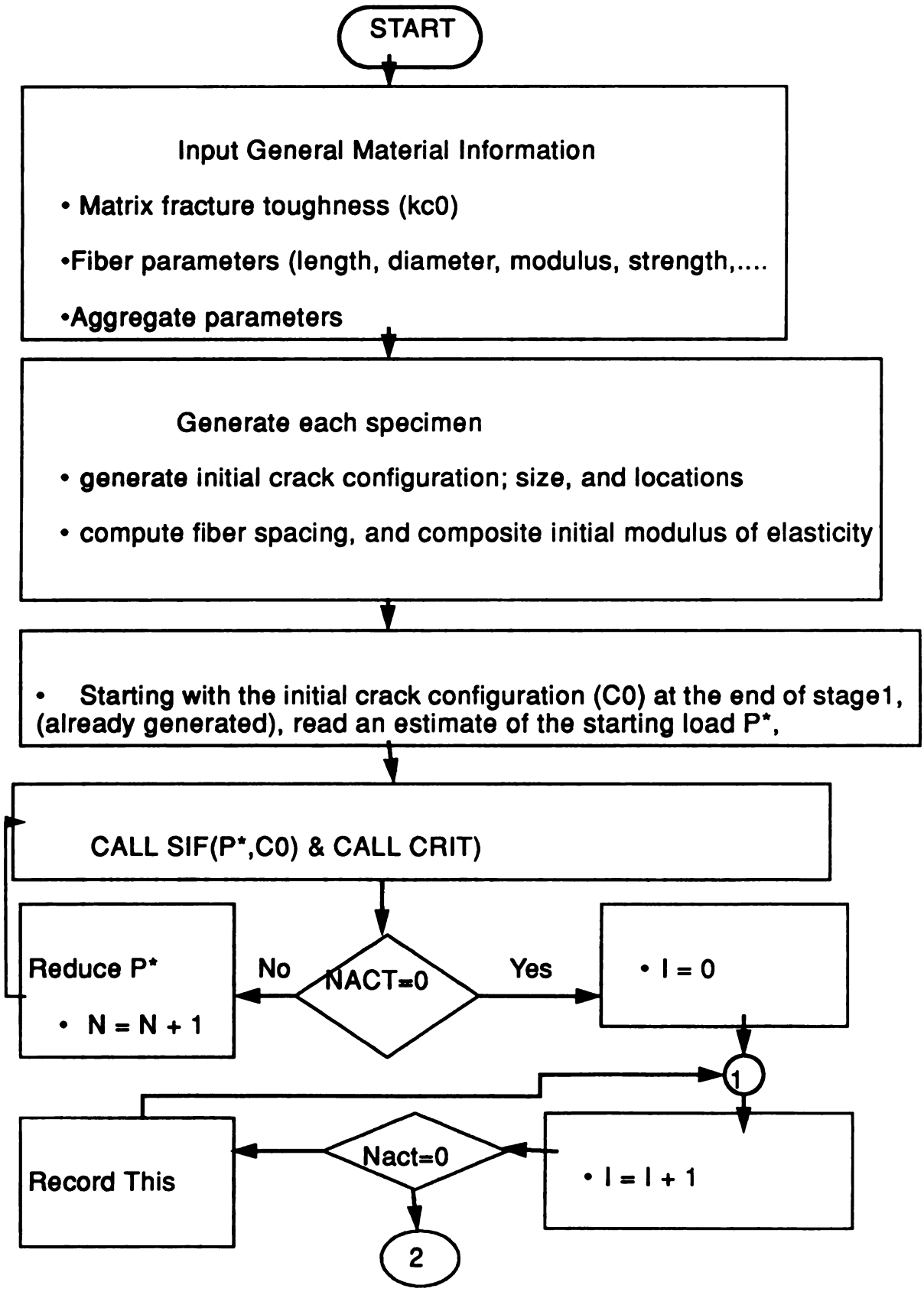


FIGURE 5•2 Detailed flow Chart Of the Main Program.

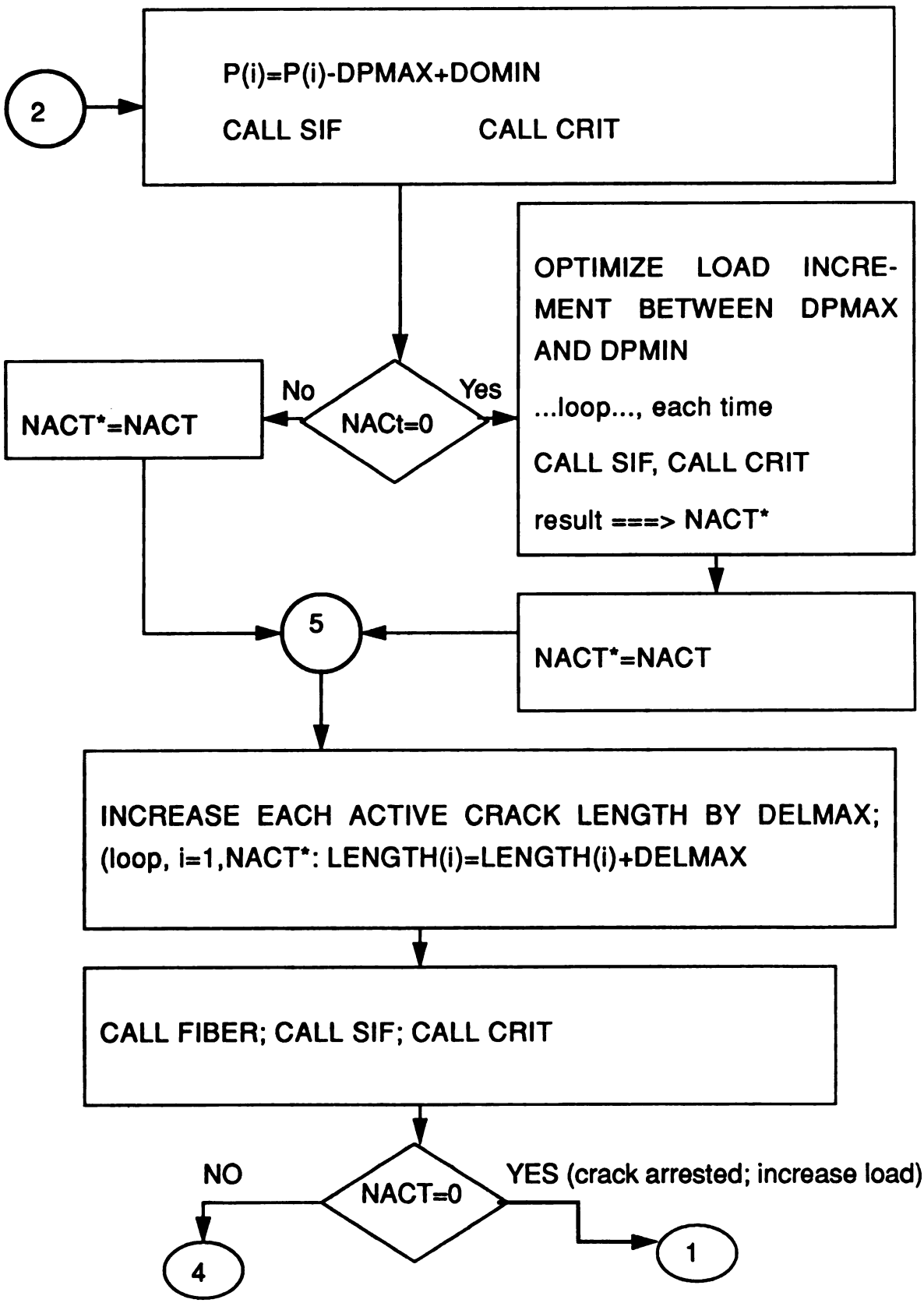


FIGURE 5.2 (Continued)

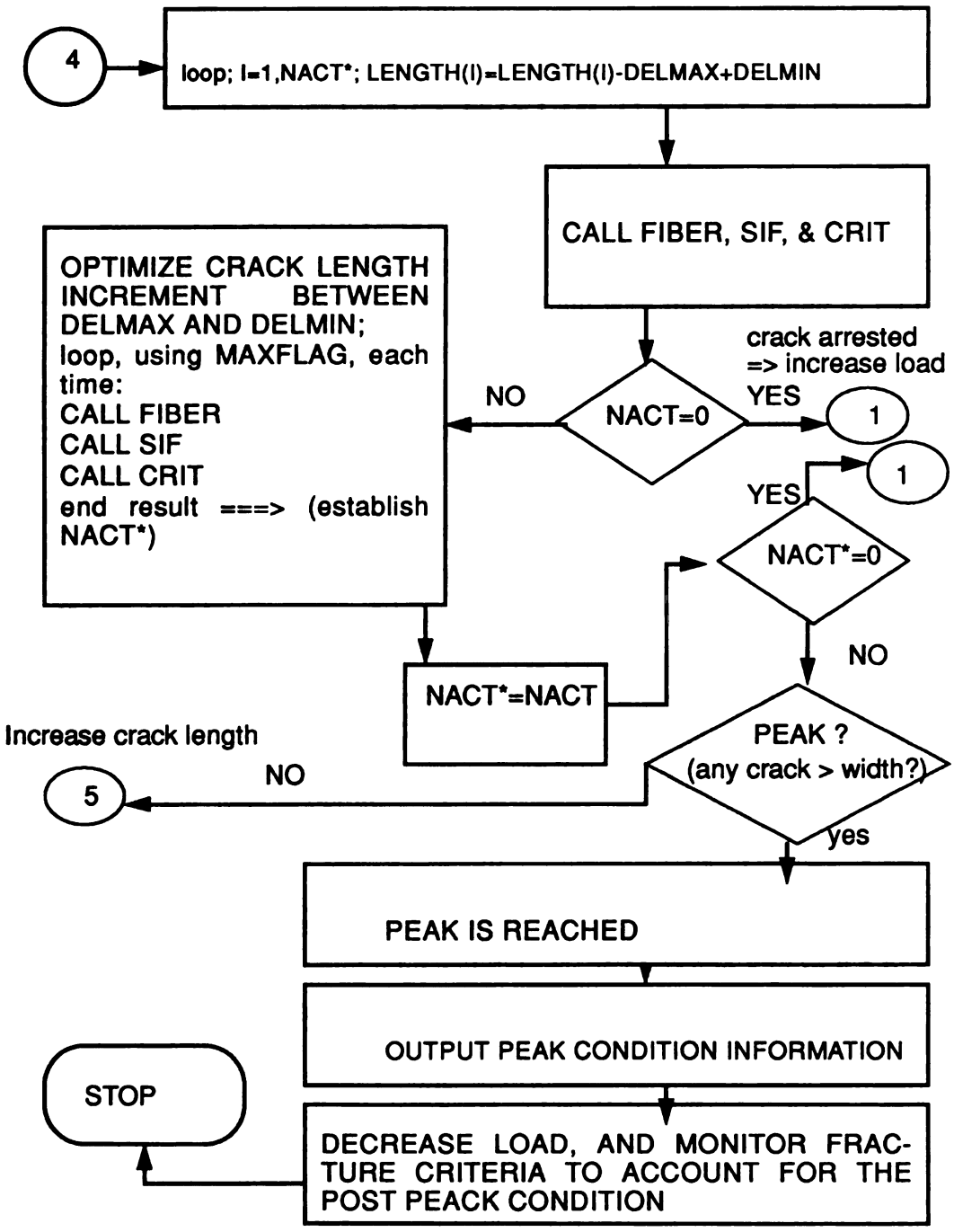


FIGURE 5.2 (continued)

CHAPTER 6

VERIFICATION OF THE MODEL AND DESCRIPTION OF INPUTS AND OUTPUTS

6.1 Introduction

The main thrust of this stage of the investigation is to ensure that the behavior of the model (program) is compatible with that intended in its programmed structure (i.e., the program does what it was designed to do). This stage is mainly about checking of the logical flow of the program, and includes the correction of syntax errors in the program statements, as well as the debugging of the program.

The verification of the program was done as the program was being edited. This stage is usually lengthy, especially if the program is very long and the logical flow is complicated as in the current case. One of the outcomes of this stage, in our case, was the decision to use double precision variables rather than single precision variables, after realizing in the earlier verification stage that some simple relations do not hold even thought the logical flow is correct when using single precision variables.

6.2 Input

The main program reads from a file called 'frc2.dat'. All the read statements are in free format a typical data file is shown in Figure 6.1 b. The content of the data file is explained below in Figure 6.1 a.

Line Order of variables (free format)

```
 1 TITLE
 2 NMAT NTEST NRAND
 3 FTYPE F MODF FBL DF IFBFLAG SIGULT FDMG
 4 ISEED NL
 5 P1 NS1 DPMAX DPMIN NMAX NMIN MAXFLAG
 6 DPP NLP
 7 NBOND NVOID M
 8 MOD0 TKI0 TAU W H D AGGRAD AGGVOL
 9 TOLS TOL1
 10ITERPOST
 11 NVAR VAR VARMIN DELVAR
 12IFILE ISTAT
 13 ALTAU
 14 CONFLEV
 15 EFCT
```

(a) Order of variables within each line

```
'c w/c=.42|vf=0-4|nc=6'
1 1 2
'CARBON FIBER' .03 5404.9 .393701 .0005709 1 110.942 0
1 11
.50 5 .002 .001 1 1 2
.001 5
1 1 8
1500 .180 .20 1.1811 1.0 .472441 0.0 .001
0.005 0.005
50
1 'F' 0.015 .0318
1 1
.3
95
1.0
```

(b) typical data file of the input data file FRC2.DAT. 'FRC2.dat'

FIGURE 6.1 Input Data File; Variables Names and Typical Example.

Table 6.1: Description of the Data File Input 'frc2.dat'

line numb.	Variable name	Type	Description
1	title	char	Problem title up to 40 characters between single cotes
2	nmat	int	material flag, currently not used, use 1
2	ntest	int	type of test flag, only tension test is supported currently, use 1
2	nrand	int	# of specimens per material to be generated, use 2 or more, more than 5 may take too long
3	ftype	char	fiber description ex: 'carbon', 'steel',...
3	f	real	fiber content (vf in%)
3	modf	real	fiber modulus of elasticity
3	fbl	real	fiber length
3	df	real	fiber diameter
3	ifbflag	int	flag for fiber spacing computation, use 1
3	sigult	real	fiber ultimate strength
3	fdmg	real	shear free portion of embedded fiber length between (0 and 2) use 0, if not sure
4	iseed	int	seed, for random # generation, any integer
4	nl	int	currently not used use 1
5	p1	real	initial estimate of peak load, any value>0.
5	ns1	int	# of points in stress-strain curve between point A* and A1, use (10 to 50)
5	dpmax	real	maximum load increment, 1 pound, (.001 kip)
5	dpmin	real	minimum load increment,.5pound, (.0005 kip)
5	nmax	int	maximum number of fiber spaces used in incremental crack propagation, >=1, use 1
5	nmin	int	minimum number of fiber spaces used in incremental crack propagation,>=1, use 1
5	maxflag	int	maximum number of binary iteration between nmax and nmin (or dpmax and dpmin) to establish the correct crack propagation, >=1, use 1
6	dpp	real	decrement of load in the post peak
6	nlp	int	# of fiber spacing to crack propagation (use 1), increase in post peak
7	nbond	int	# of cracks originating from aggregate-matrix bond region
7	nvoid	int	# of cracks originating from matrix voids
7	m	int	# of integration discrete parts, any values of NC=NBOND + NVOID> use 10, 5 is very time consuming

Table

line numb	
8	
8	
8	
8	
8	
8	
9	
1	
11	
11	
11	
11	
12	
12	
1	
14	
15	

Table 6.1 (continued)

line numb.	Variable name	Type	Description
8	mod0	real	matrix initial modulus of elasticity
8	tki0	real	matrix fracture toughness
8	tau	real	tension specimen width
8	h	real	tension specimen depth
8	aggrad	real	1/2 average fine aggregate size
8	aggvol		tolerance on stress-strain curve point A*
9	tol1	real	tolerance on stress strain curve point A1
10	iterpost	int	number of post-peak points to be generated
11	nvar	int	# of treatments to be generated for the statistical parametric study
11	varchar		variable name to be used in the statistical parametric study (e.g. 'F' for fiber content)
11	varminreal		minimum value of the variable to be studied
11	delvar	real	increment of the variable to be studied
12	ifile	int	1 ==> files for graphics output are produced 0 ==> files for graphics output are not produced
12	istat	int	1 ==> statistical report of the parametric study on a chosen variable is produced (REPORT2.STAT) 0 ==> no statistical report is produced
13	altau	real	fiber-matrix bond reduction factor at the post-peak region (< 1)
14	conlev	int	confidence level for the statistical analysis (75-95)
15	efct	real	fiber effectiveness factor < 1.

the previously described variables (Table 6.1) should appear in the data file in the order shown in Figure 6.1a.

6.3 OUTPUT

There are three types of outputs that can be produced by the software FRC and the post processor PPOST. The post processor PPOST is written in Fortran using the NCAR Graphics package. The source code of PPOST is shown in appendix B. PPOST uses the graphics data files (output 2) produced by FRC and process then into graphics plots. (output 3) Therefore PPOST should always be run after FRC has been run, with the option IFILE = 1 in the data file. Output 1, and output 3 contains important information regarding the problem. Typical outputs are shown in Appendices D and E. However output2 is just an intermediate step toward the production of output 3 and its discussion is irrelevant.

A preprocessor, PREP, was written with the purpose of easily and interactively generating the input data file 'FRC2.DAT'. The source code of the preprocessor is shown in Appendix C.

The steps required to use the software successfully are shown in Figure 6.2.

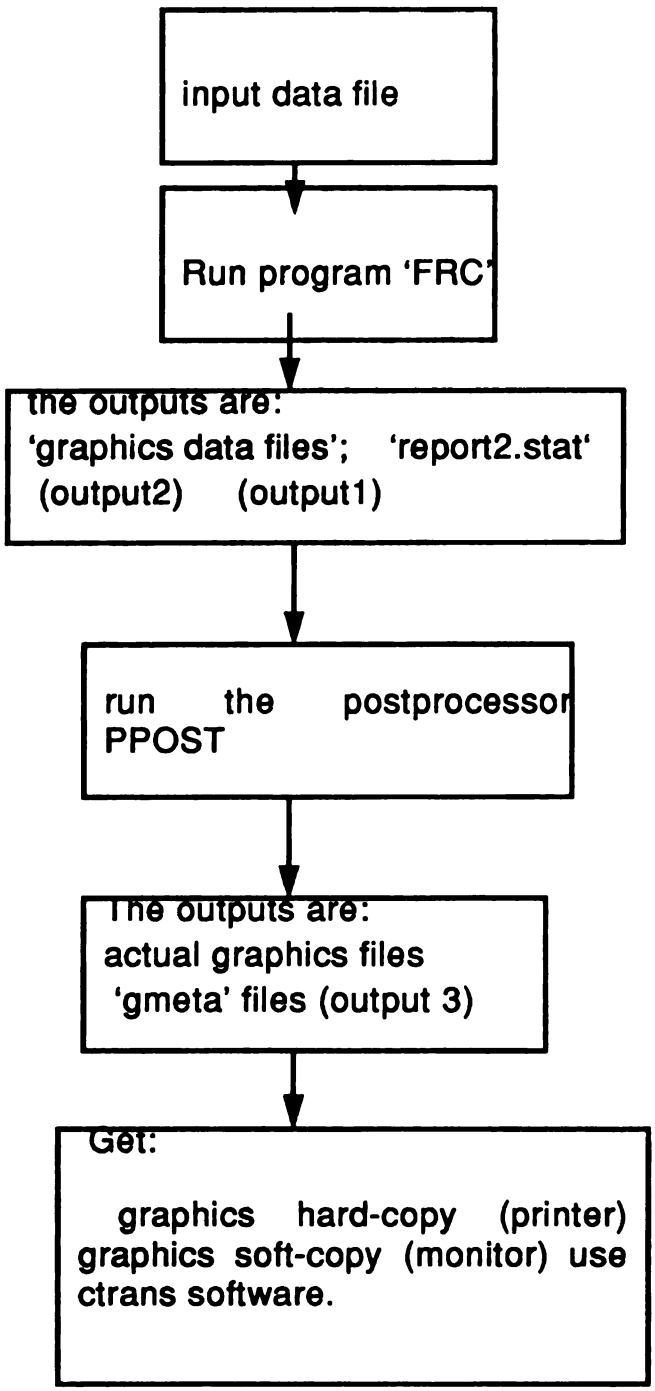


FIGURE 6.2 Types of Outputs Produced by the Software and the Postprocessor; and the Steps Required for Running The Program.

CHAPTER 7

Validation

7.1 INTRODUCTION

The validation of the model establishes the degree of correlation between the model and the system by comparing the available system data with results produced by the model. In our case, the validation process involves the comparison of experimental stress-strain curves with those produced by the program. The parameters that are used to establish the correlation are: the peak stress, the peak strain, and the toughness (area underneath the stress-strain curve), with the assumption that the initial experimental and theoretical stiffnesses are the same. In order to establish the validity and credibility of the model, a rigorous statistical methodology is needed. The methodology adopted in this validation process is described in the following:

(1) Establishment of the stability of the model with increasing number of cracks (NC) used, in order to establish the optimum number of cracks to be used with the model. This optimum number is defined as the smallest number of cracks that will practically produce the same output as any other higher number of cracks. The statistical procedure used is analysis of variance (ANOVA) with multiple comparison of the outputs, using a reasonable range for the number of cracks (NC=2,... 20).

(2) Establishment of the comparability of the outputs generated by the model to actual experimental stress-strain curves. This is done using the Student's-t test statistic (T-TEST). The comparison will be carried out using fiber reinforced cement matrices described in Table 7.1 and with the stress-strain curves shown in Figures 7.1, 7.2, and 7.3. Peak toughness in Table 7.1 refers to the area underneath the tensile stress-strain curve up to the peak stress, and total toughness refers to the total area underneath the stress-strain curve.

Table 7.1: Materials Used in the Validation Process.

La bel	Fiber Type	W/C	VF (%)	Reference	Peak Stress (ksi)	Peak Strain 10^{-3}	Peak Toghns 10^{-3} ksi	Total Toghns 10^{-3} ksi
C1	Carbn	.42	0	7.1,7.2,7.3	.55	.55	.25	.25
C2	Carbn	.42	1.72	7.1,7.2,7.3	.8	1.9	1.5	1.5
C3	Carbn	.42	3.98	7.1,7.2,7.3	1.2	4.8	5.2	5.2
C4	Carbn	.29	0	7.1,7.2,7.3	.65	.35	.101	.101
C5	Carbn	.29	2.04	7.1,7.2,7.3	1.1	.6	.48	.48
C6	Carbn	.29	4.03	7.1,7.2,7.3	1.75	1.8	1.36	1.36
S1	Steel	.5	0	7.4,7.5	.405	.174	.03524	.03524
S2	Steel	.5	1.5	7.4, 7.5	.524	.217	.05685	.702

The fiber properties and the specimens geometries that are associated with the above materials are as follow:

	(a) Carbon fiber:	(b) Steel fiber:
Fiber length	0.4 in.	1.0 in.
Fiber diameter	0.0006 in.	0.016 in.
Fiber tensile strength	110 ksi	200 ksi
Fiber modulus of elasticity	5405 ksi	29,000 ksi
Specimen width	1.18 in.	2 in.
Specimen depth	0.47 in.	0.75 in.
Specimen length	1.0 in.	3.25 in.
Matrix modulus of elasticity	1500 ksi (w/c=.42) 3000 ksi (w/c=.29)	3920 ksi

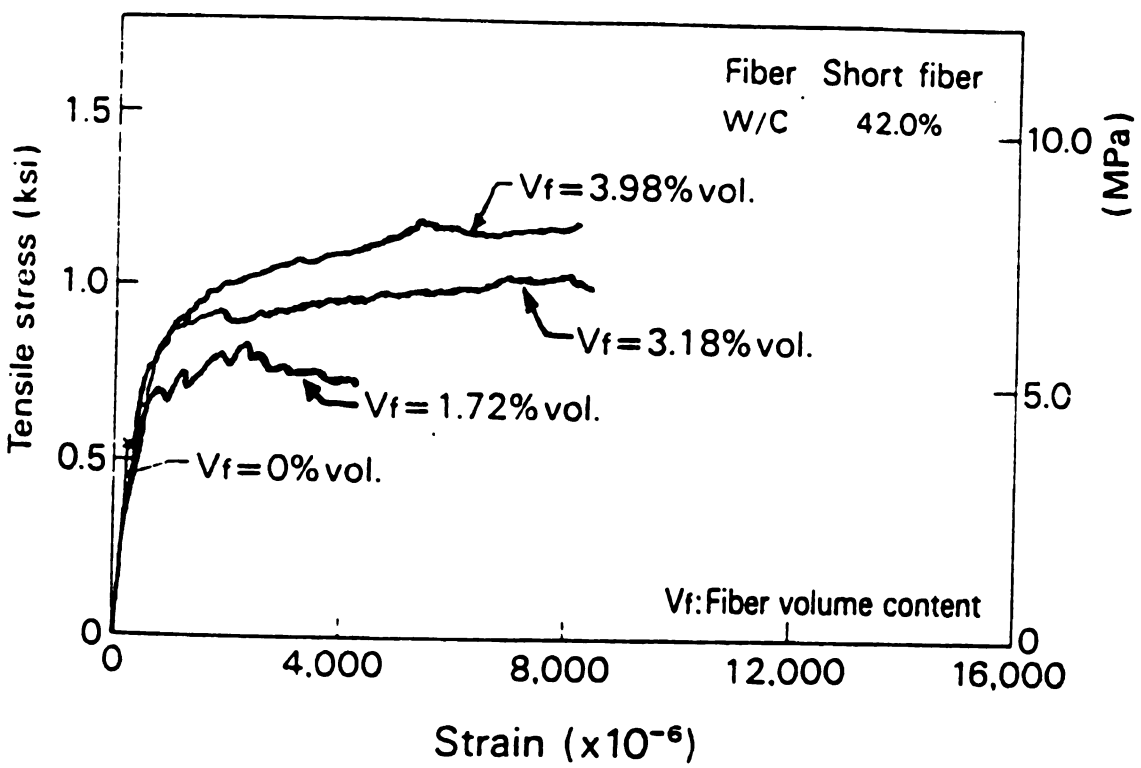


FIGURE 7.1

Experimental Stress-Strain Curves for Carbon Fiber Based Cement Materials, W/C=.42.

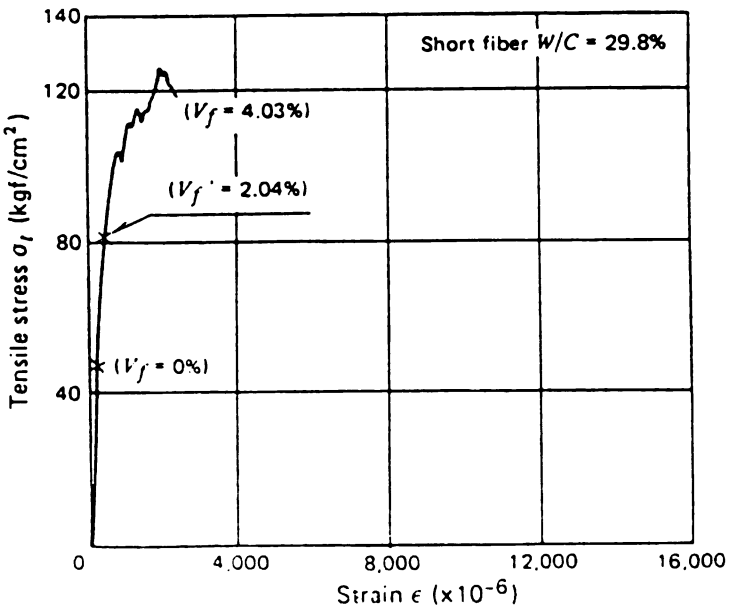


FIGURE 7.2 **Experimental Stress-Strain Curves for Carbon Fiber Based Cement Materials, W/C=.29.**

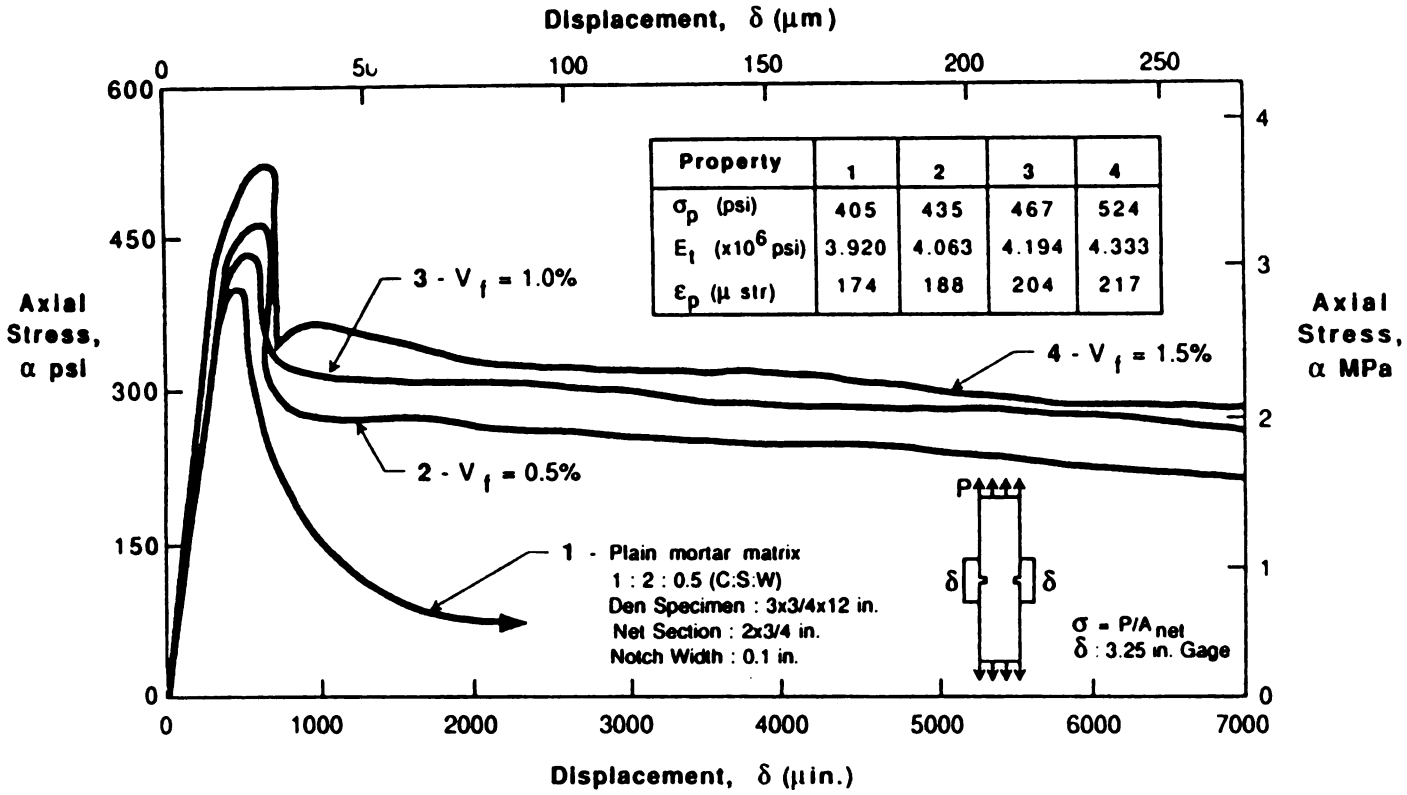


FIGURE 7.3 Experimental Stress-Strain Curves for Steel Fiber Based Cement materials, W/C=.5.

7.2 General description of the response surface generator and optimization software "Design-Expert"

"Design-Expert" is a commercial software developed for the purpose of statistical data analysis and presentation. This software is used in this chapter and the following one. Therefore, a general description of the software capabilities is presented in this section.

In general, the software "Design-Expert" helps the user to understand relationships between several variables (X1, x2, ...) and one or more response variables (R1, R2, ...). "Design-Expert" can accomplish the following types of goals:

- Response surfaces: One response variable is plotted in the form of contour lines as a function of two variables, while the remaining variables are held constants.
- Maximizing a response variable.
- Optimization: The word optimization, as used in this dissertation, refers to the process of establishing the range of some variables (X1, X2, ...) that allows some response variables (R1, R2, ...) to meet some specifications (or constraints).

This software handles up to six variables, and it is required that all variables be quantitative. Also, the user must provide enough data (i.e. variables and responses) for the software to work effectively. After the data are provided, the software fits a model for each response as a function of the variables. The model can be either linear, or quadratic, or cubic, and the software provides the best fit model.

Optimization, as done by "Design-Expert" gives a graphical display of the region of the explanatory variables that simultaneously satisfies the constraints (or the specification requirements). The constraints are entered as lower and upper values of each response. Once the constraints are entered, the contours corresponding to each constraint are plotted and labeled as: (R1_LO, R2_LO,...) for lower constraint limits and (R1_HI, R2_HI,....) for upper (or higher) constraint limits. In addition, regions are shaded (or filled in) if one or more constraint fail within the region. Blank regions (non-shaded) do satisfy all constraints and they are referred to as the optimum region (see Figures 7.10, 7.11, and 7.12).

7.3 Optimum number of cracks (NC)

It is not computationally efficient to consider a relatively high number of cracks in mode 1; therefore, an optimum number of cracks needs to be established, to be used with the model. The optimum number of cracks is defined as the smallest number of cracks that gives results comparable to those obtained with any other higher number of cracks. The comparison is based on the carbon fiber mixes labeled C2 and C3 in Table 7.1 . The comparison is done using the analysis of variance capabilties of the statistical package SPSS (Reference 7.6). The results show that the optimum number of cracks is in the range of 5 to 9. These results are shown in the Figures 7.4 to 7.9, and also in Table 7.2.

Table 7.2 presents the data produced by the model using the carbon fiber mixes labeled C2 (Vf=1.72%) and C3 (Vf=3.98%) in Table 7.1, for a varying number of cracks (NC). The number of cracks (NC) was varied from 2 to 20. In Table 7.2, the notations PKSTRS, PKSTRN, and TOGHNS, mean peak stress, strain at peak stress (or peak strain), and toughness up to peak stress, respectively. These three parameters characterize each stress-strain curve uniquely.

Figures 7.4 and 7.6 show the effect of the number of cracks on the peak stresses of the materials labeled C3 (Vf=3.98%) and C2 (Vf=1.72%) respectively. The smooth lines on these figures result from regression analysis of the data, and show that the peak stresses are higher for lower number of cracks; however, the trend in peak stress versus the number of cracks flattens after a certain number of cracks (optimum number of cracks).

Figure 7.5 and 7.7 present the effects of the number of cracks (NC) used by the model on the peak strain and toughness of materials. The observed trend is that the characteristics of the stress-strain curves stabilize after a certain number of cracks (optimum number).

The optimum number of cracks is the smallest number number of cracks that produces results comparable to those obtained with any other higher number of cracks. This optimum number of cracks is statistically established in Figures 7.8 and 7.9.

Figure 7.8 is an output of the multiple comparison test for the data of the material labeled C2 (Vf=1.72%). The variables considered for the multiple comparison tests are

peak stress (PKSTRS); peak strain (PKSTRN); and toughness (TOGH). The data are devided into seven groups depending on the number of cracks used (Grp2, Grp4, Grp6, Grp10, Grp14, Grp16, Grp20). The means of the variables corresponding to these groups are displayed from smallest to largest as shown in Figure 7.8. Each pairs of means are compared using the analysis of variance results. Pairs of means that are significantly different, at 0.05 significance level (95% confidence level) are indicated with an asterisk at the lower half of the matrix (see Figure 7.8). At the top matrix of Figure 7.8, the three asterisks to the right of "Grp2 " indicate that two cracks produce peak stresses (PKSTRS) that are significantly different from the peak stresses produced by 14, 16, and 20 cracks.

In summary, Figure 7.8 indicates that the optimum number of cracks is 5 to 6. That is, the model results produced by this optimum number of cracks are significantly comparable to the model results produced by any other higher number of cracks.

Figure 7.9 is similar to Figure 7.8; however, it is related to the material labeled C3 (Vf=3.98%). Figure 7.9 indicates that the optimum number of cracks for material C3 is 7 to 9.

The established optimum number of cracks are expected to drop to smaller values if the significance level of 0.05 is relaxed to 0.1.

Table 7.2: Analytical Values Obtained for the Stress-Strain Curve Parameters with Different Number of the Number of Cracks (NC).

NC	vf=1.72%	vf=1.72%	vf=1.72%	vf=3.98%	vf=3.98%	vf=3.98%
NC	PKSTRS	PKSTRN	TOGHNS	PKSTRS	PKSTRN	TOGHNS
2	1.680	2.146	1.804	2.094	2.860	3.190
2	1.182	1.512	0.895	1.928	2.518	2.590
2	1.278	1.635	1.046	2.023	2.722	2.960
2	1.534	1.960	1.504	1.873	2.627	2.673
2	1.272	1.626	1.035	1.999	2.719	2.894
4	1.645	2.103	1.732	2.009	2.870	3.209
4	1.343	1.718	1.155	1.810	2.493	2.484
4	1.240	1.588	0.987	1.742	2.636	2.608
4	1.654	2.114	1.750	2.112	2.943	3.375
4	1.430	1.830	1.310	2.062	2.8301	3.112
6	1.342	1.719	1.16	1.831	2.926	3.104
6	1.169	1.501	0.88	1.916	2.791	3.063
6	1.265	1.622	1.028	1.736	2.41	2.291
6	1.195	1.533	0.919	1.916	2.695	2.892
6	1.169	1.5	0.879	2.167	3.232	3.914
10	1.211	1.556	0.945	1.946	3.249	3.678
10	1.248	1.602	1.002	1.627	2.478	2.308
10	1.164	1.494	0.8714	1.469	1.974	1.547
10	1.219	1.568	0.9586	1.826	3.33	3.675
10	1.451	1.862	1.354	1.51	2.664	2.514
14	1.209	1.557	0.944	1.508	2.531	2.306
14	1.174	1.516	0.8923	1.609	2.773	2.687
14	1.202	1.55	0.934	1.685	3.265	3.475
14	0.993	1.28	0.637	1.803	3.608	4.148
14	1.167	1.505	0.881	1.635	2.159	1.87
16	1.218	1.569	0.958	1.667	3.323	3.529
16	1.232	1.589	0.9821	1.656	3.605	3.995
16	1.16	1.495	0.8696	1.72	2.816	2.862
16	1.125	1.455	0.8206	1.691	2.86	2.898
16	1.145	1.677	1.0501	1.649	3.182	3.149
20	1.216	1.575	0.96	1.669	3.913	4.367
20	1.223	1.58	0.969	1.571	2.419	2.145
20	1.23	1.59	0.9803	1.922	3.39	3.902
20	1.08	1.4	0.7577	1.667	2.913	2.945
20	1.19	1.544	0.9211	1.664	2.609	2.522

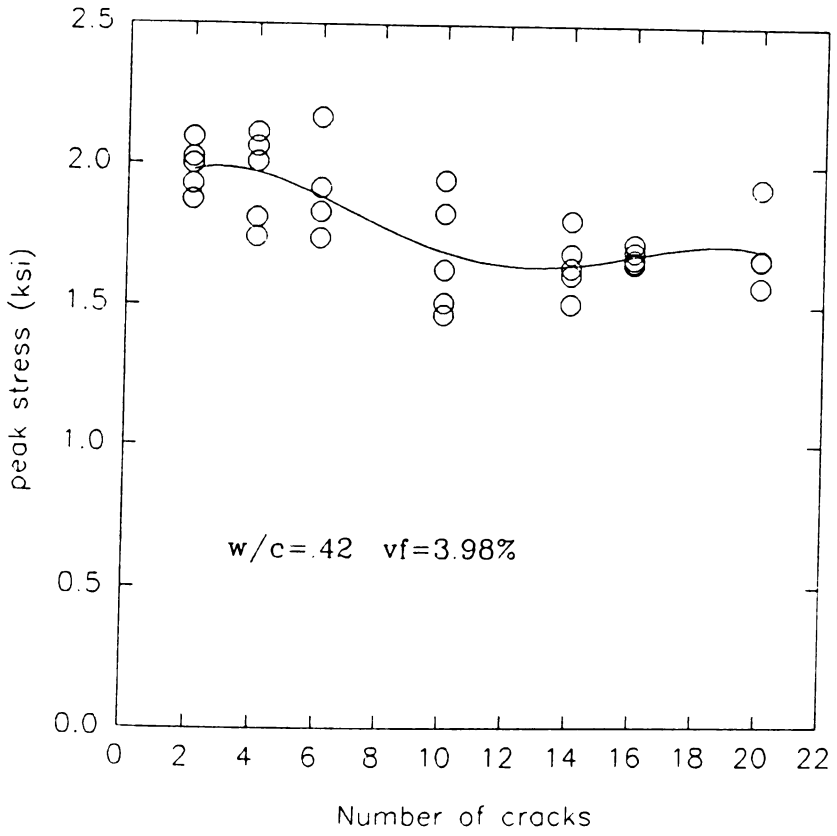


FIGURE 7.4 **Peak Stress Vs. Number Of Cracks for Vf=3.98% (carbon fiber and w/c=.42).**

Peak Strain (10^{-3})

Peak Toughness (10^{-3} ksi)

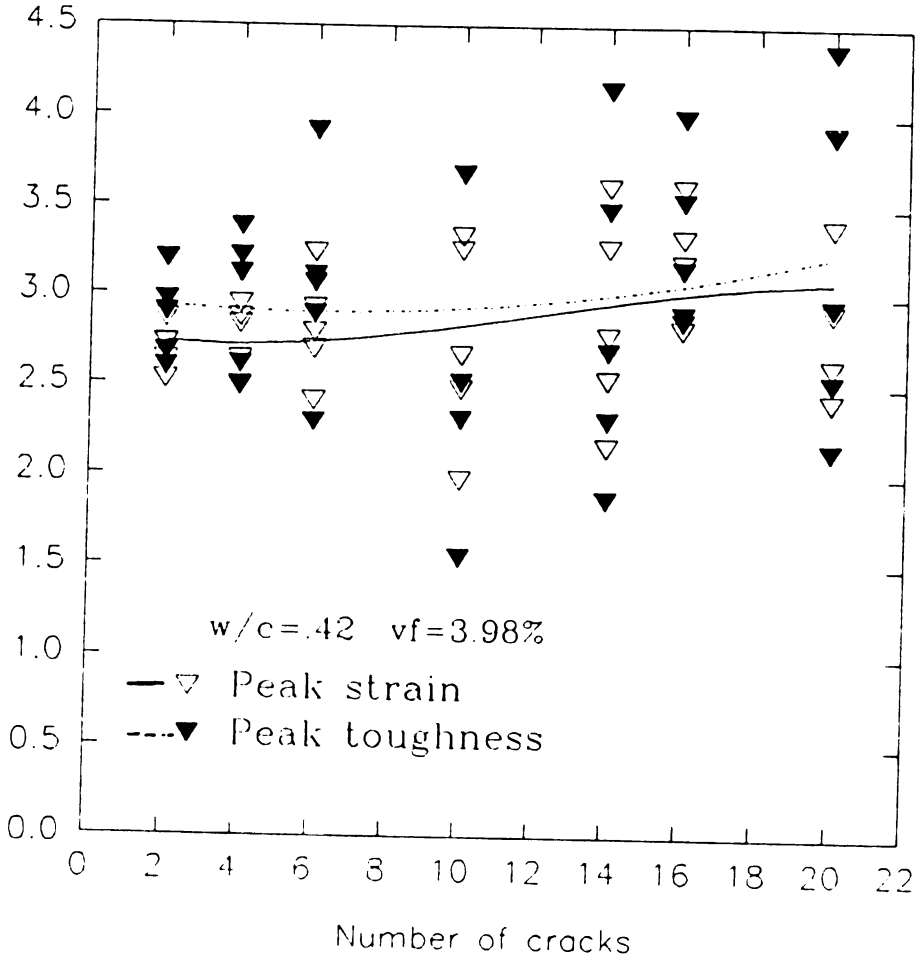


FIGURE 7.5 **Peak Strain and Toghness Vs. Number of Cracks for Vf=3.98% (carbon fiber w/c=.42).**

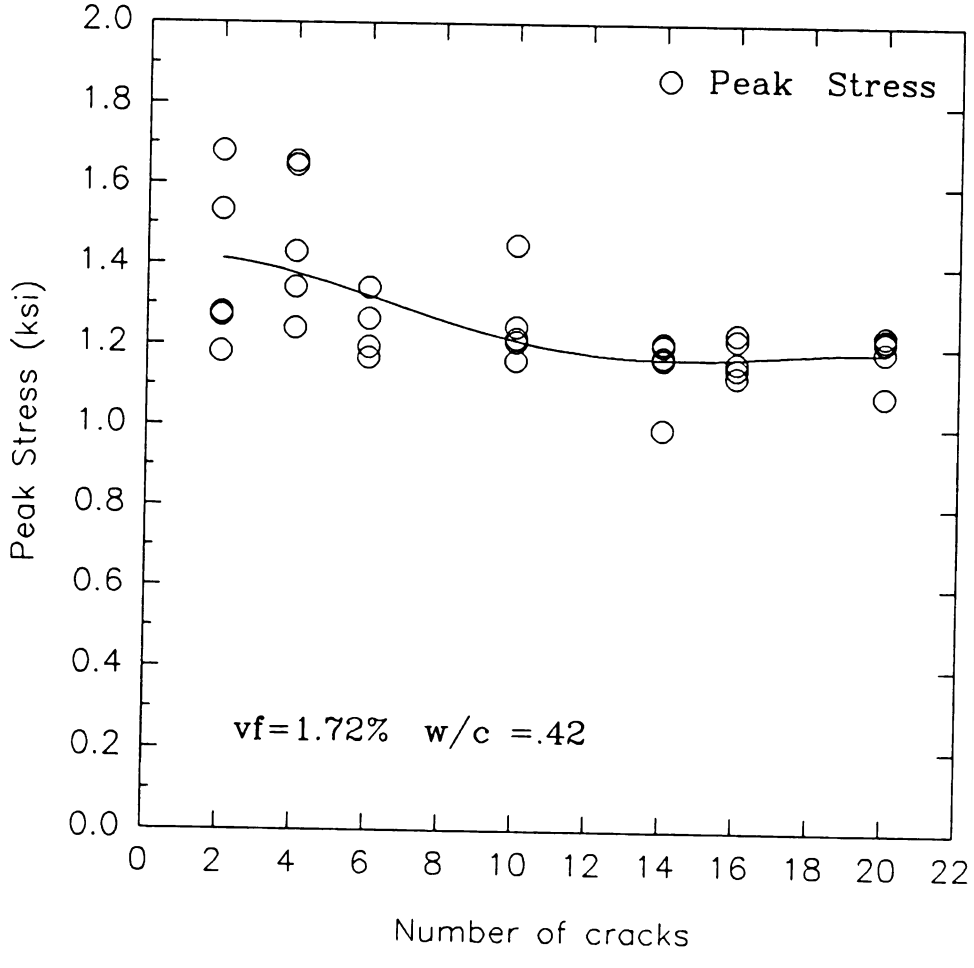


FIGURE 7.6 **Peak Stress Vs. Number Of Cracks for Vf=1.72% (carbon fiber and w/c=.42).**

Peak Strain (10^{-3})

Peak Toughness (10^{-3} ksi)

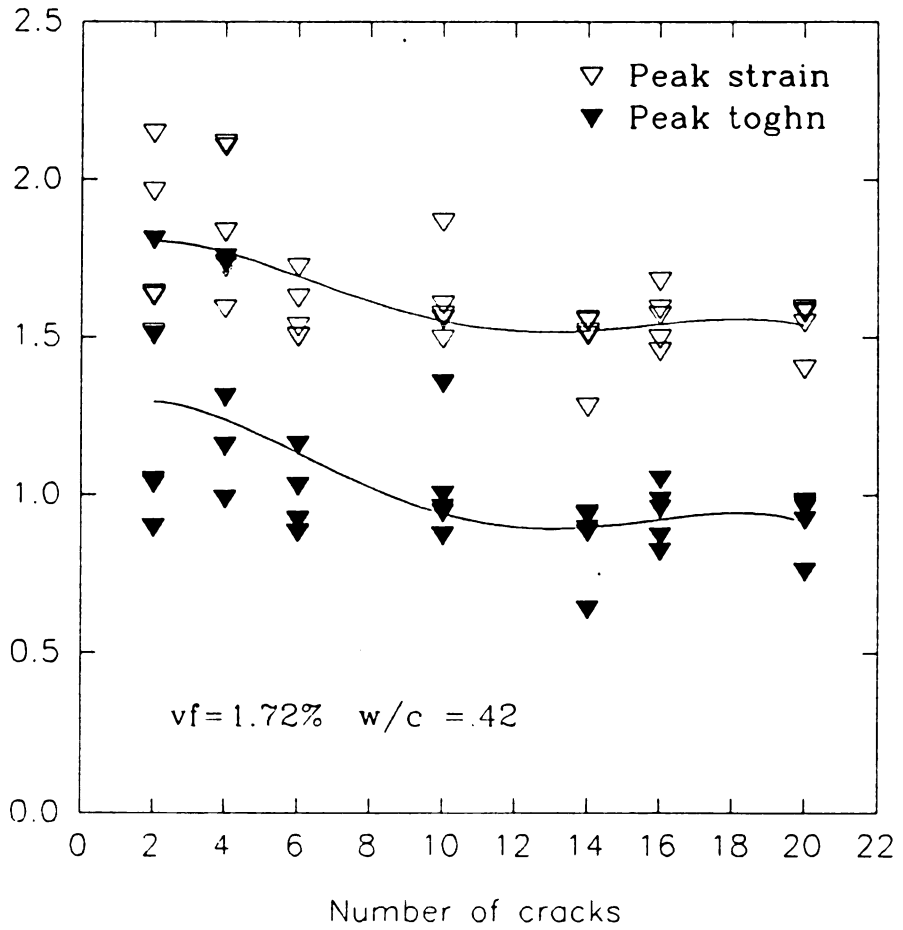


FIGURE 7.7 **Peak Strain and Toghness Vs. Number Of Cracks for Vf=1.72% (carbon fiber and w/c=.42).**

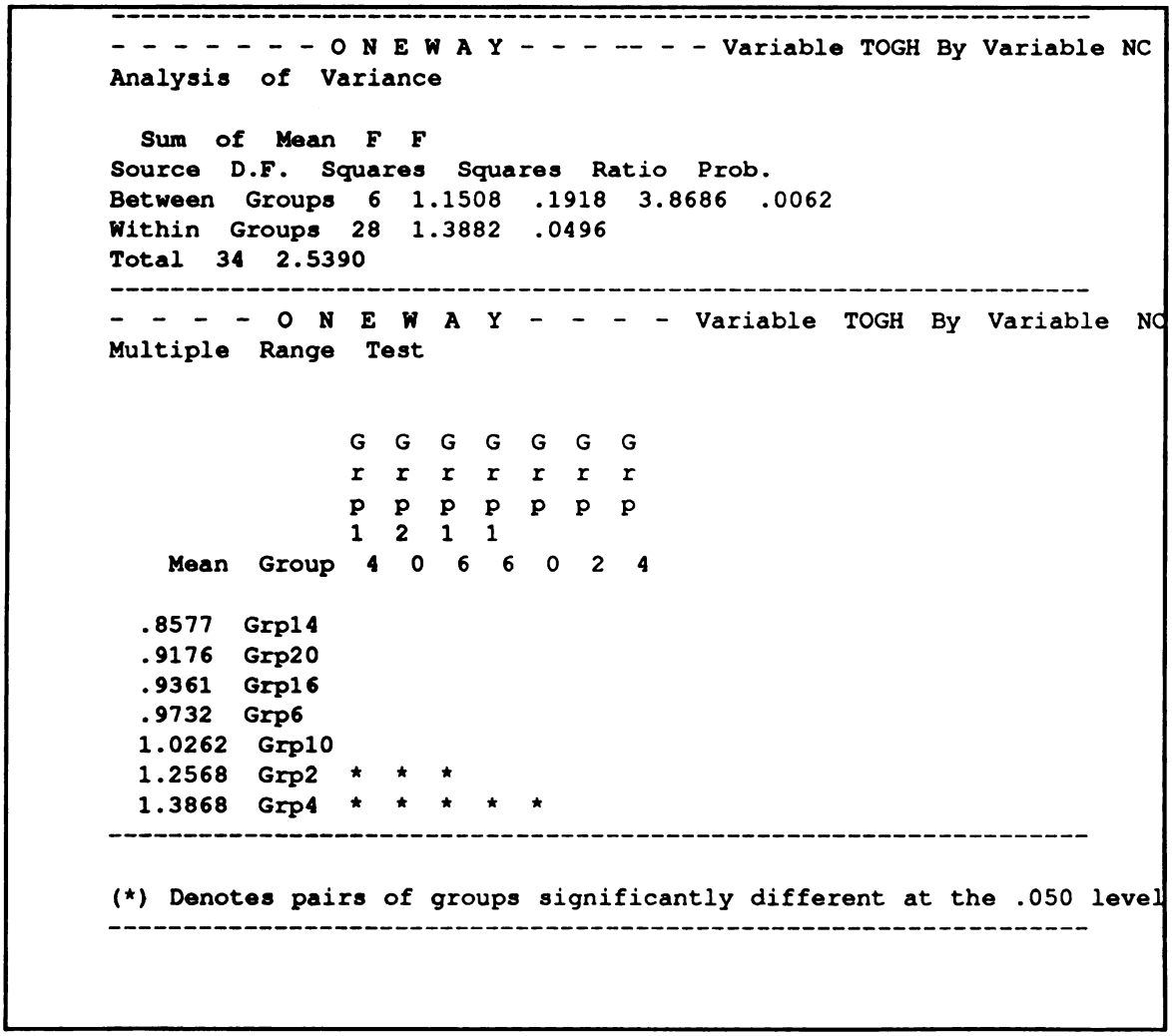
```
------------------------------------------------------------
ONEWAY /VARIABLES PKSTRS PKSTRN TOGH BY NC (2,20) /RANGES LSD.
------------------------------------------------------------
- - - - O N E W A Y - - - -Variable PKSTRS By Variable NC
Analysis of Variance
Sum of Mean F F
Source D.F. Squares Squares Ratio Prob.
Between Groups 6 .4157 .0693 4.4333 .0028
Within Groups 28 .4376 .0156
Total 34 .8533
------------------------------------------------------------------
- - - - - O N E W A Y - - - - - -Variable PKSTRS By Variable NC
Multiple Range Test
                G G G G G G G
                r r r r r r r
                p p p p p p p
                1 1 2 1
  Mean Group     4 6 0 6 0 2 4
  1.1490 Grp14
  1.1760 Grp16
  1.1878 Grp20
  1.2280 Grp6
  1.2586 Grp10
  1.3892 Grp2  * * *
  1.4624 Grp4  * * * * *
------------------------------------------------------------------
- - - O N E W A Y - - - - -Variable PKSTRN By Variable NC
Analysis of Variance

  Sum of Mean F F
  Source D.F. Squares Squares Ratio Prob.
Between Groups 6 .5910 .0985 3.8008 .0068
Within Groups 28 .7257 .0259
Total 34 1.3167
------------------------------------------------------------------
- - - O N E W A Y - - - - -Variable PKSTRN By Variable NC
Multiple Range Test

              G G G G G G G
              r r r r r r r
              p p p p p p p
              1 2 1 1
  Mean Group   4 0 6 6 0 2 4

  1.4816 Grp14
  1.5378 Grp20
  1.5570 Grp16
  1.5750 Grp6
  1.6164 Grp10
  1.7758 Grp2  * * *
  1.8706 Grp4  * * * * *
```

FIGURE 7.8 SPSS-Statistical Multiple Comparisons for Vf=1.72%.



```
------------------------------------------------------------------
- - - - - - - - O N E W A Y - - - - -- - - Variable TOGH By Variable NC
Analysis of Variance

  Sum of Mean F F
Source D.F. Squares Squares Ratio Prob.
Between Groups 6 1.1508 .1918 3.8686 .0062
Within Groups 28 1.3882 .0496
Total 34 2.5390
------------------------------------------------------------------
- - - - - O N E W A Y - - - - - Variable TOGH By Variable NC
Multiple Range Test


               G G G G G G G
               r r r r r r r
               p p p p p p p
               1 2 1 1
    Mean Group 4 0 6 6 0 2 4

  .8577 Grp14
  .9176 Grp20
  .9361 Grp16
  .9732 Grp6
 1.0262 Grp10
 1.2568 Grp2  *  *  *
 1.3868 Grp4  *  *  *  *  *
------------------------------------------------------------------

(*) Denotes pairs of groups significantly different at the .050 level
------------------------------------------------------------------
```

FIGURE 7.8 (Continued)

```
------------------------------------------------------------
ONEWAY /VARIABLES STRS398 STRN398 TOGH398 BY NC (2,20) /RANGES
LSD.
------------------------------------------------------------
- - O N E W A Y -- - - Variable STRS398 By Variable NC
Analysis of Variance
Sum of Mean F F
  Source D.F. Squares Squares Ratio Prob.
Between Groups 6 .6584 .1097 5.8578 .0005
Within Groups 28 .5245 .0187
Total 34 1.1829
------------------------------------------------------------
- - O N E W A Y - - Variable STRS398 By Variable NC
Multiple Range Test
(*) Denotes pairs of groups significantly different at the .050
level
------------------------------------------------------------
                G G G G G G G
                r r r r r r r
                p p p p p p p
                1 1 1 2
  Mean Group    4 0 6 0 6 4 2

  1.6480 Grp14
  1.6756 Grp10
  1.6766 Grp16
  1.6986 Grp20
  1.9132 Grp6  *   *   *   *
  1.9470 Grp4  *   *   *   *
  1.9834 Grp2  *   *   *   *
------------------------------------------------------------
```

FIGURE 7.9 SPSS-Statistical multiple Comparison For vf=3.98%.

```
------------------------------------------------------------
- - - O N E W A Y - - - - Variable STRN398 By Variable NC
Analysis of Variance
Sum of Mean F F
  Source D.F. Squares Squares Ratio Prob.
Between Groups 6 .9055 .1509 .8334 .5544
Within Groups 28 5.0704 .1811
Total 34 5.9759
------------------------------------------------------------
- - O N E W A Y - - - Variable STRN398 By Variable NC
Multiple Range Test
No two groups are significantly different at the .050 level
------------------------------------------------------------
- - O N E W A Y - - - -Variable TOGH398 By Variable NC
Analysis of Variance
Sum of Mean F F
Source D.F. Squares Squares Ratio Prob.
Between Groups 6 1.0640 .1773 .3720 .8905
Within Group 28 13.3488 .4767
Total 34 14.4128
------------------------------------------------------------
- - O N E W A Y - - Variable TOGH398 By Variable NC
Multiple Range Test
No two groups are significantly different at the .050 level
------------------------------------------------------------
```

FIGURE 7.9 (Continued)

7.4 Comparison of model outputs with experimental carbon fiber cement results

In this section, the model results are compared against the experimental results of carbon fiber cement (mixes C1 through C6 in Table 7.1).

7.4.1 optimum model Parameters (KIC, TAU) Using "Design- Expert" Software.

All the input variables are fixed except for the fracture toughness (KIC) and the shear strength (TAU). These two parameters were not reported with experimental results. The objective here is to determine if close comparison between model and experimental results can be obtained at reasonable values of KIC and TAU. In this section, an optimum range of values for KIC and TAU is established for achieving close comparison with test results, using the optimization software "Design-Expert" (Reference 7.7), to analyze the model data shown in Tables 7.7, and 7.8.

The meaning of optimization, herein, is the same as the definition introduced in section 7.2.

In the case of the materials having a water to cement ratio of 0.42 the variables are:

X1=Vf=Fiber content

X2=KIC=Fracture toughness

X3=TAU=Interfacial shear strength

The responses are:

R1=Peak stress

R2=Peak strain

R3=Peak toughness

The optimization problem can be specifically stated as:

What range of the variables X2 (KIC) and X3 (TAU) meet the following constraints or specifications: the model responses and the experimental responses have to be comparable with an allowable error margin of 10% to 30% (of the experimental responses).

The allowable error range is within what is established experimentally.

The above constraint has to be met for every level of fiber content (i.e. X1=0%; X1=1.72%; X1=3.18%; and X1=3.98%) with the understanding that a shear bond associated with X1=Vf=0% is meaningless and therefore, it is ignored in the final decision regarding the optimum range of KIC (X2) and TAU (X3).

In Figure 7.10, the optimum ranges of KIC and TAU are shown separately for each fiber content. The constraints are reflected by the lines labeled (R1_LO; R1_HI; R2_LO; R2_HI;...). The constraints limits, used with Figure 7.10 are as follows (Table 7.3):

Table 7.3: Constraint Limits on the Response Variables for the Carbon Fiber Cement Based Materials with a Water to Cement Ratio of 0.42.

	R1=Peak Stress (ksi)		R2=Peak Strain (10-3)		Toughness (10-3 ksi)	
	R1_LO	R1_HI	R2_LO	R2_HI	R3_LO	R3_HI
X1=Vf=0%	0.5	0.6	0.5	0.7	0.5	0.7
X1=Vf=1.72%	0.6	0.8	2.0	2.5	1	1.5
X1=Vf=3.18%	0.9	1.1	6	8	5.5	7.0
X1=Vf=3.98%	1.0	1.2	9	11	6	8.0

By definition KIC is the fracture toughness of the matrix (without any fiber effect). Therefore, KIC is independent of the fiber content. Also, TAU is assumed independent of the fiber content (as discussed in the analysis phase).

For the above constraints to be met for every fiber content, the overall optimum range of KIC and TAU is the intersection of all the optimum ranges corresponding to each fiber content (see Figure 7.10).

The analysis of Figure 7.10 gives the following results regarding the optimum ranges of KIC and TAU (Table 7.4):

Table 7.4: Optimum Ranges of KIC and TAU Corresponding to Carbon Fiber Matrix (w/c=0.42)

	Optimum ranges for each fiber content	
	KIC (ksi $in^{1/2}$)	TAU (ksi)
X1=Vf=0% X1=Vf=1.72% X1=Vf=3.18% X1=vf=3.98%	0.1 to 0.12 0.12 to 0.17 0.119 to 0.17 0.117 to 0.18	not applicable 0.09 to 0.5 0.09 to 0.35 0.09 to 0.5
Overall Optimum Range	~0.12	0.09 to 0.35

The optimum range of KIC and TAU shown above (Table 7.4) are well within the experimentally acceptable ranges of these parameters. As presented in the analysis phase, KIC and TAU depends on many material variables. The experimentally established range of KIC is 0.05 to 0.3 ksi $in^{1/2}$. The experimentally established range of the bond strength (TAU) of carbon fibers in cement matricies is from very low values up to about 1 ksi.

Since we do not know the exact experimental values for KIC and TAU corresponding to the materials at hand, the overall optimum range of KIC and TAU (Table 7.4) are only to serve as guiding values toward producing model responses that are comparable to the experimental results. The comparison is done in the next section.

Figure 7.11 is similar to figure 7.10, except that the optimization process is done for carbon fiber cement-based materials associated with a water to cement ratio of 0.29 (see Table 7.1).

In Figure 7.11, the variables are;

X1=Vf=fiber content

X2=TAU=bond strength

X3=KIC=fracture toughness

The responses are:

R1=peak stress

R2=peak strain

The toughness responses will be verified during the actual model-experimental comparison of results.

Similar to the previous case (i.e. w/c=0.420), the optimization process can be described as follows:

What range of variables X2 (TAU) and X3 (KIC) meet the following constraints: the model response and the experimental responses are comparable with an allowable error margin up to 30% of the experimental values. This constraint has to be met for every fiber content (i.e. 0%, 2.04%, and 4.03%). Again, the optimum range of the shear bond (TAU) associated with Vf=0% is meaningless.

The numerical values of the constraints are shown below in Table 7.5.

Table 7.5: Constraint Limits on the Response Variables for the Carbon Fiber Cement Based Matirials with a Water to Cement Ratio of 0.29

	R1=Peak Stress (ksi)		R2=Peak Strain (10-3)	
	R1_LO	R1_HI	R2_LO	R2_HI
X1=Vf=0%	0.5	0.7	0.25	0.4
X1=Vf=2.04%	1	1.3	0.5	0.7
X1=Vf=4.03%	1.5	1.8	1.5	2.5

The overall optimum range of KIC and TAU is the intersection of all the optimum ranges corresponding to each fiber content (Figure 7.11). Analysis of Figure 7.11 gives the following optimum ranges of KIC and TAU (Table 7.6):

Table 7.6: Optimum Ranges of KIC and TAU Corresponding to Carbon Fiber Matrix (w/c=0.29)

	Optimum ranges for each fiber content	
	KIC (ksi $in^{1/2}$)	TAU (ksi)
X1=Vf=0%	0.18 to ~0.23	not applicable
X1=Vf=2.04%	0.133 to 0.22	0.75 to 0.85
X1=Vf=4.03%	0.167 to 0.26	0.6 to 0.9
Overall Optimum Range	0.167 to 0.22	0.6 to 0.85

The above overall optimum range are within experimentally acceptable ranges, and they will serve as guiding values in the actual comparison of model-experimental responses in the next sections. It is important to notice that the optimum ranges of KIC and TAU corresponding to w/c pf 0.29 are greater in values than those corresponding to a w/c of 0.42. This can be observed by comparing the values of Table 7.6 against the values of Table 7.4.

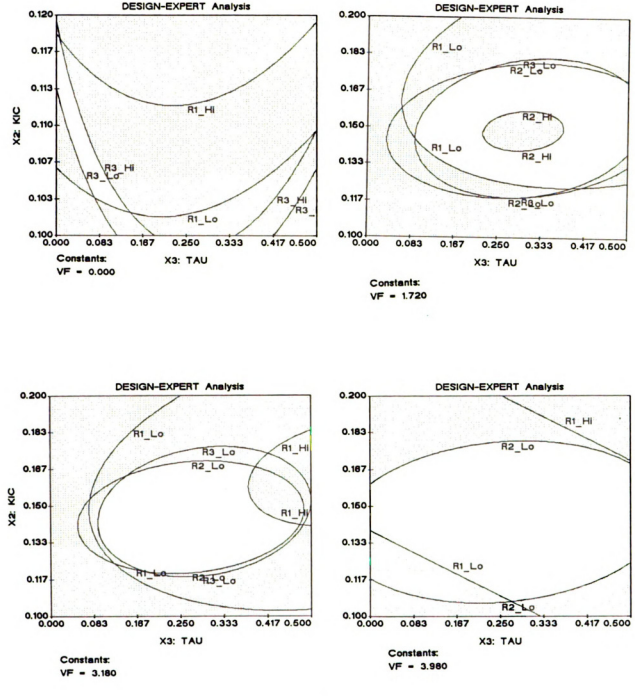


FIGURE 7.10 Preliminary Optimum Region for KIC and TAU (carbon fiber and w/c=.42).

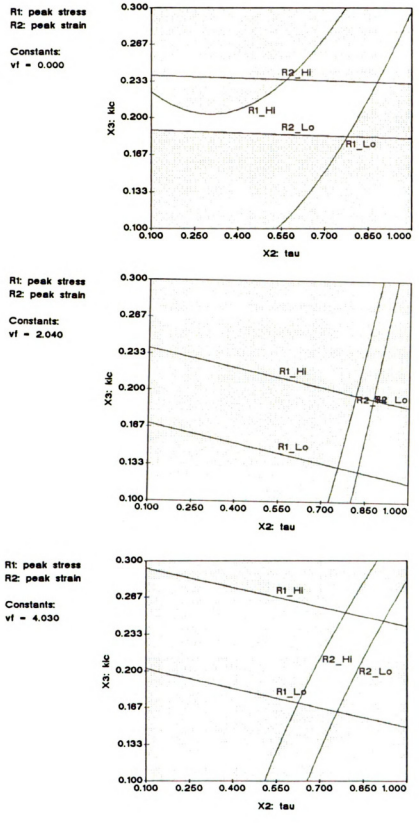


FIGURE 7.11 Preliminary Optimum Region for KIC and TAU (carbon fiber and w/c=.29).

Table 7.7: Data Used with "Design-Expert", For Optimum Model Parameters, for Carbon Fiber, w/c=.42

VF (X1)	KIC (X2)	TAU (X3)	peak stress (R1)	peak strain (R2)	toughness (R3)
%	KSI*(IN)1/2	KSI	(ksi)	10-3	10-3
0.0000	0.2000	0.1000	0.8892	1.1900	0.5350
1.9900	0.1500	0.3000	0.7135	2.8320	1.9400
1.9900	0.1201	0.3000	0.6435	2.8970	1.7520
1.9900	0.1500	0.3000	0.7135	2.8320	1.9400
3.9800	0.1000	0.1000	1.2240	8.6790	9.0730
1.9900	0.1500	0.3000	0.6780	2.6210	1.6620
0.0000	0.1000	0.5000	0.4450	0.5950	0.1340
3.9800	0.2000	0.1000	1.0001	4.6740	4.8520
1.9900	0.1799	0.3000	0.8178	3.4720	2.9000
1.9900	0.1500	0.3000	0.7002	2.7250	1.7813
0.0000	0.1000	0.1000	0.4450	0.5950	0.1340
3.1800	0.1500	0.3000	1.0920	8.5300	8.3290
1.9900	0.1500	0.1804	0.7207	3.0640	2.2270
3.9800	0.2000	0.5000	1.4426	5.6600	7.1650
1.9900	0.1500	0.4196	0.7520	4.3840	3.4100
0.0000	0.2000	0.5000	0.8890	1.1890	0.5350
3.9800	0.1000	0.5000	1.2831	5.6740	5.4430
0.8000	0.1500	0.3000	0.7570	3.7330	2.9430
1.9900	0.1500	0.3000	0.6867	2.6562	1.7100
1.9900	0.1500	0.3000	0.7894	3.3280	2.6000
1.7200	0.1500	0.4192	0.7592	4.3480	3.6000
1.7200	0.1500	0.1804	0.6892	2.9390	1.2000
1.7200	0.1201	0.3000	0.5550	2.3030	1.2250
1.7200	0.1500	0.3000	0.7050	3.5240	2.6210
0.0000	0.1799	0.3000	0.8130	4.9540	4.2450

Table 7.8: Data Used with "Design-Expert", For Optimum Model Parameters, for Carbon Fiber, w/c=.29

VF (X1)	TAU (X2)	KIC (X3)	Peak Stress (R1)	Peak Strain (R2)	Toughness (R3)
%	ksi	ksi(in)1/2	ksi	10-3	10-3 Ksi
0.0000	0.6000	0.8000	3.5610	3.572	6.433
2.0150	0.3500	0.4500	2.5190	10.225	26.594
2.0150	0.3500	0.4500	2.4330	15.080	39.914
0.0000	0.1000	0.1000	0.4450	0.446	0.100
4.0300	0.6000	0.1000	1.3263	4.014	3.990
4.0300	0.1000	0.8000	3.7860	18.806	74.636
0.0000	0.6000	0.1000	0.4450	0.446	0.100
2.0150	0.3500	0.4500	2.0950	6.181	12.560
4.0300	0.1000	0.1000	1.1102	5.808	5.760
2.0150	0.3500	0.4500	2.3240	12.397	30.906
4.0300	0.6000	0.8000	4.2460	19.044	86.361
0.0000	0.1000	0.8000	3.5610	3.572	6.433
2.0150	0.3500	0.1000	0.6110	3.087	1.815
4.0300	0.3500	0.4500	2.1780	9.589	22.419
2.0150	0.1000	0.4500	2.0920	6.990	15.101
2.0150	0.3500	0.4500	2.3430	10.971	27.493
0.0000	0.3500	0.4500	2.0040	2.010	2.038
2.0150	0.3500	0.4500	2.3430	10.971	27.493
2.0150	0.3500	0.8000	4.0930	18.023	76.791
2.0150	0.6000	0.4500	2.0600	8.845	19.045

7.4.2 Statistical comparison of the experimental and model results for carbon fiber and w/c=.42

Based on the optimum values of KIC and TAU established in the previous section, the model produced the following results (Table 7.9), for carbon fiber cement and a water to cement ratio (w/c) of 0.42.

The values of KIC and TAU that were used to produce the results shown below

are 0.120 ksi(in)$^{1/2}$ and .2 ksi respectively.

Table 7.9: Optimum Model Values for Carbon Fiber and w/c=.42

Vf (%)	Peak Stress (ksi)	Peak Strain 10-3	Peak Tough 10-3 ksi	Total Tough 10-3 ksi
0	.612 .5521 .4876 .5678	.6132 .5349 .5759 .571	.2815 .2062 .2483 .2450	.2815 .2062 .2483 .2450
1.72	.8874 .753 .8138 .7298	1.93 2.26 1.59 1.44	1.7 1.783 1.253 1.018	1.7 1.783 1.253 1.018
3.98	1.25 1.124 1.26 1.211	4.835 4.6331 4.475 4.9535	5.672 4.651 5.2643 5.196	5.672 4.651 5.2643 5.196

Plots of the model predictions versus the experimental values are shown in Figures 7.13 through 7.16.

The experimental and model data were statistically compared using T-Test in the statistical software "SPSS" (Reference 7.6). The experimental and model results were significantly comparable at a confidence level of 95%. Typical T-Test results are shown in Figure 7.12.

In order to understand the information presented in Figure 7.12, we need to review some basic statistical concepts regarding hypothesis testing using T-TEST procedures.

The purpose of hypothesis testing is to draw conclusions regarding some statistical population parameters based on results observed in a random sample. In our case, the purpose is to draw conclusions regarding the comparability of the model responses and the experimental responses. Usually, the procedure involves the following steps:

(1) Define a null hypotheses and its alternate hypotheses: In our case, the null hypotheses is: "there is no significant difference between the experimental and model responses."

(2) Calculate a test statistic (T-TEST): In the current case, The T-TEST statistic is

calculated as follows:

$$t = \frac{\bar{X}_m - \bar{X}_{exp}}{\sqrt{\frac{S_m^2}{N_m} + \frac{S_{exp}^2}{N_{exp}}}},$$

Where $\bar{X}_m$, S^2_m, and N_m are the mean, variance, and the sample size of a model response; and $\bar{X}_{exp}$, S^2_{exp}, and N_{exp} are the mean, variance, and the sample size of the experimental response.

(3) The probability, if the null hypotheses is true, of obtaining a test value at least as extreme as the one observed is determined (the observed significance level).

(4) If the observed significance level is judged small enough (according to a prefixed significance level, 5% in the current case), then the null hypotheses is rejected. Otherwise, the null hypotheses is accepted.

Figure 7.12 presents the T-TEST results corresponding to the materials labeled C1, C2, and C3 in Table 7.1. These materials are characterized by a w/c of 0.42 and fiber contents of 0%, 1.72%, and 3.98%. For each fiber content, the model responses (identified by Group2 in Figure 7.12) are compared to the experimental responses (identified by Group 1 in Figure 7.12). The responses considered, for each fiber content, uniquely represent the stress-strain curve of the material. These responses are: peak stress (STRS0, STRS172, STRS398 in Figure 7.12); peak strain (STRN0, STRN172, STRN398 in Figure 7.12); and toughness (TOGH0, TOGH172, TOGH398 in Figure 7.12). Numbers at the end of the response labels identify the fiber contents.

In Figure 7.12, the T-TEST results of each response are separated by dotted lines from one another. The most important result in each block of Figure 7.12 is the observed significance level given under the heading "2-Tail Prob.". This value is needed in order to make the decision wether to reject or accept the null hypotheses of no difference between the model and experimental results. The interpretation of a small "2-Tail Prob." is straightforward: it is unlikely (small probability) that the two population means are equal, hence, the decision would be the rejection of the null hypotheses.

All the observed significance levels in Figure 7.12 are large enough to accept the null hypotheses of no difference between model and experimental results. Therefore, it is concluded that the model and experimental results are comparable at 5% significance level (or 95% confidence level).

```
T-TEST /GROUPS GROUP ('exp','mod') /VARIABLES STRS0 STRN0 TOGH0 STRS172 STRN172
 TOGH172 STRS398 STRN398 TOGH398 .
-----------------------------------------------------------------------
Independent samples of GROUP      identifes wether the value is experiment
Group 1: GROUP EQ exp             Group 2: GROUP EQ mod
t-test for: STRS0      stresses at vf=0 and w/c=.42

                Number                    Standard    Standard
                of Cases      Mean        Deviation   Error

     Group 1       4         .5563          .043        .021
     Group 2       4         .5549          .052        .026


                Pooled Variance Estimate  Separate Variance Estimate

   F    2-Tail      t    Degrees of 2-Tail     t    Degrees of  2-Tail
 Value  Prob.    Value    Freedom    Prob.   Value     Freedom     Prob.

  1.46   .765     .04        6       .969     .04       5.80        .969
-----------------------------------------------------------------------
t-test for: STRN0      peak strain at vf=0% w/c=.42

                Number                    Standard    Standard
                of Cases      Mean        Deviation   Error

     Group 1       4         .5715          .019        .010
     Group 2       4         .5738          .032        .016


                Pooled Variance Estimate  Separate Variance Estimate

   F    2-Tail      t    Degrees of 2-Tail     t    Degrees of  2-Tail
 Value  Prob.    Value    Freedom    Prob.   Value     Freedom     Prob.

  2.70   .436    -.12        6       .906    -.12       4.95        .907
-----------------------------------------------------------------------
t-test for: TOGH0      toghness at vf=0% and w/c=.42

                Number                    Standard    Standard
                of Cases      Mean        Deviation   Error

     Group 1       4         .2438          .043        .021
     Group 2       4         .2453          .031        .015


                Pooled Variance Estimate  Separate Variance Estimate

   F    2-Tail      t    Degrees of 2-Tail     t    Degrees of  2-Tail
 Value  Prob.    Value    Freedom    Prob.   Value     Freedom     Prob.

  1.92   .606    -.06        6       .956    -.06       5.46        .957
-----------------------------------------------------------------------
t-test for: STRS172    stresses at vf=1.72 and w/c=.42

                Number                    Standard    Standard
                of Cases      Mean        Deviation   Error

     Group 1       4         .8000          .082        .041
     Group 2       4         .7960          .070        .035


                Pooled Variance Estimate  Separate Variance Estimate

   F    2-Tail      t    Degrees of 2-Tail     t    Degrees of  2-Tail
 Value  Prob.    Value    Freedom    Prob.   Value     Freedom     Prob.

  1.34   .815     .07        6       .943     .07       5.87        .943
-----------------------------------------------------------------------
```

FIGURE 7.12 Typical Output of T-Test results, For Comparison of Experimental and Model Results (Carbon Fiber, w/c=.42).

t-test for: STRN172 peak strain at vf=1.72 and w/c=.42

	Number of Cases	Mean	Standard Deviation	Standard Error
Group 1	4	1.8625	.304	.152
Group 2	4	1.8050	.366	.183

Pooled Variance Estimate				Separate Variance Estimate			
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
1.45	.767	.24	6	.817	.24	5.80	.817

---

t-test for: TOGH172 toghness at vf=1.72% and w/c=.42

	Number of Cases	Mean	Standard Deviation	Standard Error
Group 1	4	1.5000	.410	.205
Group 2	4	1.4385	.364	.182

Pooled Variance Estimate				Separate Variance Estimate			
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
1.27	.850	.22	6	.830	.22	5.92	.830

---

t-test for: STRS398 stresses at vf=3.18 and w/c=.42

	Number of Cases	Mean	Standard Deviation	Standard Error
Group 1	4	1.1979	.069	.035
Group 2	4	1.2113	.062	.031

Pooled Variance Estimate				Separate Variance Estimate			
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
1.25	.858	-.29	6	.783	-.29	5.93	.783

---

t-test for: STRN398 strain at vf=3.18% and w/c=.42

	Number of Cases	Mean	Standard Deviation	Standard Error
Group 1	4	4.7600	.205	.102
Group 2	4	4.7242	.212	.106

Pooled Variance Estimate				Separate Variance Estimate			
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
1.06	.953	.24	6	.816	.24	5.99	.816

---

t-test for: TOGH398 toghness at vf=3.18% and w/c=.42

	Number of Cases	Mean	Standard Deviation	Standard Error
Group 1	4	5.1909	.129	.065
Group 2	4	5.1958	.420	.210

Pooled Variance Estimate				Separate Variance Estimate			
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
10.53	.084	-.02	6	.983	-.02	3.56	.983

FIGURE 7.12 (continued)

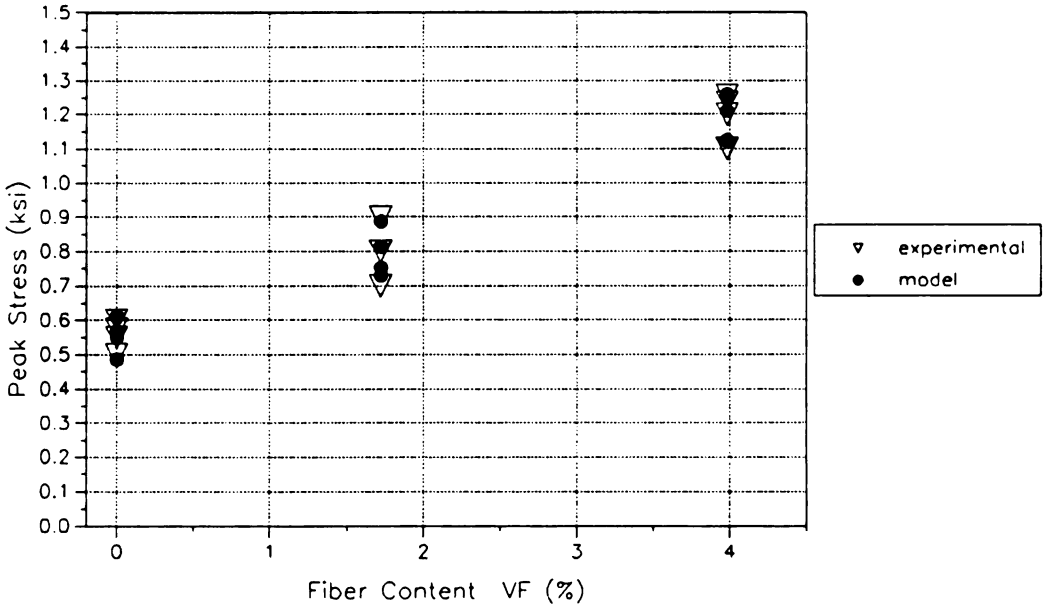


FIGURE 7.13 Experimental Vs. Model Results, Peak Stress (carbon fiber and w/c=.42).

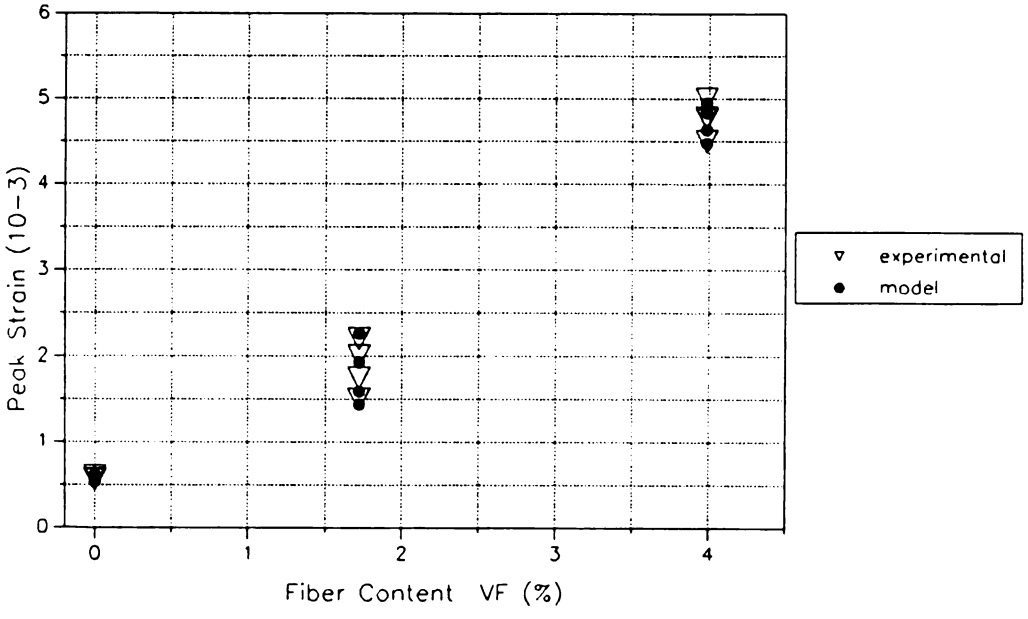


FIGURE 7.14 Experimental Vs. Model Results, Peak Strain (carbon fiber and w/c=.42).

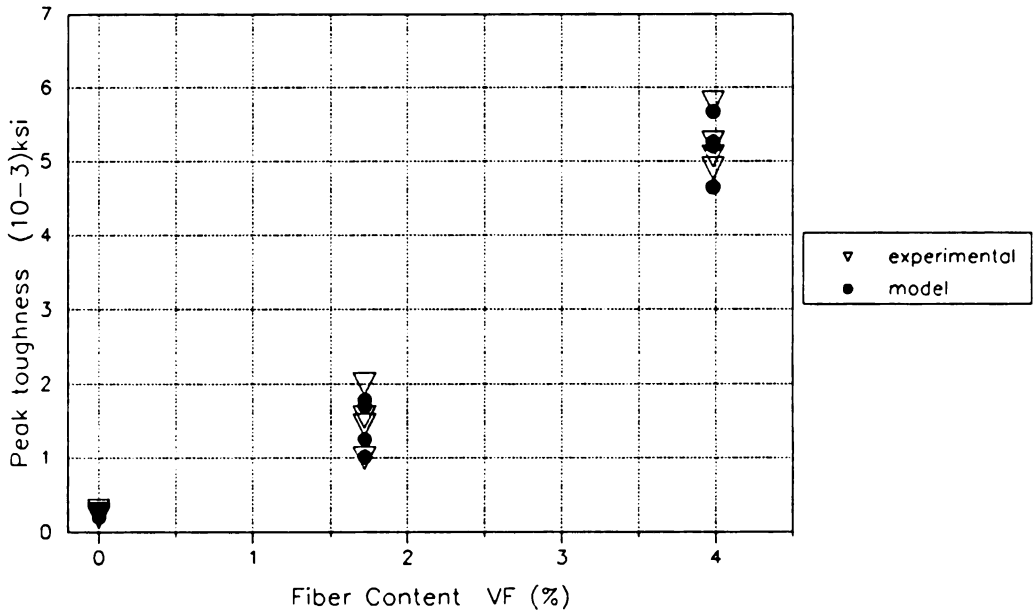


FIGURE 7.15 **Experimental Vs. Model Results, Peak Toghness (carbon fiber and w/c=.42).**

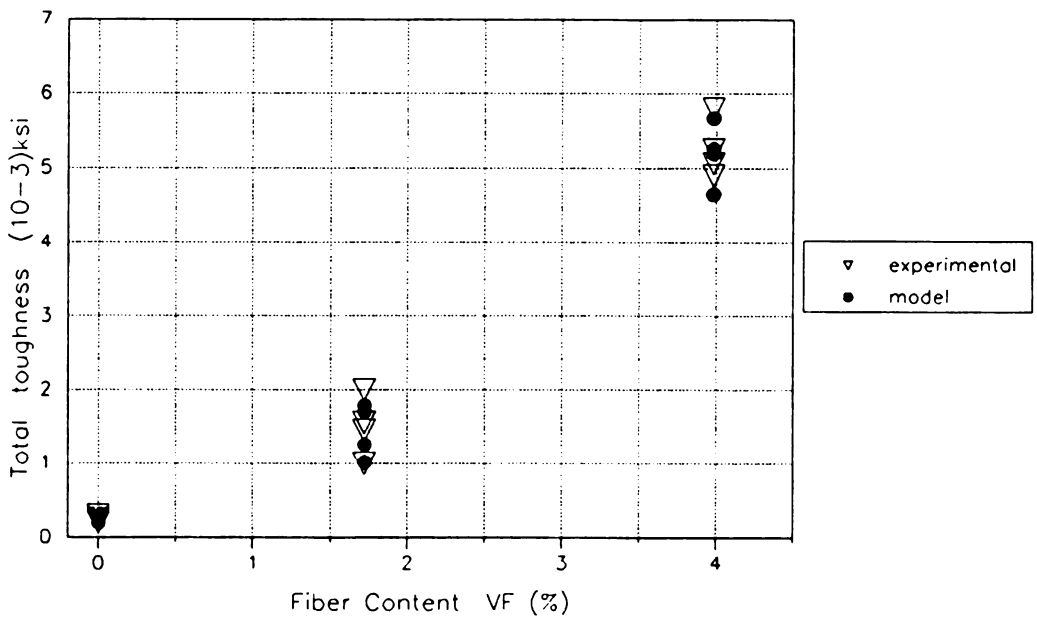


FIGURE 7.16 **Experimental Vs. Model Results, Total Toghness (carbon fiber and w/c=.42).**

7.4.3 Statistical comparison of the experimental and model results for carbon fiber and w/c=.29

Based on the analysis presented in section 7.4.1, values of KIC=0.2 ksi(in)$^{1/2}$, and TAU=0.6 ksi were used, in order to produce the model responses for comparison with the experimental results.

The optimum model results for carbon fiber cement with water to cement ratio of 0.29 are shown in Table 7.10.

It is important to notice in Table 7.10 that the model results are different in rep-

Table 7.10: Values for carbon fiber and w/c=.29

Vf (%)	Peak Stress (ksi)	Peak Strain 10-3	Peak Tough 10-3 ksi	Total Tough 10-3 ksi
0.0	.730 .585 .645 .654 .7034	.292 .234 .258 .231 .354	.1066 .070 .080 .12 .11	.1066 .070 .080 .12 .11
2.03	1.162 1.0351 .933 .997 1.045	.7722 .5882 .5876 .654 .734	.6405 .431 .395 .432 .532	.6405 .431 .395 .432 .532
4.02	1.753 1.978 1.845 1.825 1.79	1.5 1.823 1.734 1.768 1.8756	.85 1.1 .92 1.4 1.7	.85 1.1 .92 1.4 1.7

etitions of the same material conditions. This is due to the stochastic generation of the structure of each material, as it was detailed in the analysis phase. The stochastic generation of the structure of each specimen (5 specimens in table 7.6) is unique and different from any other specimen. This reflects the inherent differences in cement-based composite specimen of the same material, when experimentally tested. In general, these inherent differences are due to the way the material is manufactured.

The model and the experimental results were statistically compared using the T-Test method (Reference 7.6). The two results were comparable at a 95% confidence level. The results are graphically shown in Figures 7.17 through 7.20.

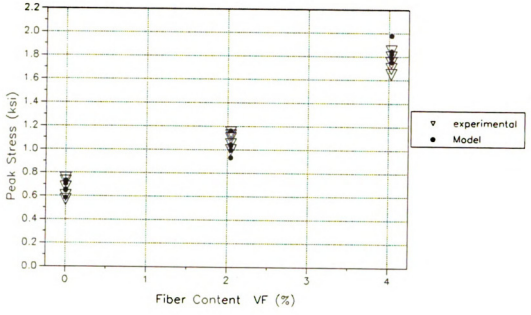


FIGURE 7.17 **Experimental Vs. Model Results, Peak Stress (carbon fiber and w/c=.29).**

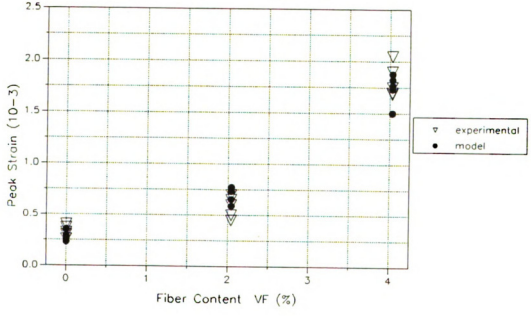


FIGURE 7.18 **Experimental Vs. Model Results, Peak Strain (carbon fiber and w/c=.29).**

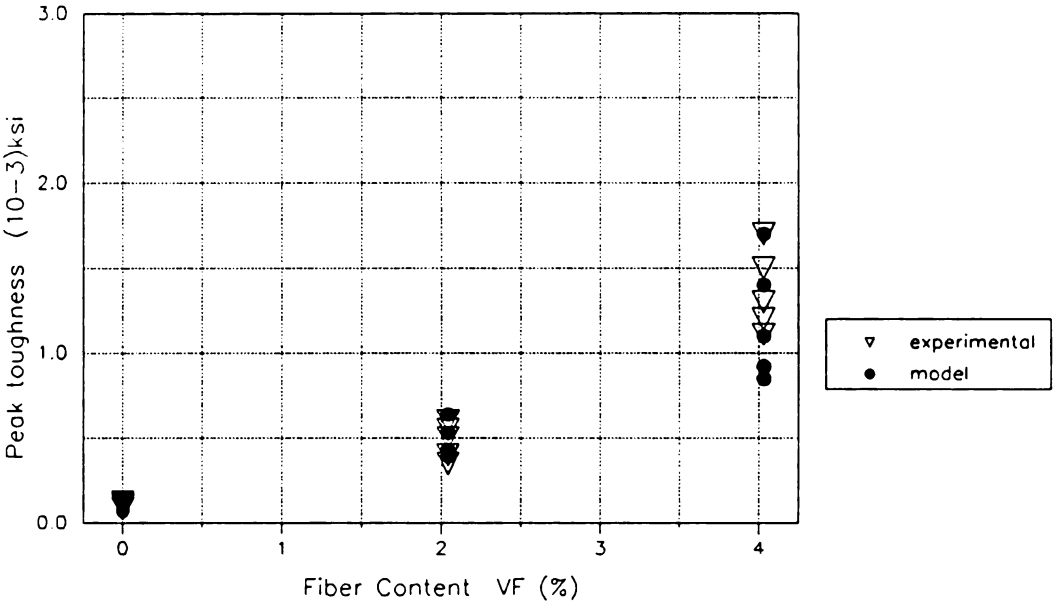


FIGURE 7.19 **Experimental Vs. Model Results, Peak Toghness (carbon fiber and w/c=.29).**

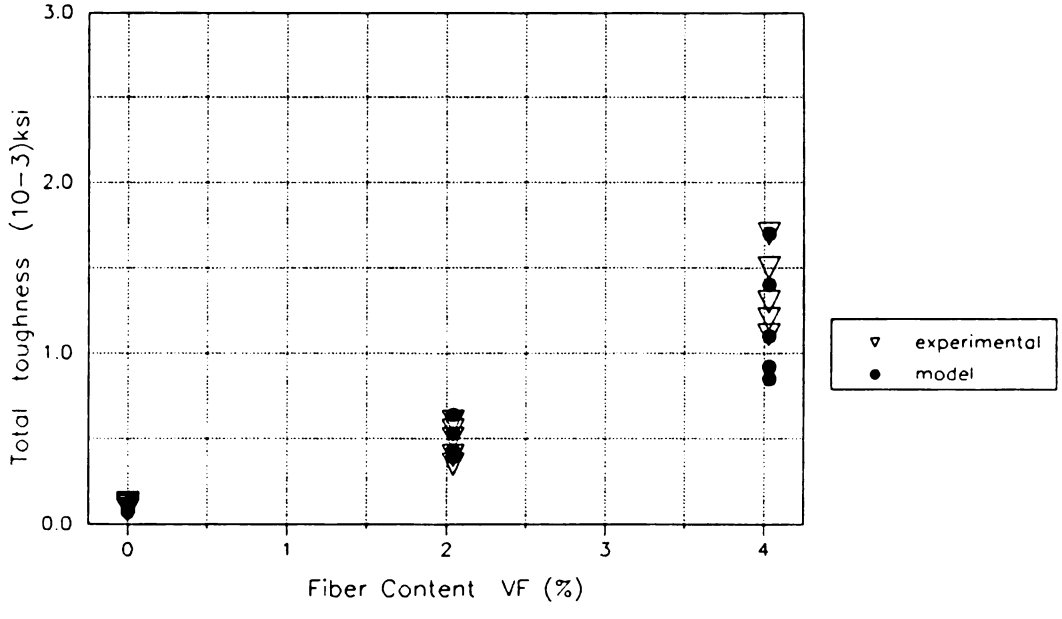


FIGURE 7.20 **Experimental Vs. Model Results, Total Toghness (carbon fiber and w/c=.29).**

7.5 Comparison of model output with experimental steel fiber cement results

In this section, the model results are compared against the experimental data for steel fiber cement (mixes S1 and S2 of Table 7.1).

7.5.1 Optimum KIC, to be used with the model

Unlike the cases of carbon cement, only the fracture toughness (KIC) is unknown. The shear strength, TAU, is fixed to 0.6 ksi (Reference 7.4). Therefore the optimization of the input variables is done with respect to KIC only, using the optimization software "Design-Expert" (Reference 7.7). The established optimum range of KIC is shown in Figure 7.21.

Figure 7.21 is similar in concept to Figures 7.10 and 7.11. The optimization process is as described previously in section 7.2.

The optimization problem is to find the range of KIC that meets the following constraints: The model and experimental responses have to be comparable with an allowable error margin of up to 30% of the experimental results, for a fiber content of 0%, 0.5%, 1%, 1.5%. The established optimum KIC (ksi(in)$^{1/2}$) ranges are as follows:

0.075 to 0.94 for Vf=0%

~0.08 to 0.089 for Vf=0.5%

0.086 to 0.092 for Vf=1%

0.084 to 0.092 for Vf=1.5%

The overall optimum range is the intersection of the above ranges: 0.086 to 0.089. This overall optimum range is within the experimentally acceptable ranges. The values established, so far, for KIC reflect the effects of w/c on the matrix fracture toughness KIC (KIC decreases with increasing w/c).

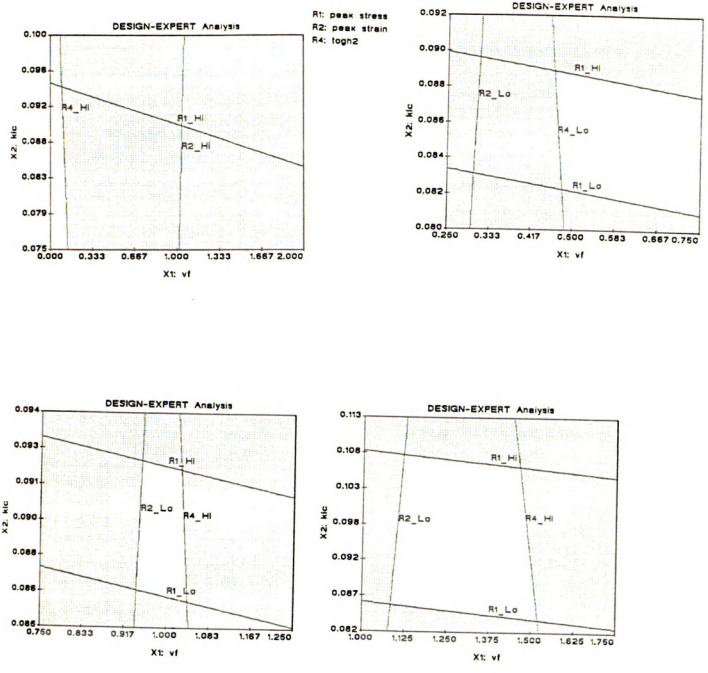


FIGURE 7.21 Preliminary Optimum Region For KIC (Steel Fiber and w/c=.50).

7.5.2 Statistical comparison of the experimental and model results for Steel fiber and w/c=.50

An optimum value of KIC=.08 ksi(in)$^{1/2}$ was used to produce the model results shown in Table 7.11.

In Table 7.11, five responses were generated for each material to reflect the inherent variations in the experimental responses of cement based materials, as described previously.

The above data as well as the corresponding experimental ones are plotted in Figures 7.22 through 7.25. Statistical comparison of data was made, and the experimental and analytical results were found to be comparable at a confidence level of 95%.

Table 7.11: Optimum model values for steel fiber and w/c=.50

Vf (%)	Peak Stress (ksi)	Peak Strain 10-3	Peak Tough 10-3 ksi	Total Tough 10-3 ksi
0	.3984 .4297 .409 .370 .4297	.1597 .1721 .1638 .1483 .1721	.0318 .037 .0355 .0247 .037	.0318 .037 .0355 .0247 .037
1.5	.572 .377 .600 .7123 .3718	.1964 .1297 .2062 .2446 -----	.0562 .055 .051 .065 ----	.889 .814 .857 .806 .714

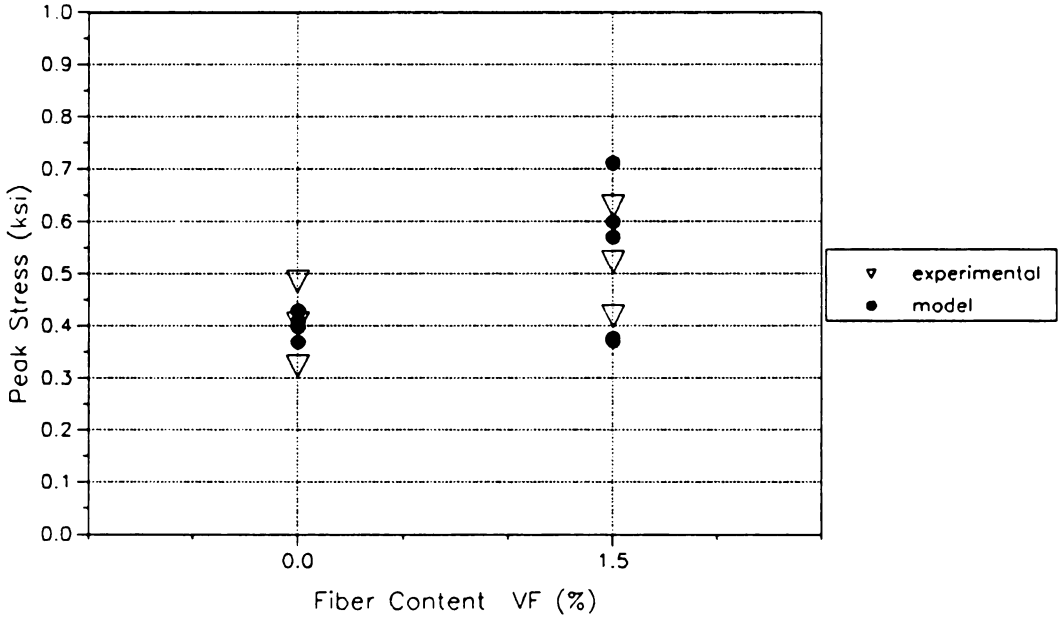


FIGURE 7.22 Experimental Vs. Model Results, Peak Stress (Steel Fiber and w/c=.50).

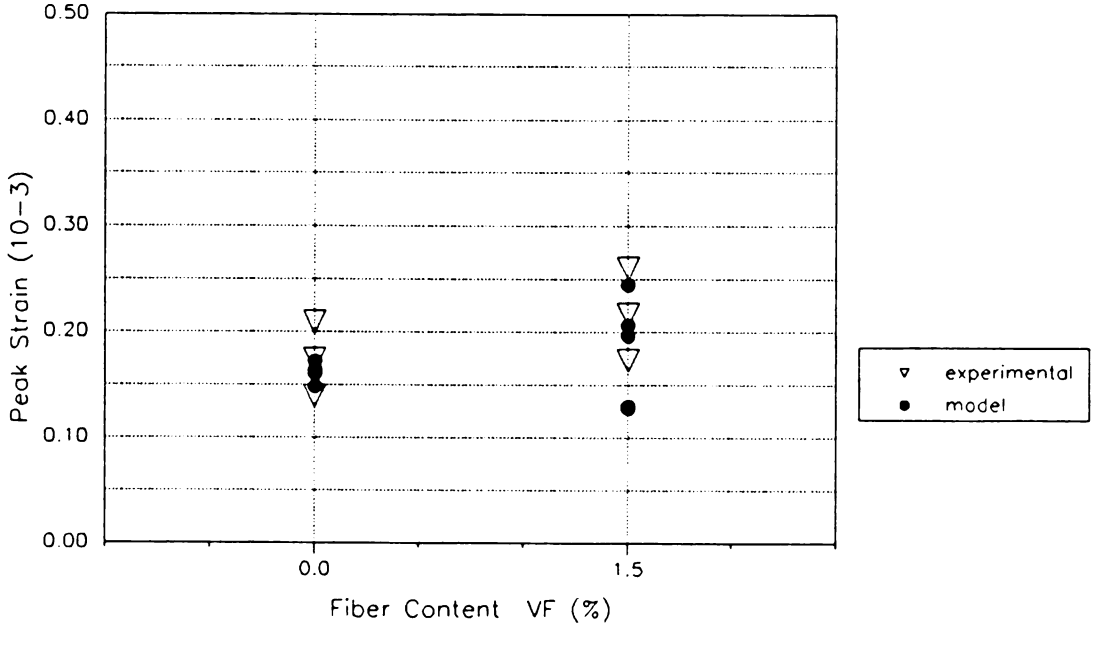


FIGURE 7.23 Experimental Vs. Model Results, Peak Strain (Steel Fiber and w/c=.50).

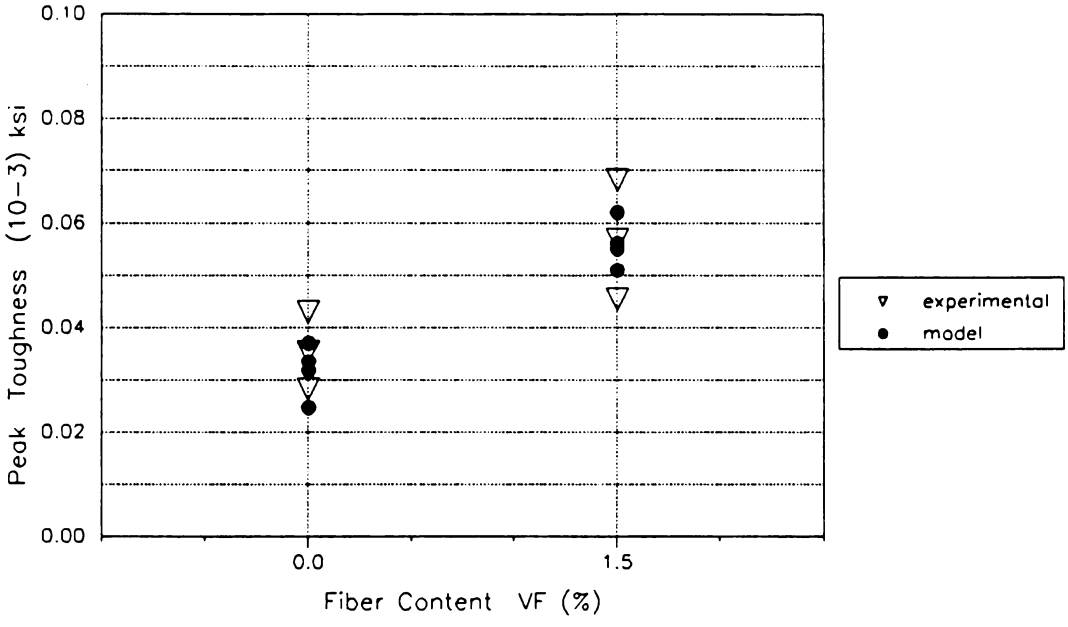


FIGURE 7.24 **Experimental Vs. Model Results, Peak Toghness, (Steel Fiber and w/c=.50).**

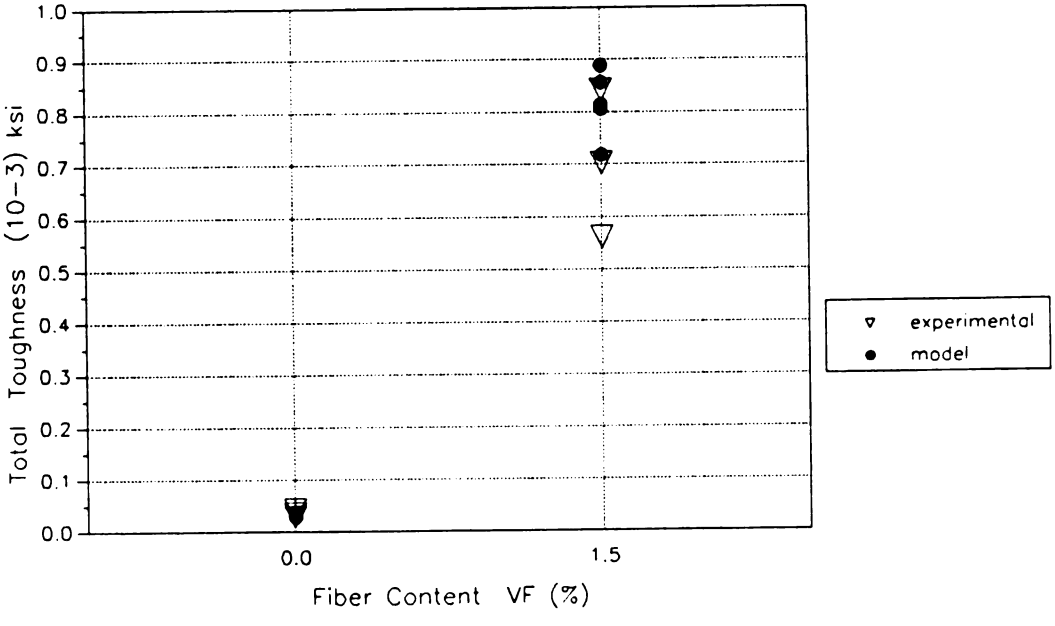


FIGURE 7.25 **Experimental Vs. Model Results, Total Toghness, (Steel Fiber and w/c=.50).**

7.6 Conclusions

The purpose of the validation process of a theoretical model is to establish the correlation between the model and the actual system outputs. In our case, one objective of the validation process was to confirm that the model results and actual experimental results are comparable.

One of the crucial input variables of the model is the number of cracks (NC). Because of the way cement-based materials are manufactured, each specimen contains a very large number of cracks. Practically, however, we can use only a limited number of cracks due to the availability and cost of computer computational time. It has been established (through experimental studies) that the failure of most tensile specimens is characterized by one major crack and a few secondary cracks. Therefore, only a fraction of the cracks are vital to the material behavior. Hence, the model responses are expected to stabilize as the number of cracks is increased, and one of the validation process goals is to establish the stability of the model results with higher number of cracks.

In summary, the validation process had two objectives:

(1) Investigating the stability of the model results with increasing number of cracks, and establishing of an optimum number of cracks to be used with the model.

(2) Confirming that the model results and the experimental results are comparable.

In this validation process, the model and experimental responses that are considered to uniquely represent the tensile stress-strain curve were: peak stress, peak strain, and toughness (calculated as the area underneath the stress-strain curve).

The first objective was achieved by producing data for two different materials using a varying number of cracks (NC=2,.....,20). Plots of the model responses versus the number of cracks indicated that the trends in the responses flatten (or stabilize) as the number of cracks is increased beyond a certain level (the optimum number of cracks).

In order to establish and pinpoint the optimum number of cracks, statistical multiple comparison tests were performed on a commercial statistical software "SPSS" to compare the responses produced by the model for different number of cracks, ranging from 2 to 20.

The results of the statistical multiple comparison tests indicated that the optimum

number of cracks is at least 5 for the material labeled C2 (Vf=1.72%) and at least 7 for the material labeled C3 (Vf=3.98%). These optimum numbers of cracks were established at a relatively strict and conservative significance level of 5% (confidence level of 95%). The optimum number of cracks is expected to drop to smaller values if the significance level is relaxed to a higher acceptable level of 10%. Therefore, it is recommended that at least 5 cracks be used with the model, however, reasonable and acceptable results can be achieved with lower number of cracks (NC=4, or 3, or 2).

The second objective of the validation process was met by comparing the responses produced by the model to their experimental counterparts. The comparison was repeated for eight different materials (carbon and steel fiber reinforced cement composites), and it was done using the statistical T-TEST comparison of means procedure. For each tested material, an optimization process was used to determine some unspecified inputs to the model; the optimum values were all within practical ranges.

The results of the statistical tests indicated that the model and experimental responses are comparable at a 95% confidence level.

CHAPTER 8

EXAMPLES OF APPLICATIONS OF THE MODEL

8.1 INTRODUCTION

In this chapter the use of the model is demonstrated through some case studies. The applications presented are indicative of what the model can accomplish.

First, a parametric study with respect to steel and carbon fibers is performed. This study is described in the next section. Second, the model is used to generate sufficient data to be used with an optimization software 'Design-Expert' (Reference 7.7), in order to find the fiber properties that produce the best material performance. Finally, the model was used to predict the performance of cellulosic (wood) fiber cement composites in tension.

8.2 PARAMATRIC STUDIES WITH RESPECT TO STEEL AND CARBON FIBERS

In this section we verify the common relationships between the properties of the stress-strain curve of fiber reinforced cement materials and the composite parameters such as: fiber content (Vf), fiber properties, and matrix properties. This verification supports the validation of the model and demonstrates the usefulness and benefits of the model as a research tool. In fact, the data produced for this parametric study would have required a lot of energy and time if they were to be produced experimentally.

This study is performed for carbon fiber and steel fiber, using basically the same fundamental materials used in Chapter 7. The results are presented in

terms of the stress-strain curves as a function of one of the following parameters:

(1) VF (or F): fiber content.

(2) Kc (or TKI): matrix fracture toughness.

(3) Lf (or FBL): fiber length.

(4) Df: fiber diameter.

(5) TAU: fiber-matrix bond strength.

(6) SIGULT: fiber ultimate strength.

(7) MODF: fiber modulus of elasticity.

(8) MOD0: matrix modulus of elasticity

The effects of the above variables on the composite stress-strain curve, as predicted by the model, are presented in Figures 8.1 through 8.8, for steel fiber cement composites, and in Figures 8.9 through 8.16, for carbon fiber cement composites (values of all the input parameters are shown in part (a) of the figures). In Figures 8.1 through 8.16, the effects of the above variables on peak stress and peak strain are shown in parts (c) and (d) respectively; parts (b) present the effect of the above parameters on the averaged stress-strain curves (the toughness of the composite can be depicted from the areas under the curves of part (b) of the figures). The rectangles drawn around the characteristic points of the stress-strain curves (part (b) of Figures 8.1 through 8.16) represent the variations of the stress and strain values at those points, computed as the standard deviation of five samples. Each edge of a rectangle equals two standard deviations of the corresponding variable (i.e stress or strain at the center of the rectangle). The vertical bars drawn at the defining points of the curves shown in parts (c) and (d) of Figures 8.1 through 8.16 represent the variation of the stresses (part (c)), and strains (part (d)). The length of the vertical bars equals two standard deviations of a sample of five tests.

In parts (c) and (d) of Figures 8.1 through 8.16, the labels on the plots should be interpreted as follows:

PEAK: Peak stress (or strain) values.

A*: Stress (or strain) values at point A* of the stress-strain curve, as defined in the analysis phase (see Chapter 2 for details).

ULTM: The ultimate stress (or strain) values.

FAIL: Stresses (or strains) values at an intermediate point of the postpeak stage, characterized by the following condition: "one crack had propagated through the whole width of the specimen (i.e. the specimen is in two pieces, held together by the fibers action); however, the material keeps on resisting more load through the bridging action of the fibers".

The model predictions agree with what is established in the experimental state-of-the-art on the subject matter. In general, the effects can be summarized as follows;

- An increase in the fiber content (VF) produced general improvement in all the stress-strain curve characteristic (i.e. peak stress and toughness).
- An increase in the matrix fracture toughness (Kc) produced an increase in the peak stress; however, it did not necessarily improve the toughness.
- A stronger, longer and thinner fiber, typically produces a material with better performance. However, the material performance depends concurrently on the interfacial bond strength as well as the other fiber properties (i.e. ultimate strength, and modulus of elasticity).
- There is an optimum interfacial shear strength that gives the best material performance for a fixed combination of other composite parameters. This is due to the fact that a very low shear would cause most fibers to pullout, and a very high shear would cause most fibers to break. Excess fiber pull-out may weaken the material while excess fiber rupture makes the composite brittle. Therefore, there must be an optimum shear value that gives the best material performance in regard to both strength and toughness.

Fiber length=1 in

Fiber Diameter=.016 in

KIC=.085 *Ksi* $in^{1/2}$

TAU=.6 ksi

Fiber Modulus=30,000 Ksi

Matrix Modulus=2,000 Ksi

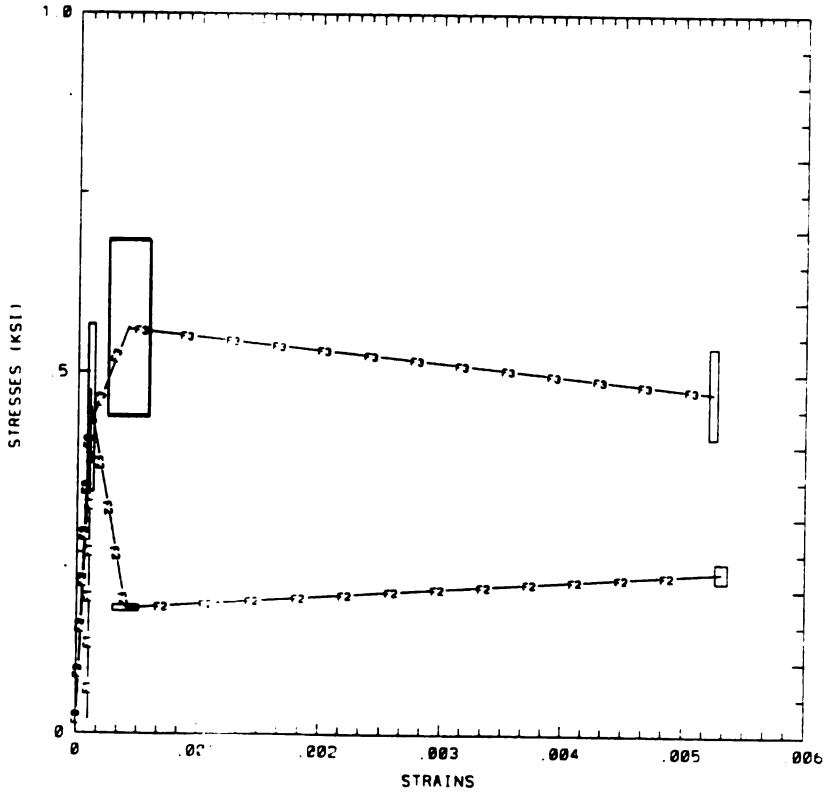
Fiber Strength=200 Ksi

PARAMETER=Fiber Content

F1: Fiber Content=0%

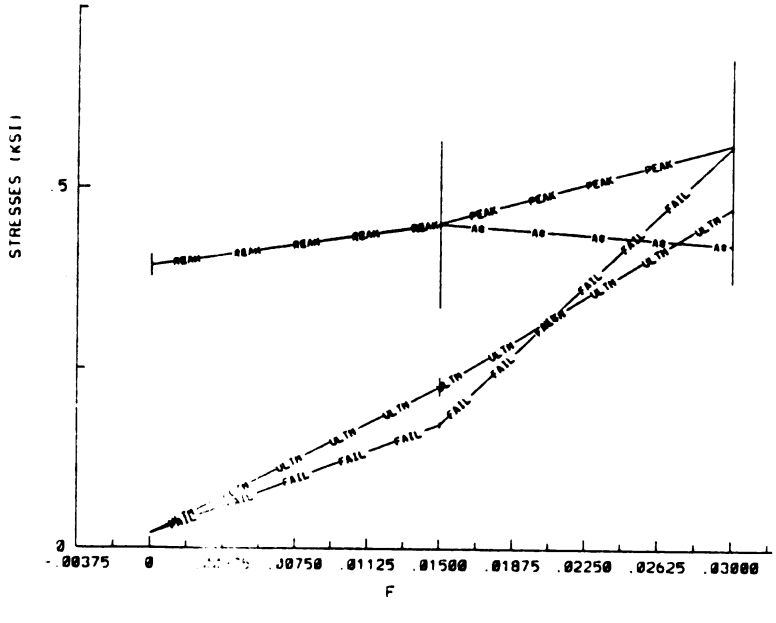
F2: Fiber Content=1.5%

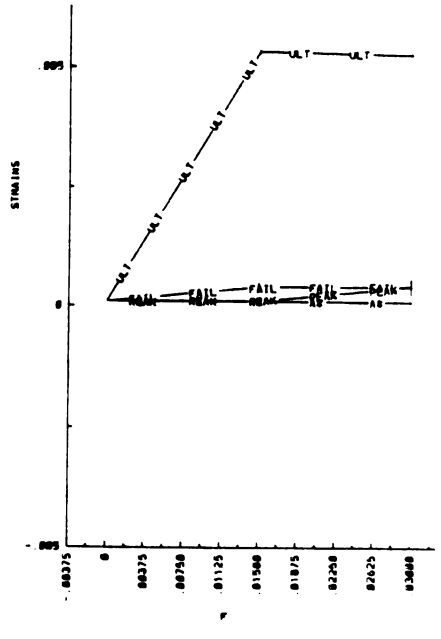
F3: fiber Content=3%



(a) Variables

(b) Averaged Curves





(c) Stresse Variations

(d) Strains Variations

FIGURE 8.1 Effect of Fiber Content (F) on the Stress-Strain Curve Paramaters of Steel Fiber Cement Composites.

Fiber length=1 in

Fiber Diameter=.016 in

Fiber Content=2%

TAU=.6 Ksi

Fiber Modulus=30,000 ksi

Matrix Modulus=2,000 Ksi

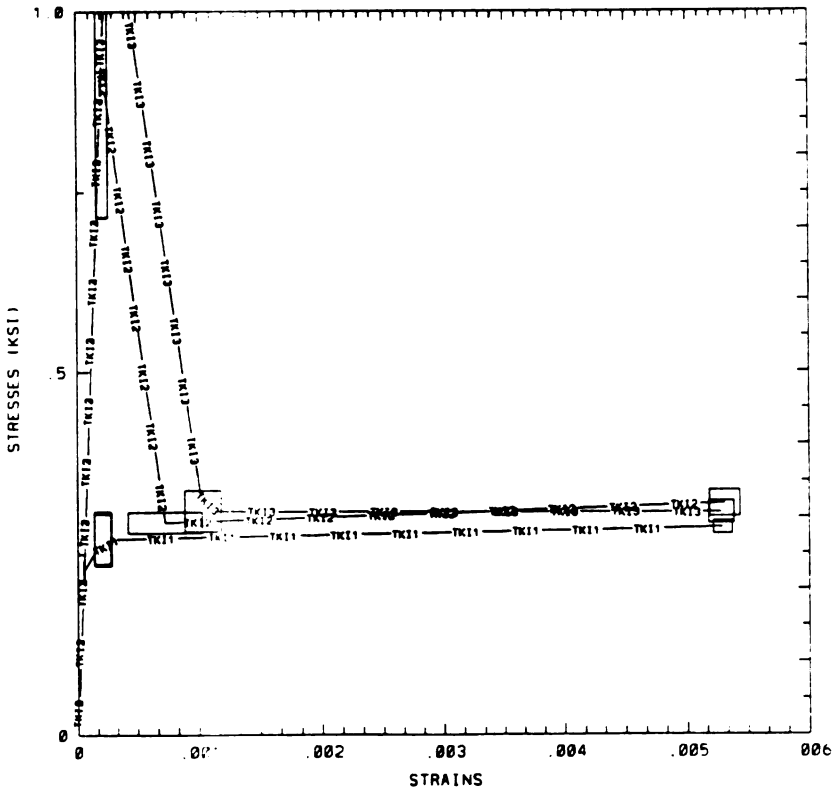
Fiber Strength=200 Ksi

PARAMETER=KIC

TKI1: KIC=.05 Ksi $in^{1/2}$

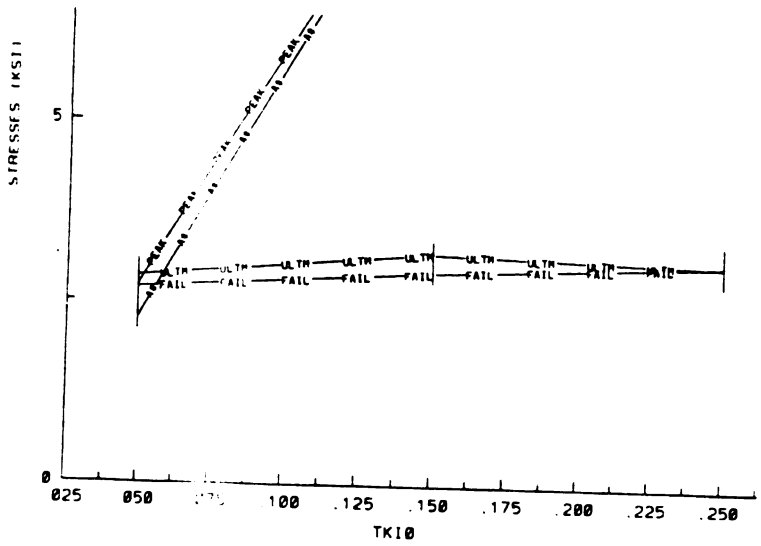
TKI2: KIC=.15 Ksi $in^{1/2}$

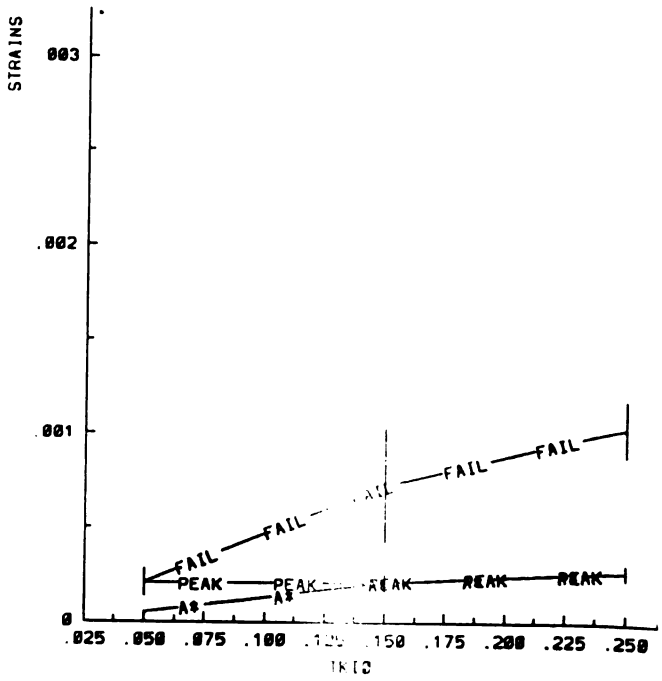
TKI3: KIC=.25 Ksi $in^{1/2}$



(a) Variables

(b) Averaged Curves





(c) Stresses Variations

(d) Strains Variations

FIGURE 8.2 Effect of the Fracture Toughness (TKI or Kc) on the Stress-Strain Curve Paramaters of Steel Fiber Cement Composites.

Fiber Content=2%

Fiber Diameter=.016 in

KIC=.085 *Ksi* $in^{1/2}$

TAU=.6 Ksi

Fiber Modulus=30,000 Ksi

Matrix Modulus=2,000 Ksi

Fiber Strength=200 Ksi

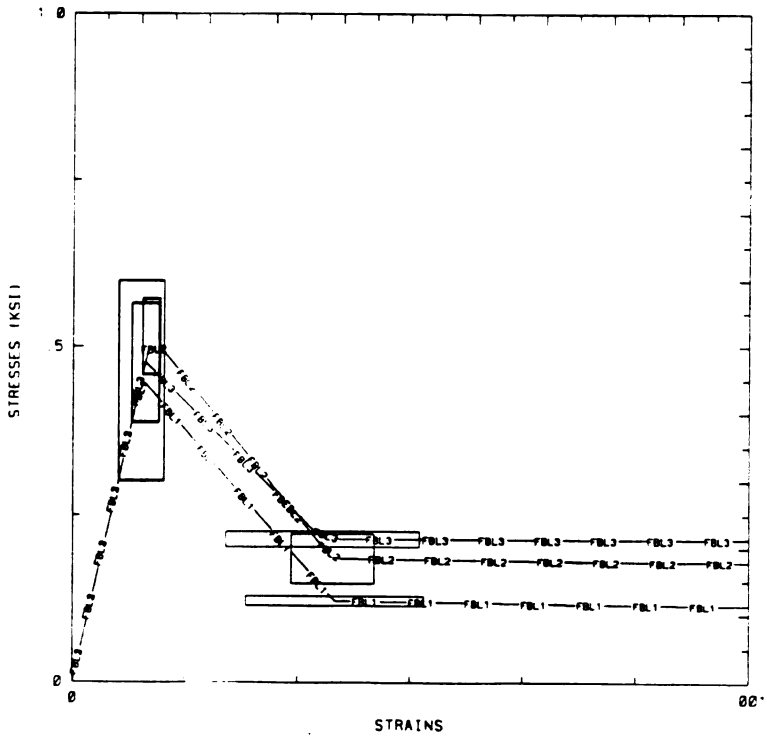
PARAMETER=Fiber Length (FBL)

FBL1: Fiber Length=.025 in

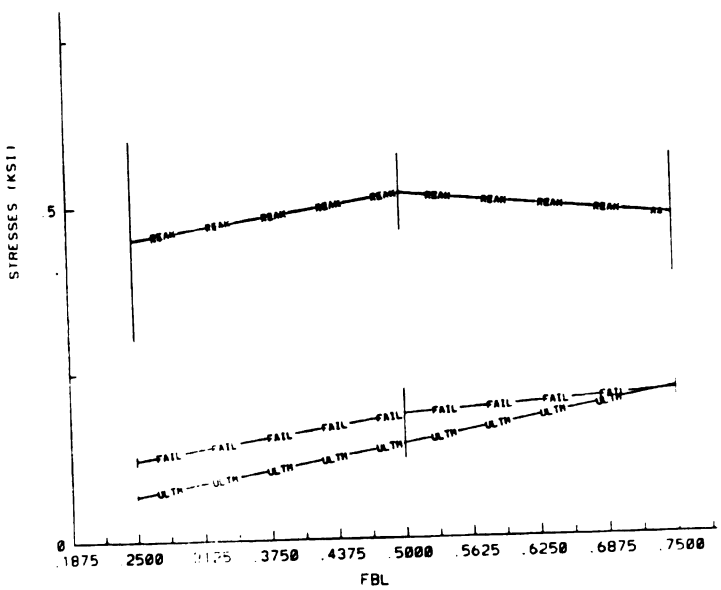
FBL2: Fiber Content=.5 in

FBL3: fiber Content=.75 in

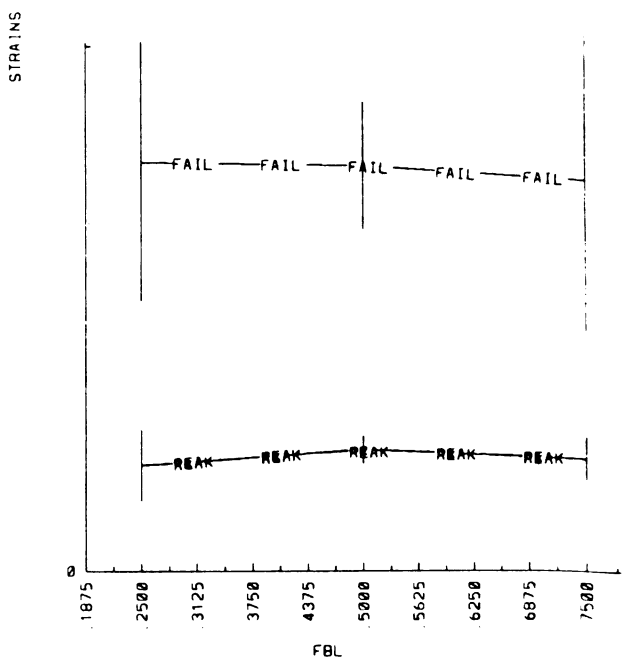
(a) Variables



(b) Averaged Curves



(c) Stresses Variations



(d) Strains Variations

FIGURE 8.3 Effect of Fiber Length (FBL) on the Stress-Strain Curve Paramaters of Steel Fiber Cement Composites.

Fiber length=1 in

Fiber Content=2%

KIC=.085 *Ksi* $in^{1/2}$

TAU=.6 Ksi

Fiber Modulus=30,000 Ksi

Matrix Modulus=2,000 Ksi

Fiber Strength=200 Ksi

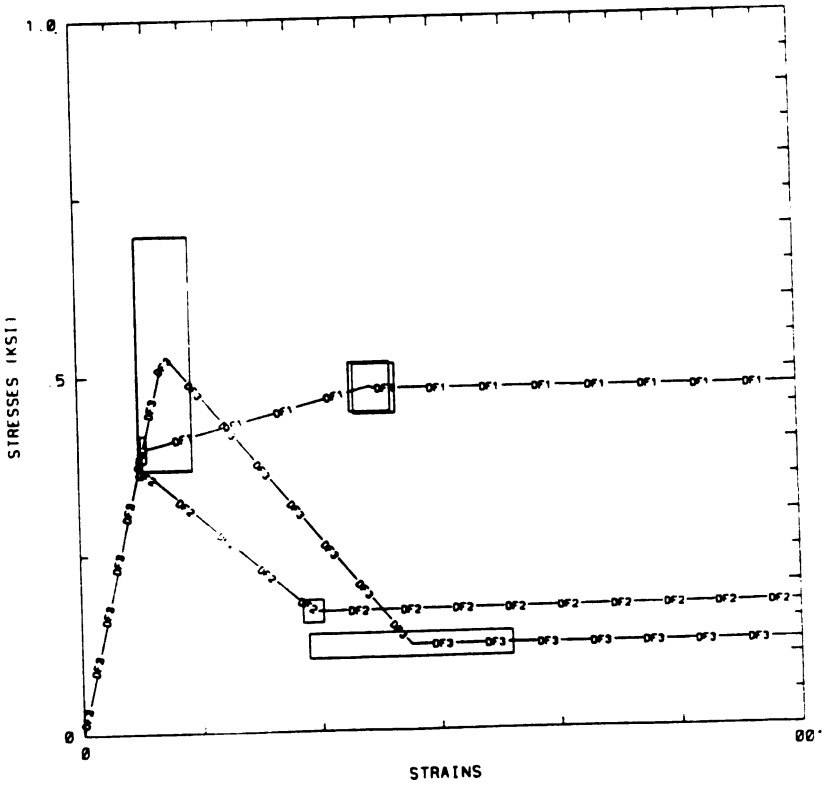
PARAMETER=Fiber Diameter (DF)

DF1: Fiber Diameter= .01 in

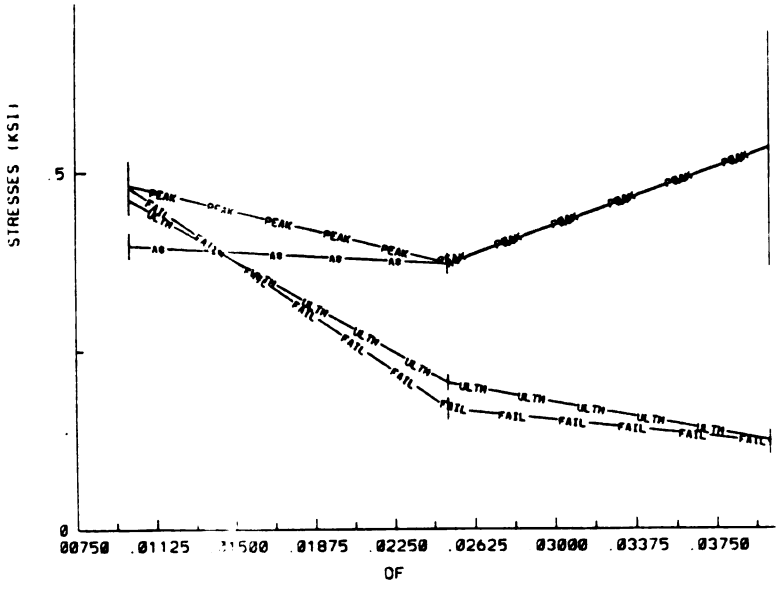
DF2: Fiber Diameter=.025 in

DF3: fiber Diameter=.04 in

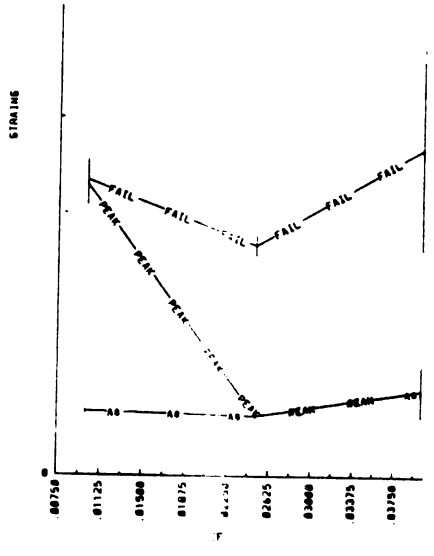
(a) Variables



(b) Averaged Curves



(c) Stresses Variations



(d) Strains Variations

FIGURE 8.4 Effect of the Fiber Diameter (Df) on the Stress-Strain Curve Paramaters of Steel Fiber Cement Composites.

Fiber length=1 in

Fiber Diameter=.016 in

KIC=.085 *Ksi* $in^{1/2}$

Fiber Content=2%

Fiber Modulus=30,000 Ksi

Matrix Modulus=2,000 Ksi

Fiber Strength=200 Ksi

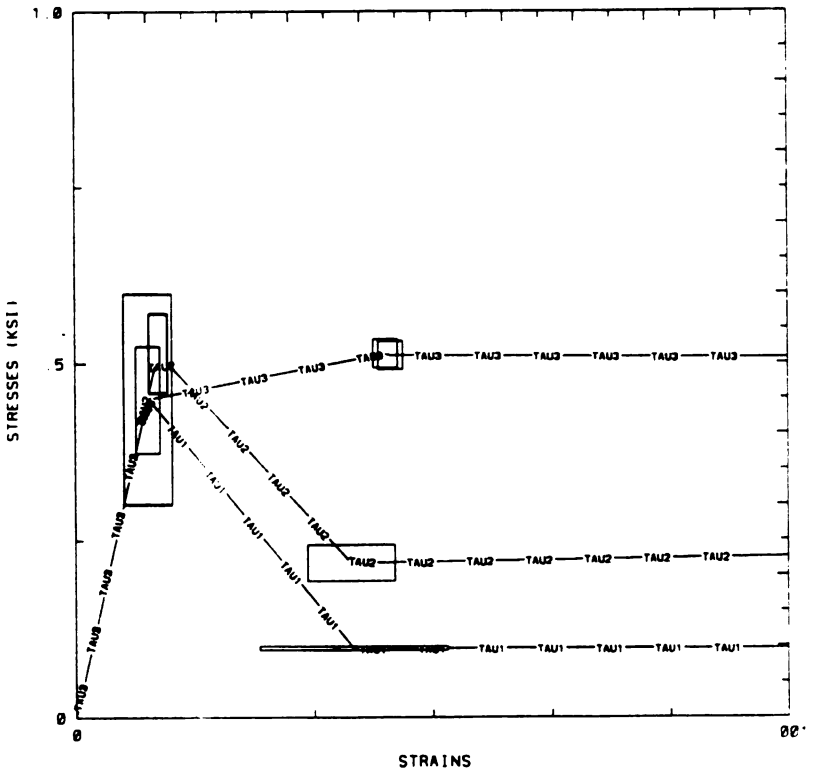
PARAMETER=TAU

TAU1: TAU=.2 Ksi

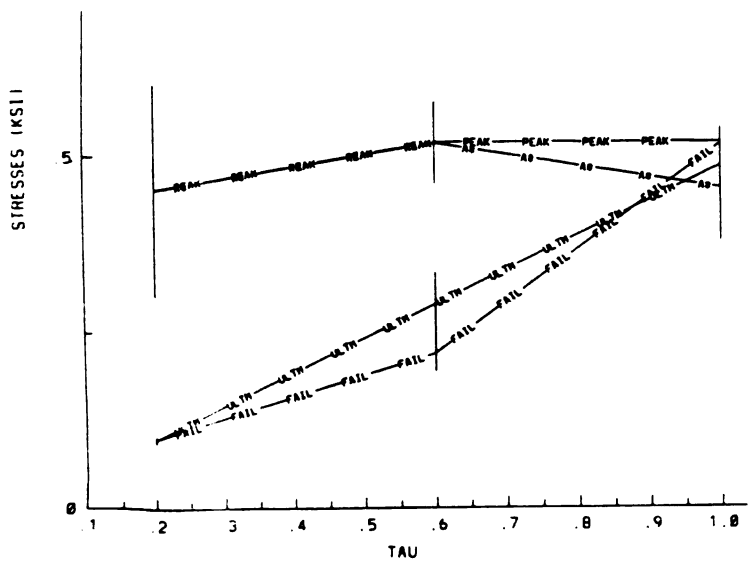
TAU2: TAU=.6 Ksi

TAU3: TAU=1 Ksi

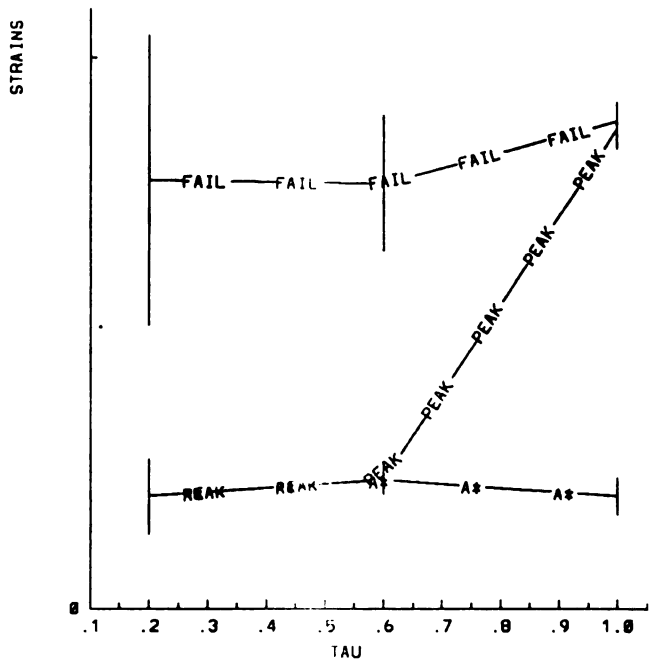
(a) Variables



(b) Averaged Curves



(c) Stresses Variations



(d) Strains Variations

FIGURE 8.5 Effect of the the Interfacial Bond Strength (TAU) on the Stress-Strain Curve Paramaters of Steel Fiber Cement Composites.

Fiber length=1 in

Fiber Diameter=.016 in

KIC=.085 *Ksi* $in^{1/2}$

TAU=.6 Ksi

Fiber Modulus=30,000 Ksi

Matrix Modulus=2,000 Ksi

Fiber Content=2%

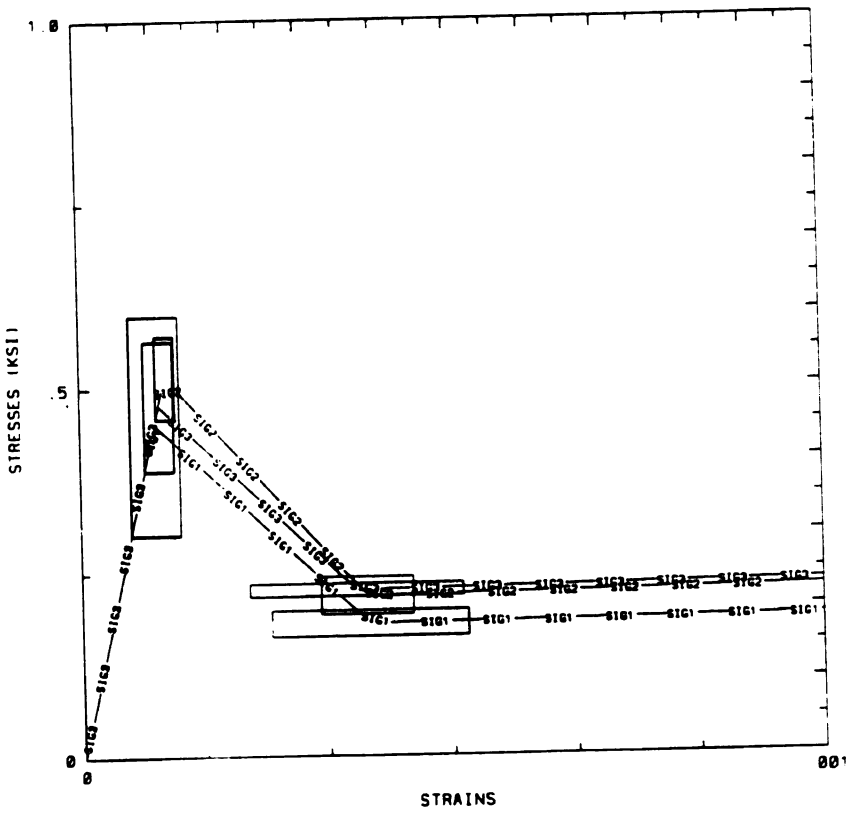
PARAMETER=Fiber Strength

SIG1: Fiber Strength=50 Ksi

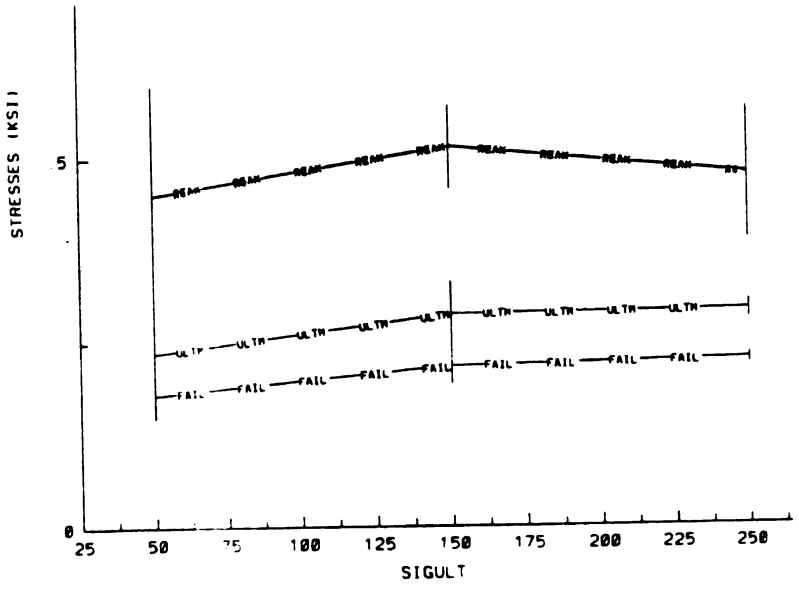
SIG2: Fiber Strength=150 Ksi

SIG3: fiber Strength=250 Ksi

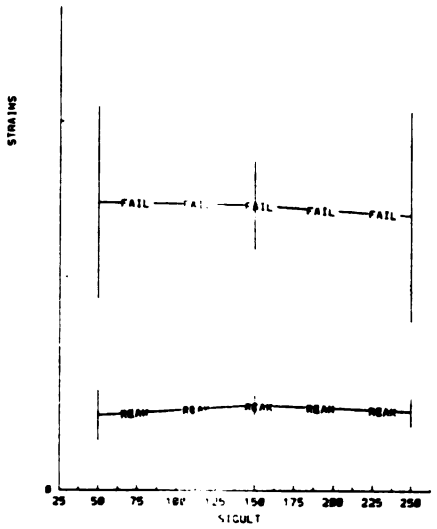
(a) Variables



(b) Averaged Curves



(c) Stresses Variations



(d) Strains Variations

FIGURE 8.6 Effect of the Fiber Ultimate Strength (SIGULT) on the Stress-Strain Curve Paramaters of Steel Fiber Cement Composites.

Fiber length=1 in

Fiber Diameter=.016 in

KIC=.085 *Ksi in$^{1/2}$*

TAU=.6 Ksi

Fiber Content=2%

Matrix Modulus=2,000 Ksi

Fiber Strength=200 Ksi

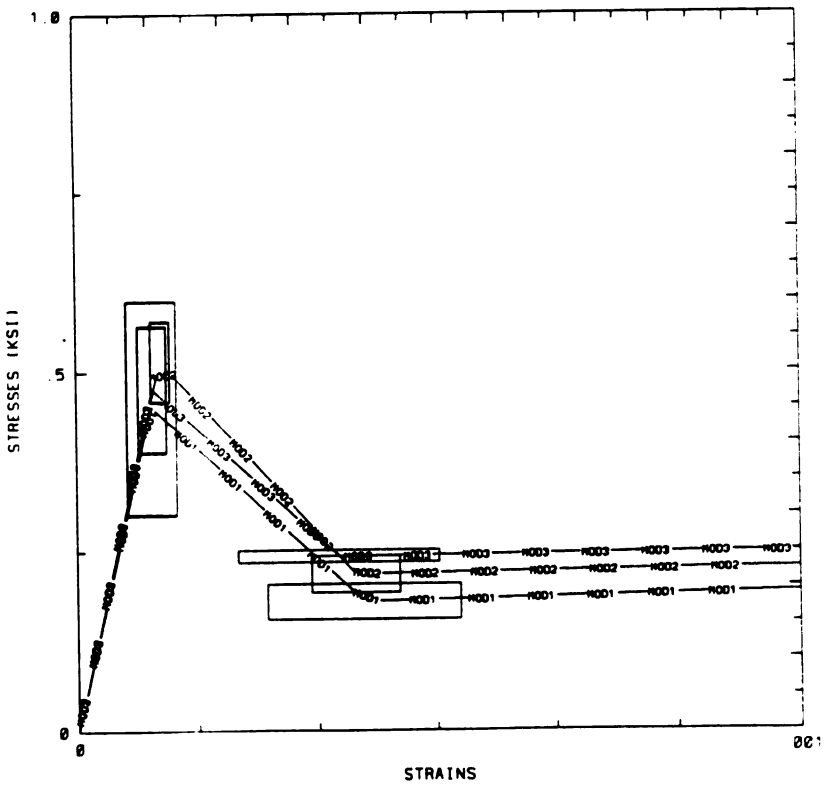
PARAMETER=Fiber Modulus

MOD1: Fiber Modulus=25,000 Ksi

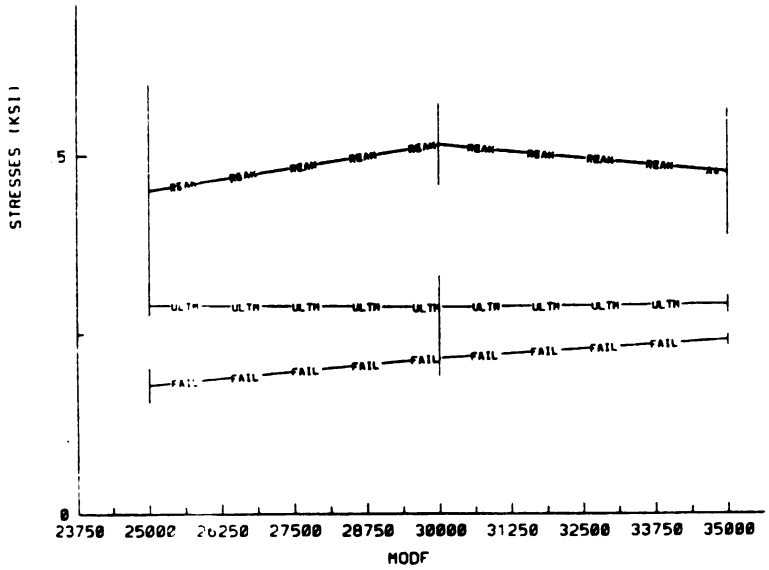
MOD2: Fiber Modulus=30,000 Ksi

MOD3: fiber Modulus=35,000 Ksi

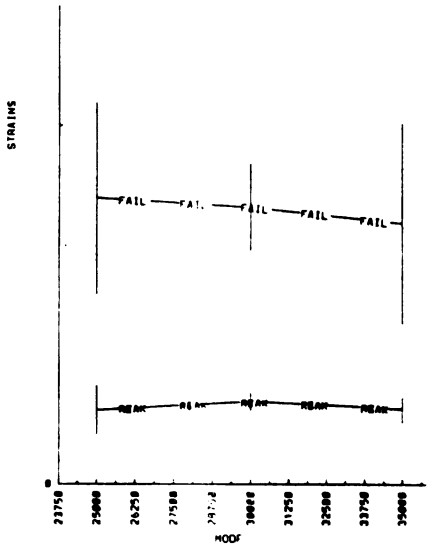
(a) Variables



(b) Averaged Curves



(c) Stresses Variations



(d) Strains Variations

FIGURE 8.7 Effect of the Fiber Modulus of Elasticity (MODF) on the Stress-Strain Curve Paramaters of Steel Fiber Cement Composites.

Fiber length=1 in

Fiber Diameter=.016 in

KIC=.085 *Ksi in$^{1/2}$*

TAU=.6 Ksi

Fiber Modulus=30,000 Ksi

Fiber Content=2%

Fiber Strength=200 Ksi

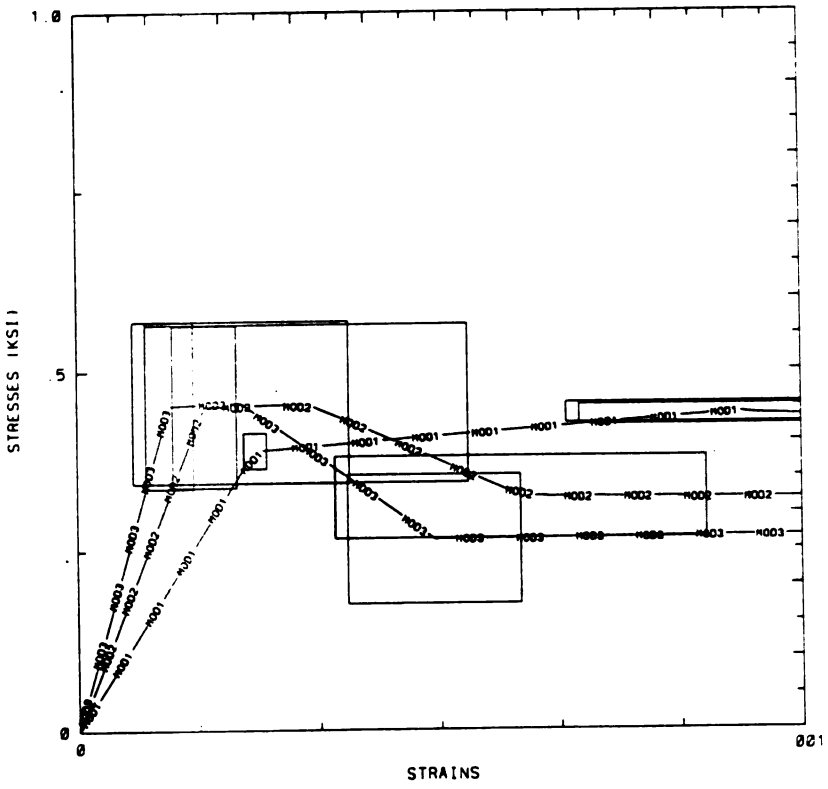
PARAMETER=Matrix Modulus

MOD1: Matrix Modulus=1,000 Ksi

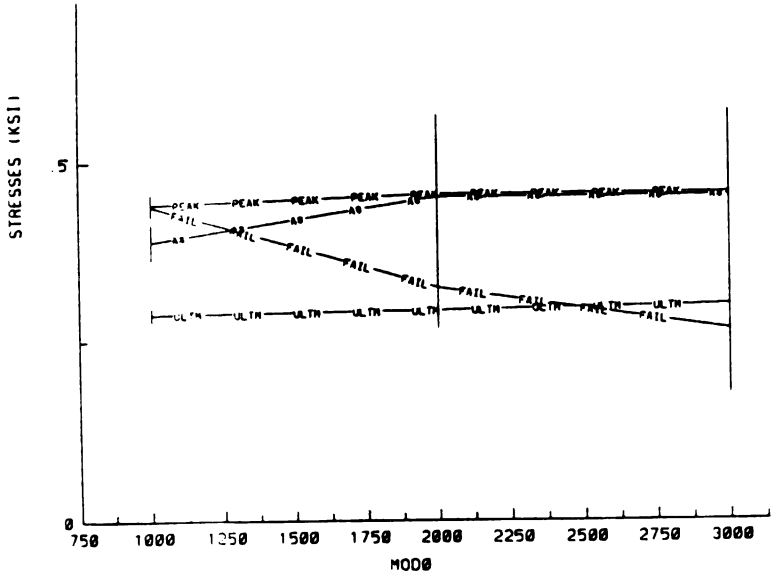
MOD2: Matrix Modulus=2,000 Ksi

MOD3: Matrix Modulus=3,000 Ksi

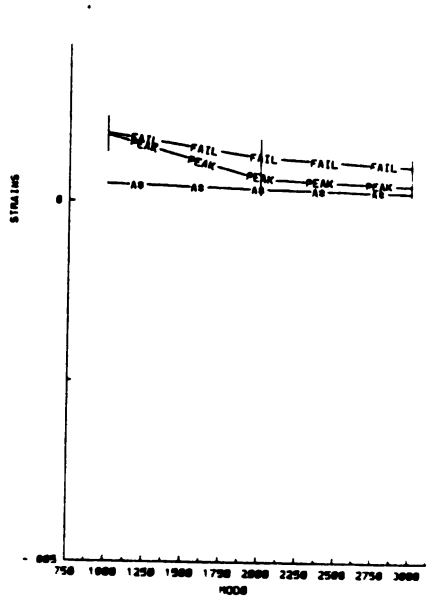
(a) Variables



(b) Averaged Curves



(c) Stresses Variations



(d) Strains Variations

FIGURE 8.8

Effect of the Matrix Modulus Of Elasticity (MOD0) on the Stress-Strain Curve Paramaters of Steel Fiber Cement Composites.

Fiber length=.394 in

Fiber Diameter=.000571 in

KIC=.18 *Ksi* $in^{1/2}$

TAU=.2 Ksi

Fiber Modulus=5,404 Ksi

Matrix Modulus=1,500 Ksi

Fiber Strength=110.9 Ksi

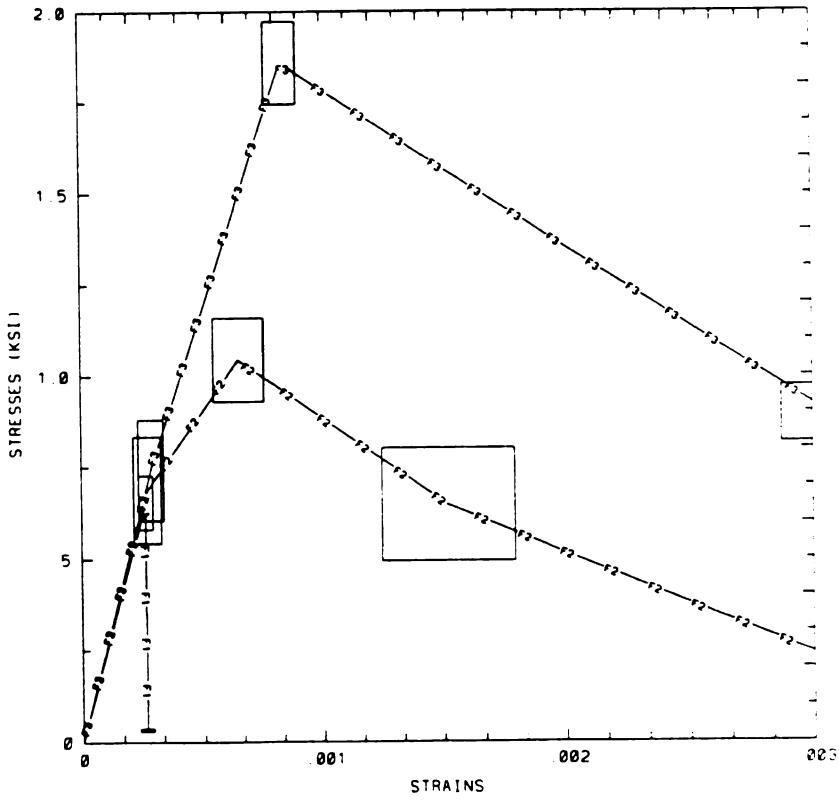
PARAMETER=Fiber Content

F1: Fiber Content=0%

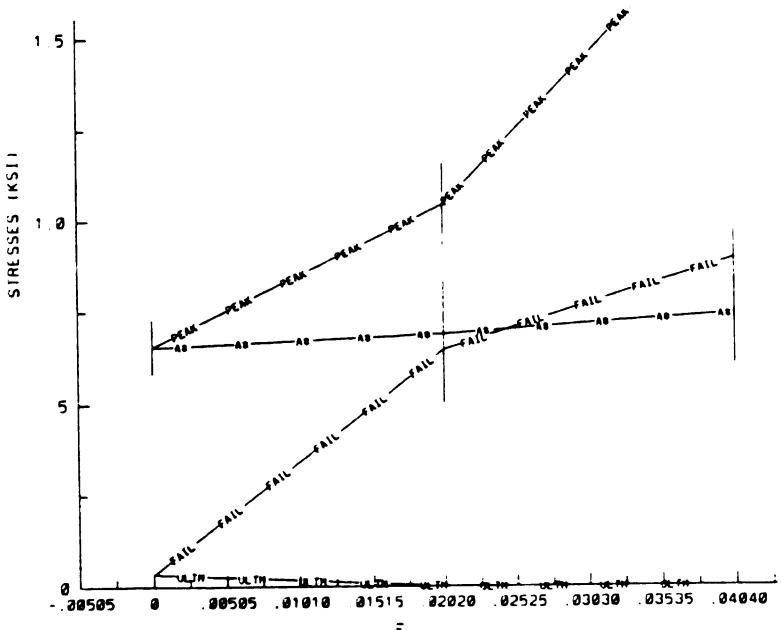
F2: Fiber Content=2%

F3: fiber Content=4%

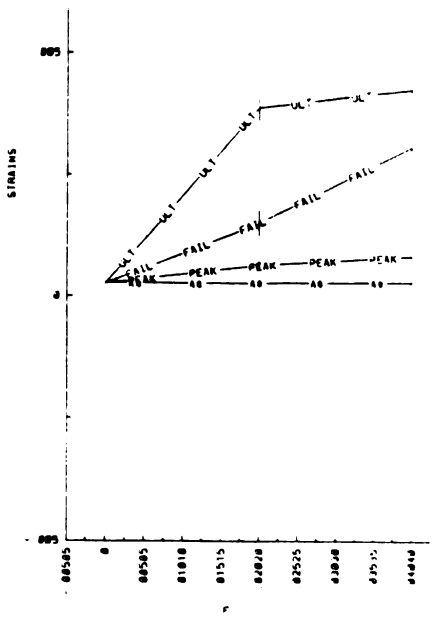
(a) Variables



(b) Averaged Stress-Strain Curves



(c) Stresses Variations



(d) Strains Variations

FIGURE 8.9 Effect of the Fiber Content (F) on the Stress-Strain Curve Paramaters of Carbon Fiber Cement Composites.

Fiber length=.394 in

Fiber Diameter=.000571 in

Fiber Content=2%

TAU=.2 Ksi

Fiber Modulus=5,404 Ksi

Matrix Modulus=1,500 Ksi

Fiber Strength=110.9 Ksi

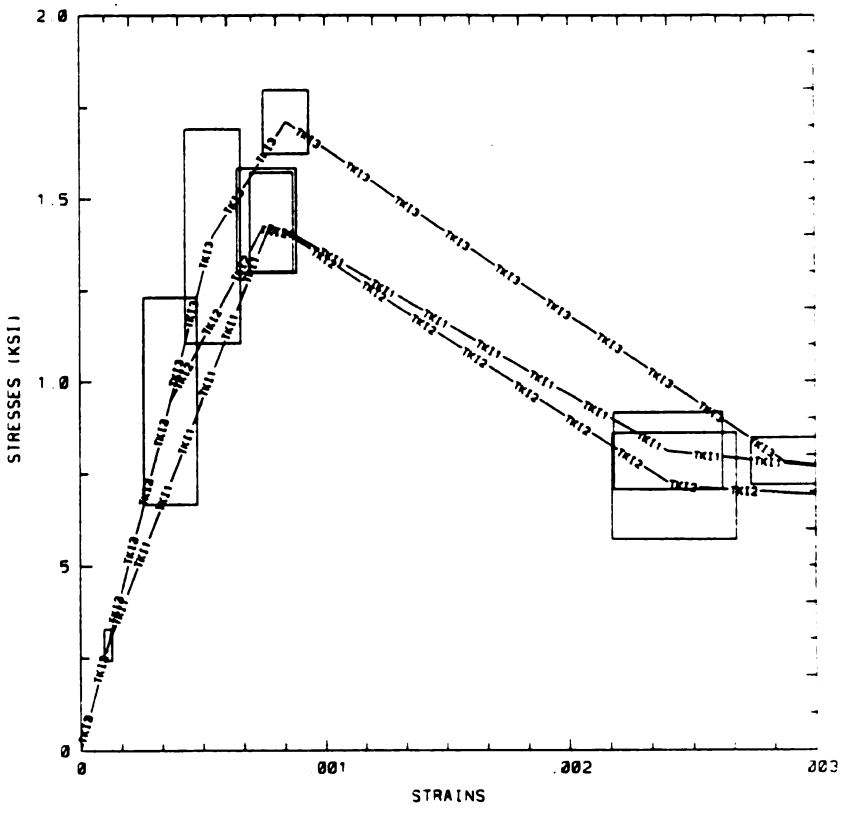
PARAMETER=KIC

TKI1: KIC=.05 Ksi $in^{1/2}$

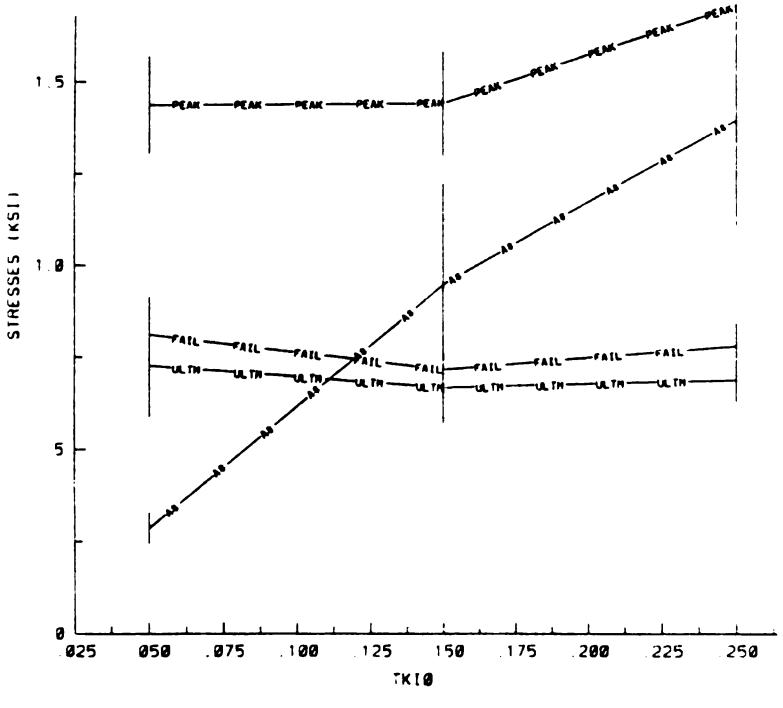
TKI2: KIC=.15 Ksi $in^{1/2}$

TKI3: KIC=.25 Ksi $in^{1/2}$

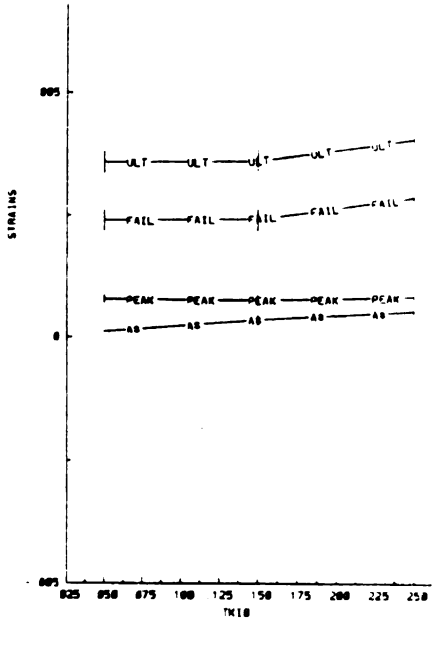
(a) Variables



(b) Averaged Curves



(c) Stresses Variations



(d) Strains Variations

FIGURE 8.10 Effect of the Fracture Toughness (TKI) on the Stress-Strain Curve Paramaters of Carbon Fiber Cement Composites.

Fiber Content=2%

Fiber Diameter=.000571 in

KIC=.18 *Ksi in$^{1/2}$*

TAU=.2 Ksi

Fiber Modulus=5,404 Ksi

Matrix Modulus=1,500 Ksi

Fiber Strength=110.9 Ksi

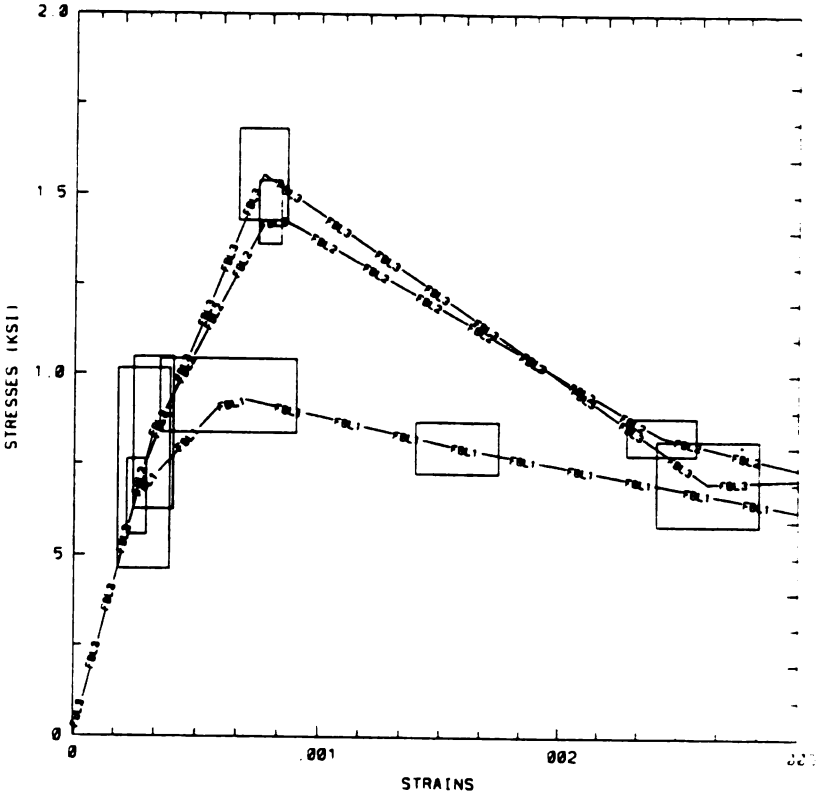
PARAMETER=Fiber Length

FBL1: Fiber Length=.05 in

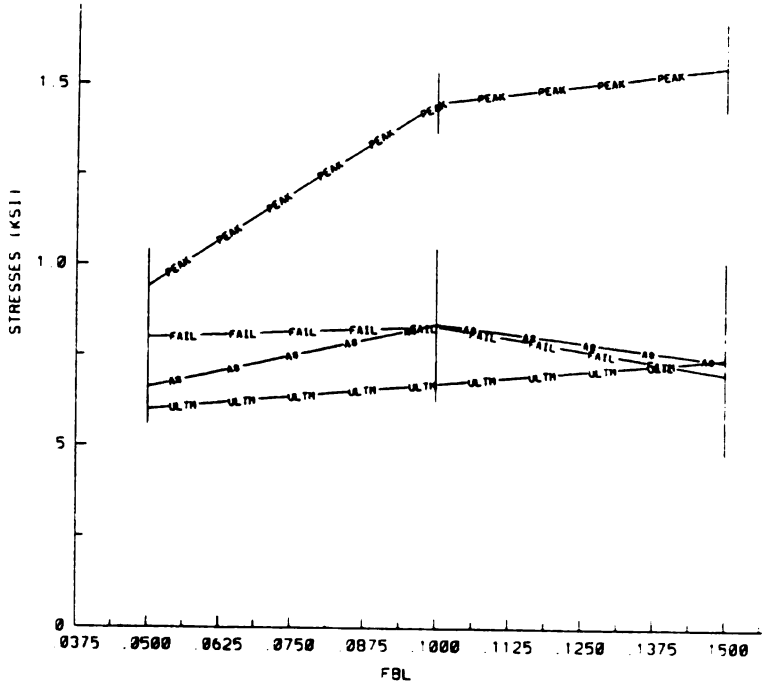
FBL2: Fiber Length=.1 in

FBL3: fiber Length=.15 in

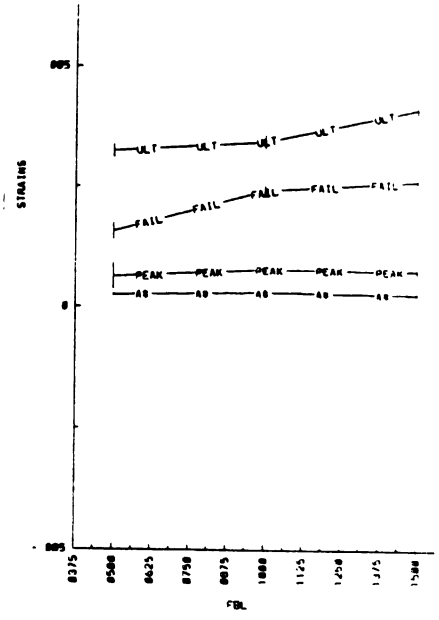
(a) Variables



(b) Averaged Curves



(c) Stresses Variations



(d) Strains Variations

FIGURE 8.11 Effect of Fiber Length (FBL) on the Stress-Strain Curve Paramaters of Carbon Fiber Cement Composites.

Fiber length=.394 in

Fiber Content=2%

KIC=.18 *Ksi* $in^{1/2}$

TAU=.2 Ksi

Fiber Modulus= 5,404 Ksi

Matrix Modulus=1,500 Ksi

Fiber Strength=110.9 Ksi

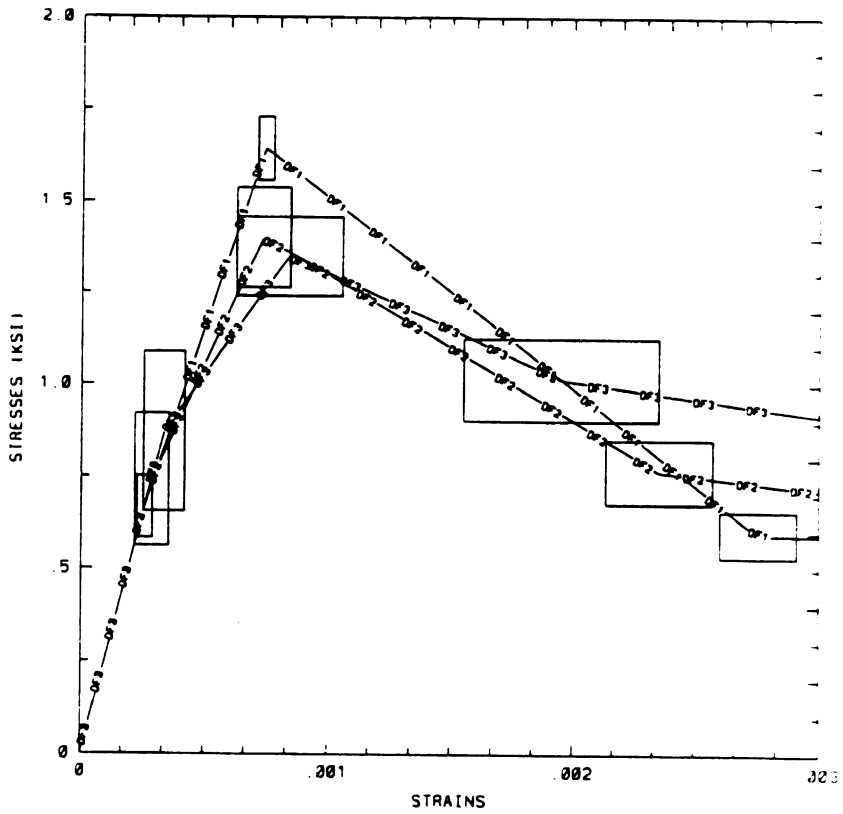
PARAMETER=Fiber Diameter

DF1: Fiber Diameter=.0004 in

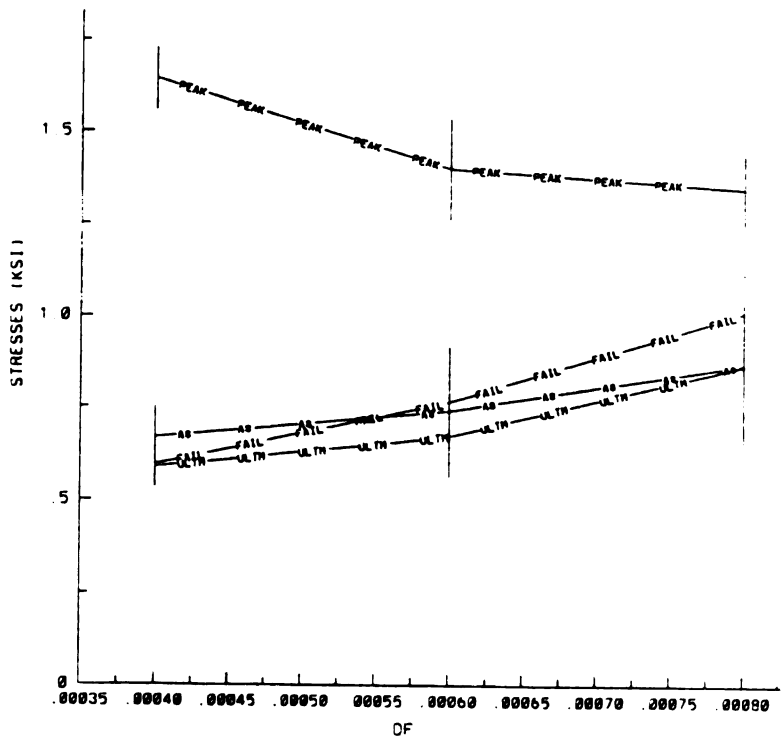
DF2: Fiber Diameter=.0006 in

DF3: fiber Diameter=.0008 in

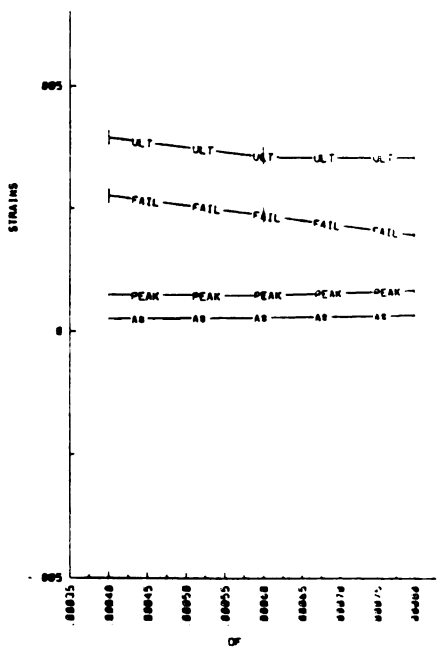
(a) Variables



(b) Averaged Curves



(c) Stresses Variations



(d) Strains Variations

FIGURE 8.12 Effect of Fiber Diameter (Df) on the Stress-Strain Curve Paramaters of Carbon Fiber Cement Composites.

Fiber length=.394 in

Fiber Diameter=.000571 in

KIC=.18 *Ksi* $in^{1/2}$

Fiber Content=2%

Fiber Modulus=5,404 Ksi

Matrix Modulus=1,500 Ksi

Fiber Strength=110.9 Ksi

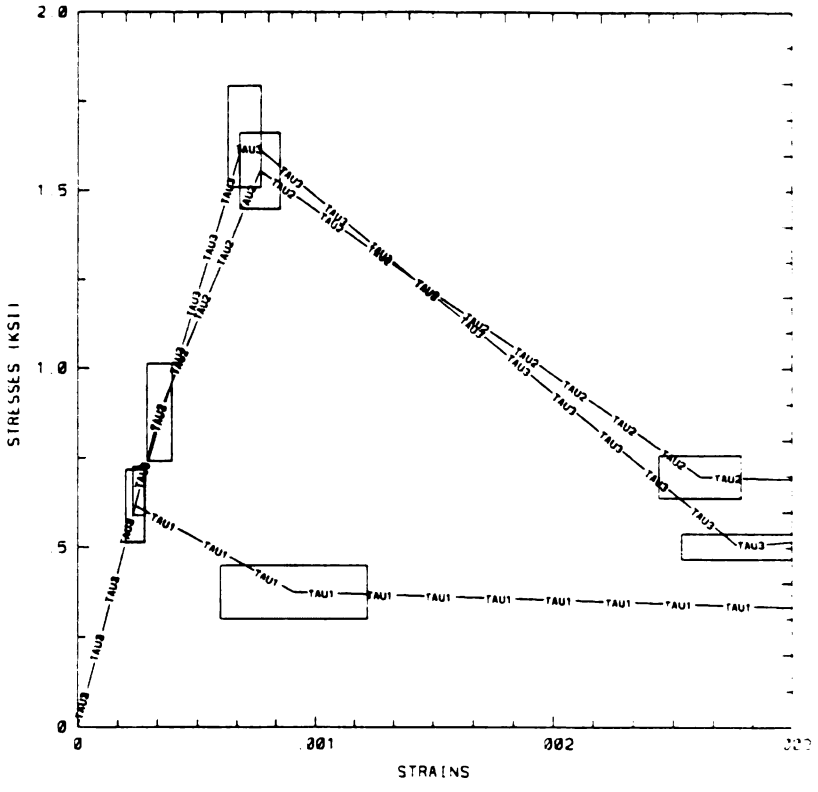
PARAMETER=TAU

TAU1: TAU=.1 Ksi

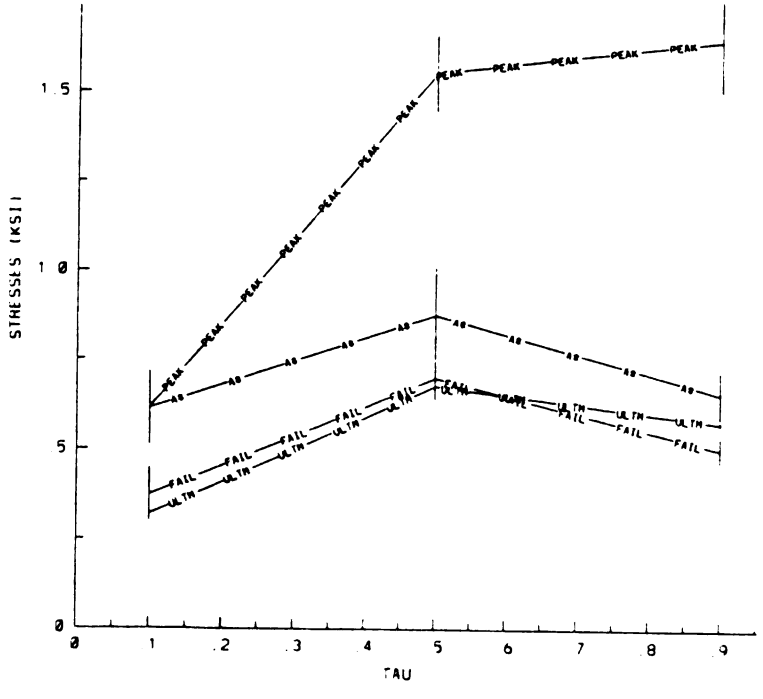
TAU2: TAU=.5 Ksi

TAU3: TAU=.9 Ksi

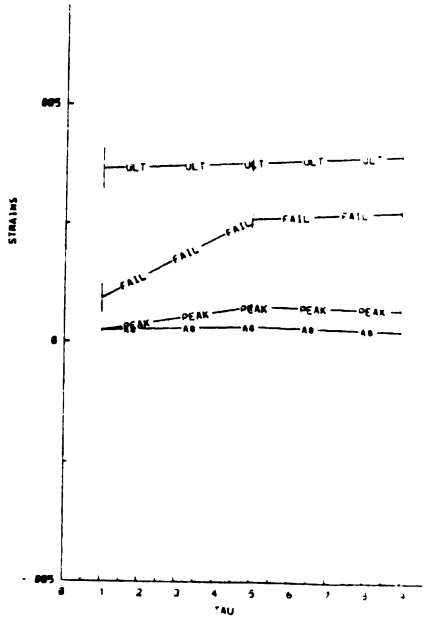
(a) Variables



(b) Averaged Curves



(c) Stresses Variations



(d) Strains Variations

FIGURE 8.13 Effect of the Interfacial Bond Strength (TAU) on the Stress-Strain Curve Parameters of Carbon Fiber Cement Composites.

Fiber length=.394 in

Fiber Diameter=.000571 in

KIC=.18 *Ksi* $in^{1/2}$

TAU=.2 Ksi

Fiber Modulus=5,404 Ksi

Matrix Modulus=1,500 Ksi

Fiber Content=2%

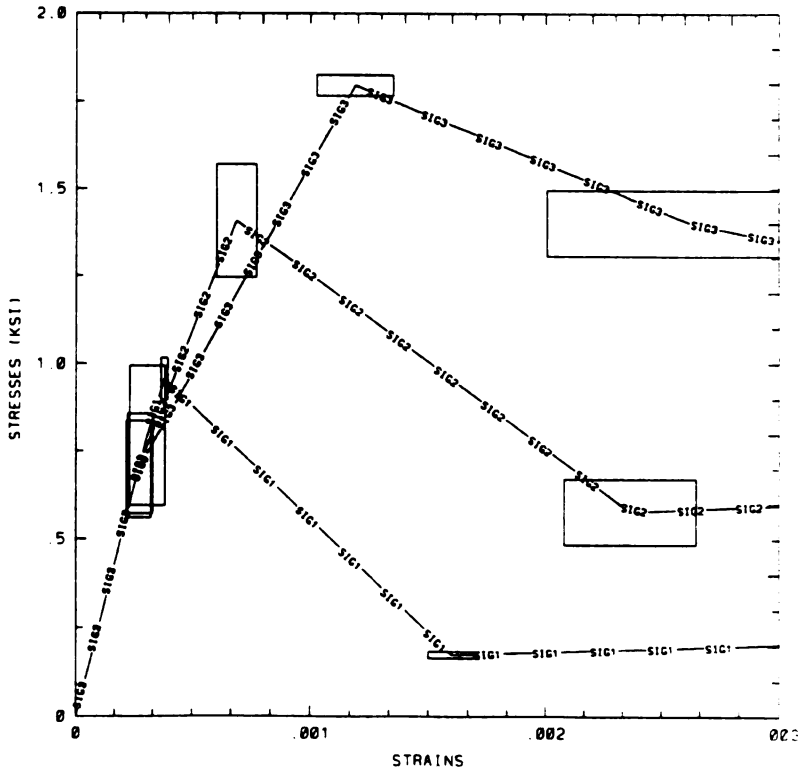
PARAMETER=Fiber Strength

SIG1: Fiber Strength=50 Ksi

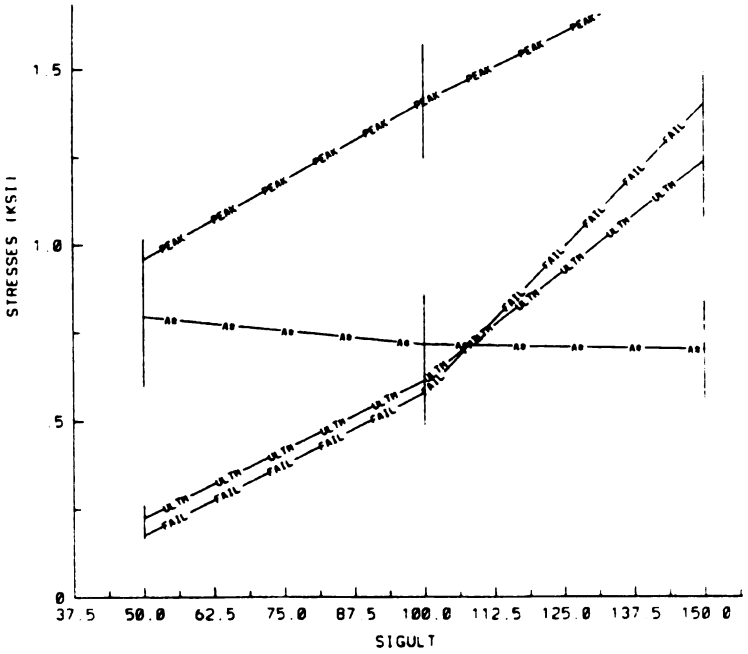
SIG2: Fiber Strength=100 Ksi

SIG3: Fiber Strength=150 Ksi

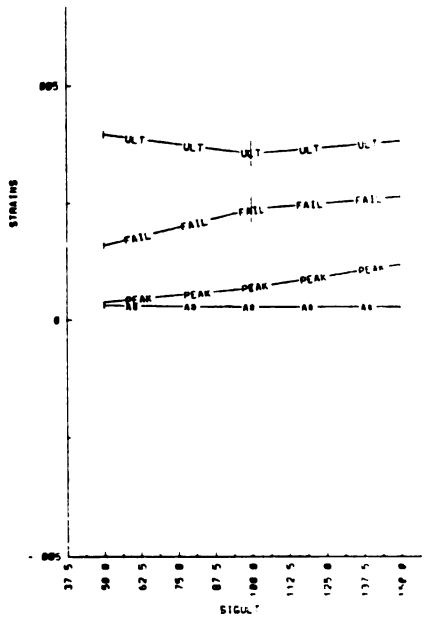
(a) Variables



(b) Averaged Curves



(c) Stresses Variations



(d) Strains Variations

FIGURE 8.14 Effect of Fiber Ultimate Strength (SIGULT) on the Stress-Strain Curve Paramaters of Carbon Fiber Cement Composites.

Fiber length=.394 in

Fiber Diameter=.000571 in

KIC=.18 *Ksi* $in^{1/2}$

TAU=.2 Ksi

Fiber Content=2%

Matrix Modulus=1,500 Ksi

Fiber Strength=110.9 Ksi

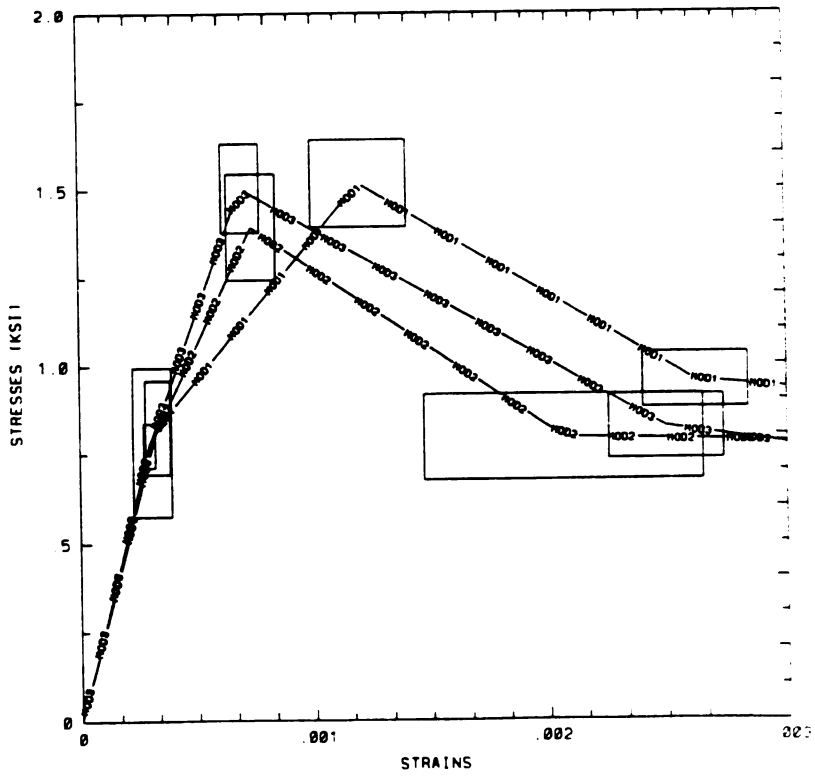
PARAMETER=Fiber Modulus

MOD1: Fiber Modulus=3,000 Ksi

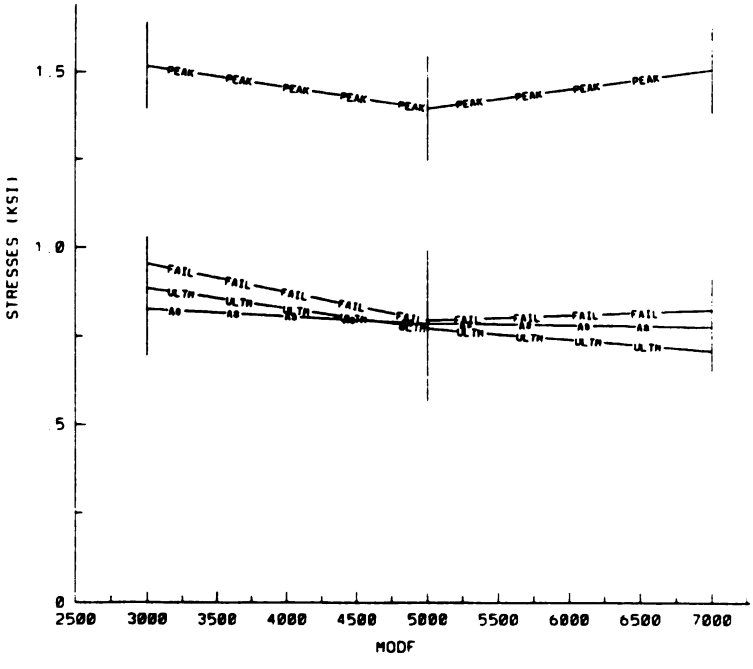
MOD2: Fiber Modulus=5,000 Ksi

MOD3: fiber Modulus=7,000 Ksi

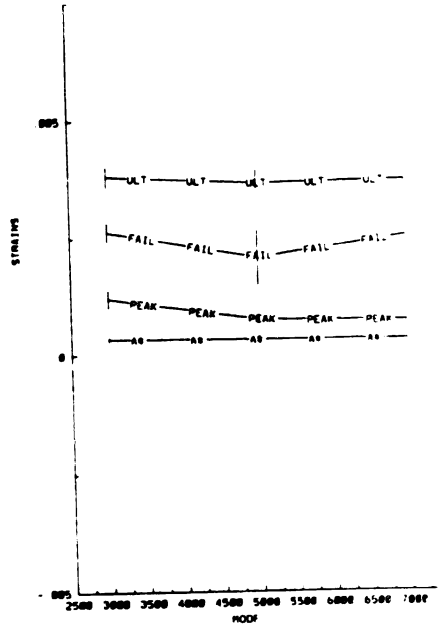
(a) Variables



(b) Averaged Curves



(c) Stresses Variations



(d) Strains Variations

FIGURE 8.15 Effect of Fiber Modulus of Elasticity (MODF) on the Stress-Strain Curve Paramaters of Carbon Fiber Cement Composites.

Fiber length=.394 in

Fiber Diameter=.000571 in

KIC=.18 *Ksi in$^{1/2}$*

TAU=.2 Ksi

Fiber Modulus=5,404 Ksi

Fiber Content=2%

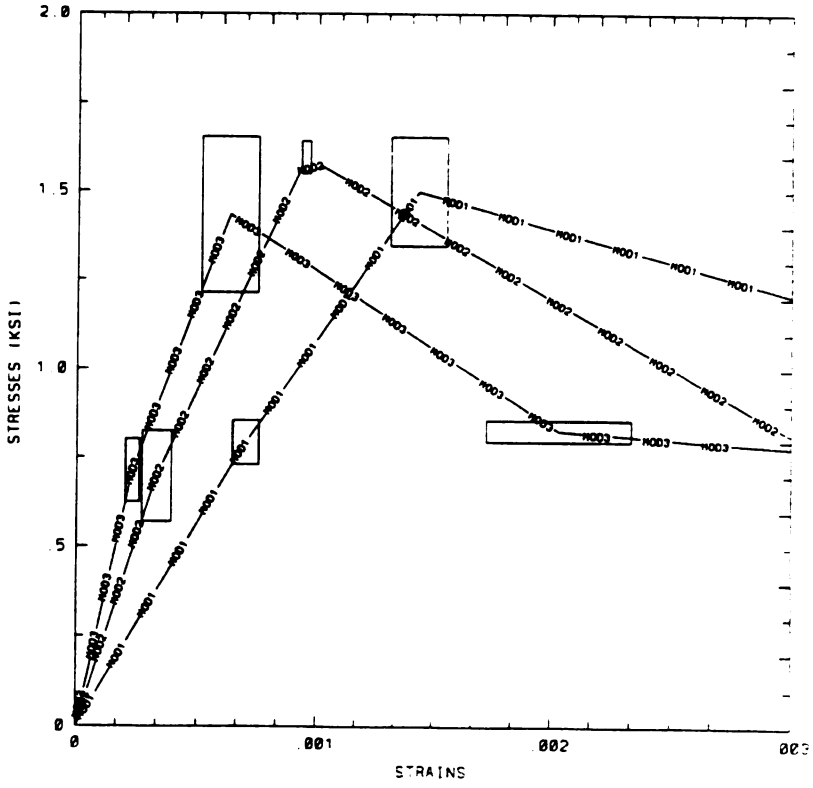
Fiber Strength=110.9 Ksi

PARAMETER=Matrix Modulus

MOD1: Matrix Modulus=1,000 Ksi

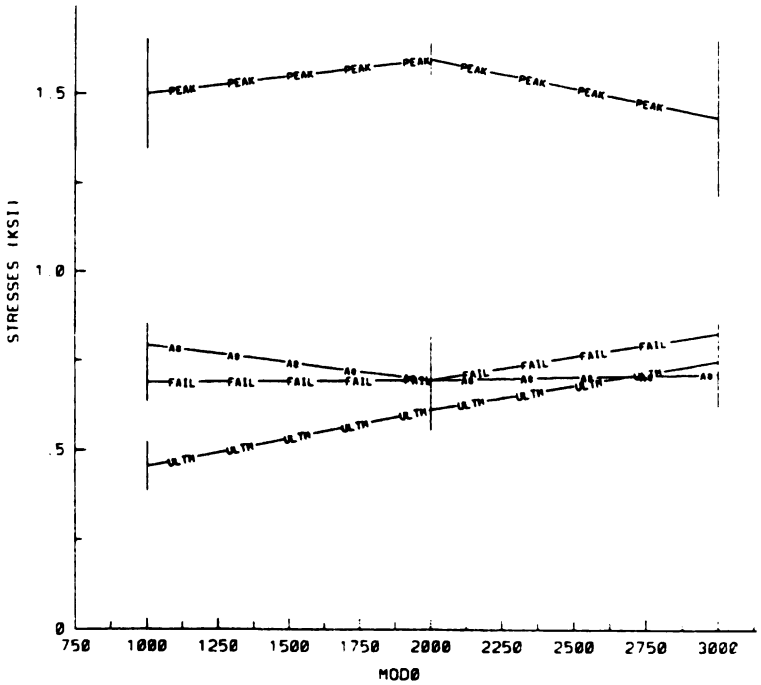
MOD2: Matrix Modulus=2,000 Ksi

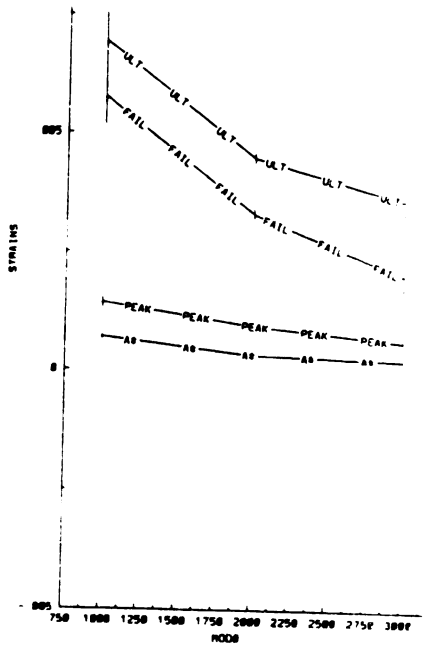
MOD3: Matrix Modulus=3,000 ksi



(a) Variables

(b) Averaged Curves





(c) Stresses Variations

(d) Strains Variations

FIGURE 8.16 Effect of Matrix Modulus of Elasticity (MOD0) on the Stress-Strain Curve Paramaters of Carbon Fiber Cement Composites.

8.3 OPTIMIZATION OF COMPOSITES WITH RESPECT TO STEEL AND CARBON FIBER REINFORCEMENT CONDITIONS

8.3.1 Optimization with respect to Carbon fiber

In this section the model is used in combination with the optimization software 'Design-Expert' in order to optimize the carbon fiber properties and the interfacial shear strength that produce a better performing cement composite.

The carbon fiber properties and their ranges selected, based on practical consideration, for use in this investigation are:

Strength: from 60 ksi to 120 ksi.

Length: from 1 mm (.039 inches) to 20 mm (.79 inches).

Diameter: from 8 μm (.000315 inches) to 20 μm (.000787 inches).

Interfacial shear strength (TAU): from 0.2 ksi to 0.7 ksi.

The modulus of elasticity of the fiber was also varied simultaneously with the strength (from 4000 ksi to 8000 ksi).

The matrix properties are chosen similar to those of the carbon fiber reinforced materials introduced in Chapter 7, with 2% fiber content.

The data produced by the model are shown below in Table 8.1. The analysis is shown in Figures 8.17 through 8.27.

Table 8.1: Data produced by the model, for the purpose of optimization of carbon fiber cement composites with respect to fiber length, diameter, strength, and bond strength.

Fiber Strength	Fiber Diameter	Fiber Length	Shear (TAU)	Peak Stress	Peak Strain	Toughne ss
ksi	inches	inches	ksi	ksi	10-3	10-3 ksi
120.00	3.15000E-04	0.0394	0.2000	1.0590	0.6500	0.3570
90.00	5.51200E-04	0.4134	0.4500	0.9180	0.6386	0.3377
60.00	3.15000E-04	0.0394	0.7000	1.0800	0.7000	0.3970
60.00	3.15000E-04	0.7874	0.2000	1.0590	0.6840	0.3750
60.00	7.87400E-04	0.0394	0.2000	1.0590	0.6840	0.3750
120.00	3.15000E-04	0.7874	0.7000	1.5660	0.9710	0.8160
60.00	7.87400E-04	0.7874	0.7000	0.8800	0.5690	0.2510
120.00	7.87400E-04	0.7874	0.2000	1.2320	1.6510	1.6550
90.00	5.51200E-04	0.4134	0.4500	1.1870	0.8452	0.6070
120.00	7.87400E-04	0.0394	0.7000	0.8800	0.5410	0.2390
120.00	7.87400E-04	0.0394	0.2000	1.0590	0.6500	0.3570
60.00	7.87400E-04	0.0394	0.7000	0.8800	0.5690	0.2510
60.00	3.15000E-04	0.7874	0.7000	0.9510	0.6200	0.3050
60.00	7.87400E-04	0.7874	0.2000	1.0590	0.6840	0.3750
120.00	3.15000E-04	0.0394	0.7000	1.1590	0.7730	0.5150
120.00	7.87400E-04	0.7874	0.7000	1.4550	0.9930	0.8630
120.00	3.15000E-04	0.7874	0.2000	1.3650	1.0100	0.8830
60.00	3.15000E-04	0.0394	0.2000	1.0590	0.6840	0.3750
90.00	5.51200E-04	0.4134	0.4500	1.2120	0.8580	0.6221
90.00	5.51200E-04	0.4134	0.4500	1.5790	0.9933	0.7846

Figures 8.17, 8.18 and 8.19 present the combined effects of fiber length, fiber diameter, and fiber strength on the peak stress, peak strain, and toughness, respectively.

From Figure 8.17, it is clear that thinner, longer and stronger fibers produce higher peak stresses. For peak strains, the same trend is observed as for the peak stresses, except that thinner fibers seem to cause a decrease in the peak strains (see Figure 8.18). As far as the toughness is concerned, the trend observed is similar to the case of strains; that is stronger and longer fibers produce higher toughness values; while thinner fibers produce slightly lower toughness values (Figure 8.19).

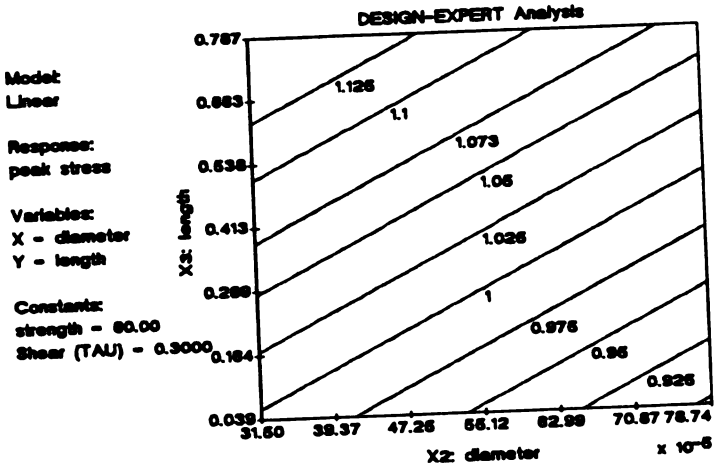
Figures 8.20, 8.21 and 8.22 present the effects of the interfacial shear strength, the fiber length, and the fiber diameter on the stress-strain curve parameters (i.e. the peak stress, the peak strain, and the toughness). The effects of the fiber length and diameter are exactly the same as in the previous cases (i.e. Figures 8.17, 8.28 and 8.19). However, the interfacial shear strength seems to:(1) have relatively small effects on peak stress (Figure 8.20); (2) higher interfacial shear strength cause lower strains and lower toughness values (Figures 8.21 and 8.22, respectively).

The observed negative effects of higher interfacial shear values are due to the fact that the range of shear values used in this study are within the optimum range, and the fiber strength was fixed, in studies of the effects of interfacial shear strength, at 100 ksi which is not high enough to sustain high shear stresses. Therefore, most of the fibers break and do not contribute positively to the material performance. Hence, it is clear that the effect of the shear strength can be accounted for more effectively by varying simultaneously the fiber strength and the shear strength. This is done in Figure 8.23, which shows the same trends as discussed previously; however, for higher fiber strength, the peak stress is shown to increase at higher interfacial shear strengths.

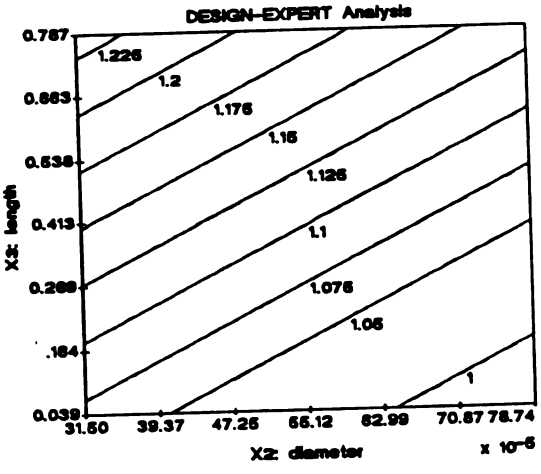
The last part of this analysis is concerned with determining the combination of fiber properties and interfacial shear strength for producing the optimum material performance, using the optimization software "Design-Expert", (Reference 7.7) (i.e. the highest values possible of peak stress, peak strain, and toughness). The results are shown in Figures 8.24 through 8.27. The effects of fiber strength on the optimum material performance, for a fixed shear strength of 0.45 ksi, is demonstrated in Figure 8.24 which shows an 8% increase in the peak stress, a 15% increase in peak strain, and a 27% increase in toughness. As the fiber strength was increases from 90 ksi to 120 ksi. Also, Figure 8.24 indicates that the optimum material performance region is characterized by the highest fiber lengths and smallest diameters possible.

Figure 8.25 shows the effect of interfacial shear strength, for a fixed fiber strength of 120 ksi, on the optimum ranges of fiber diameter and length. The shear strength was varied from 0.45 ksi to 0.7 ksi. This Figure indicates that a shear value of 0.45 ksi gives a wider range (white non-shaded region) of fiber size to choose from and still achieve the same material performance as with a higher shear of 0.7 ksi. As discussed previously, this is due to the fact that higher interfacial shear values restrain crack opening and reduce both strain values and toughness, though higher shear stresses could improve the peak stress depending on the fiber strength.

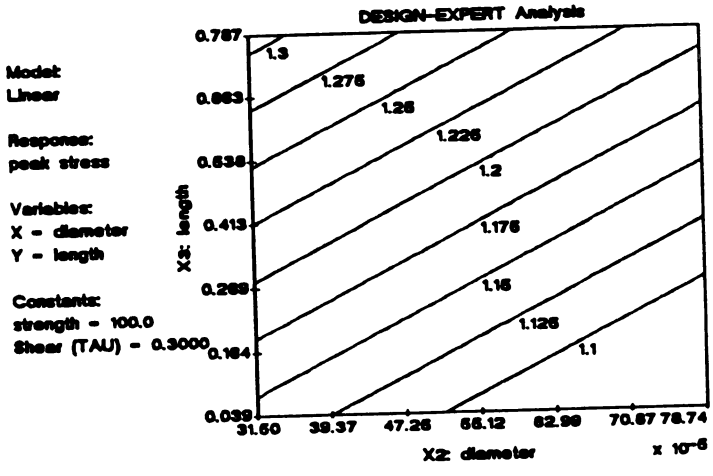
Figures 8.26 and 8.27, respectively, show the effects of fiber length and diameter on the optimum ranges of fiber strength and interfacial shear strength. It is clear from these two Figures that longer and thinner fibers allow a wider range (white non-shaded areas) of fiber strength and interfacial shear strength that can produce the same optimum material performance.



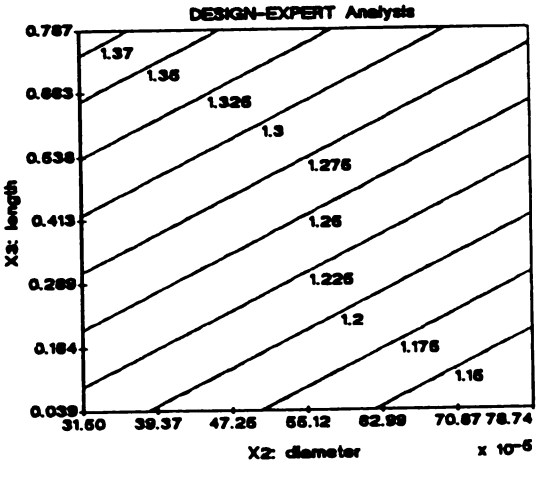
fiber strength=60ksi



fiber strength=80ksi

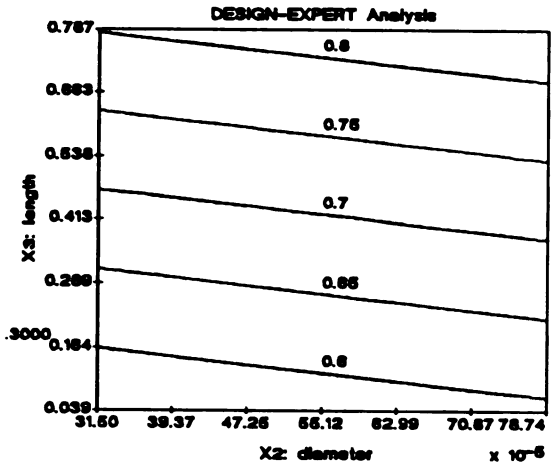


fiber strength=100ksi

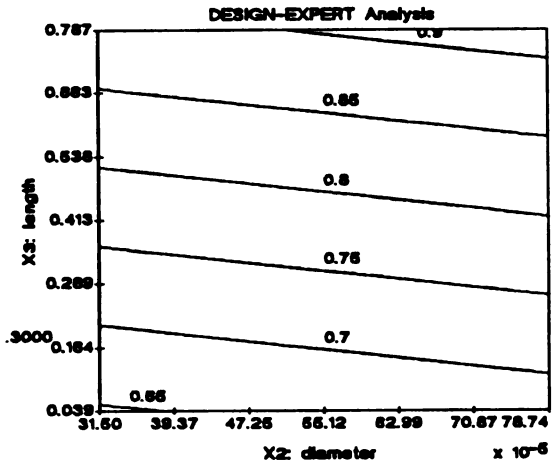


fiber strength=120ksi

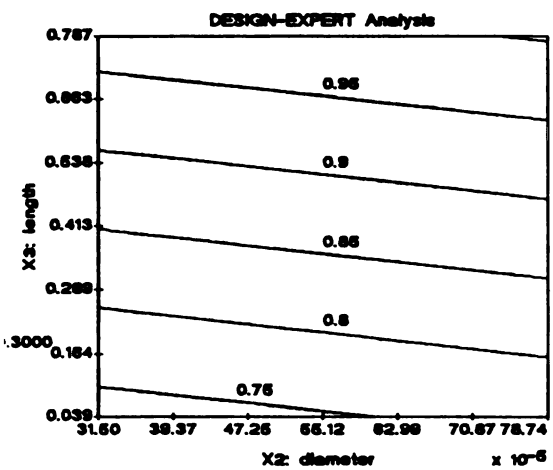
FIGURE 8.17 Combined Effects of Carbon Fiber Length, Diameter, and Strength on Peak Stress, (Units are based on KIPS and INCHES system; numbers on countour lines are peak stress values in ksi).



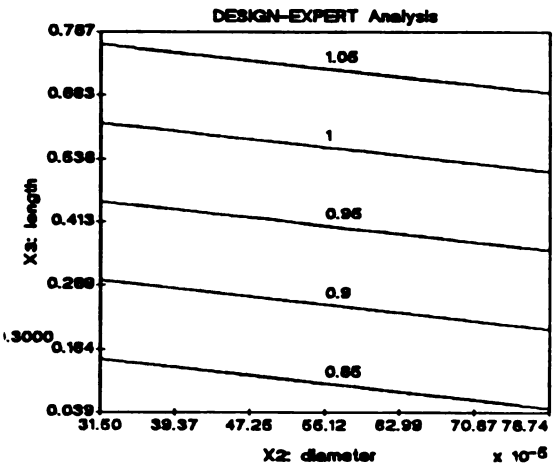
fiber strength=60ksi



fiber strength=80ksi



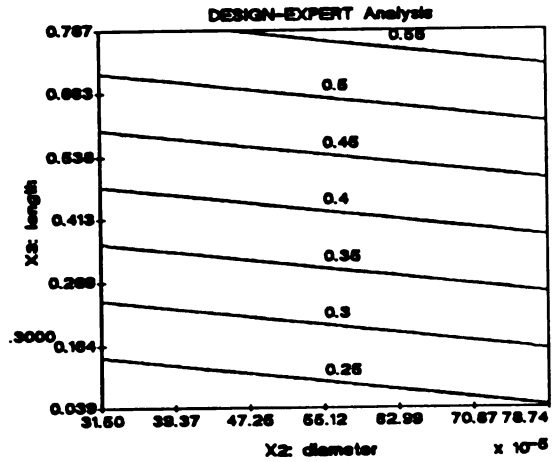
fiber strength=100ksi



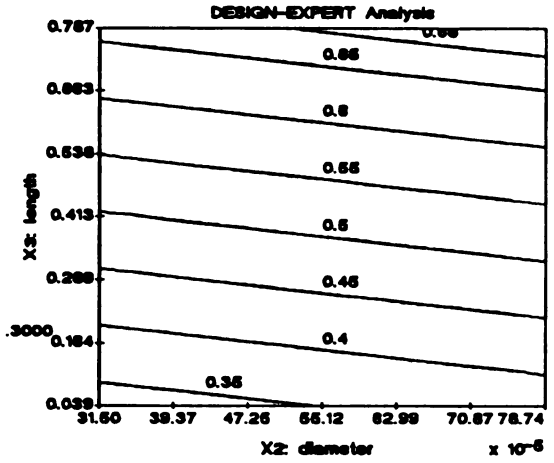
fiber strength=120ksi

FIGURE 8.18

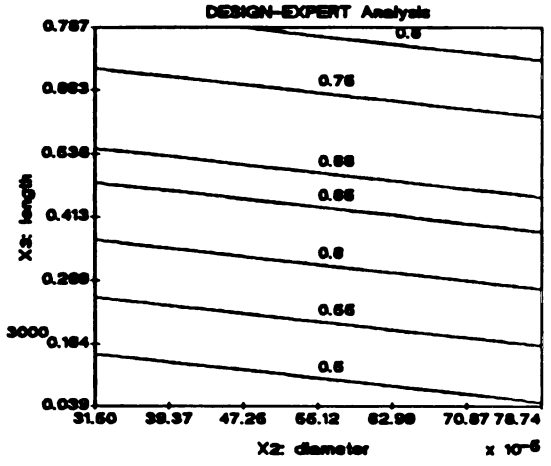
Combined Effects of Carbon Fiber Length, Diameter, and Strength on Peak Strain (Units are based on KIPS and INCHES system; numbers on countour lines are peak strain values in 10^{-3}).



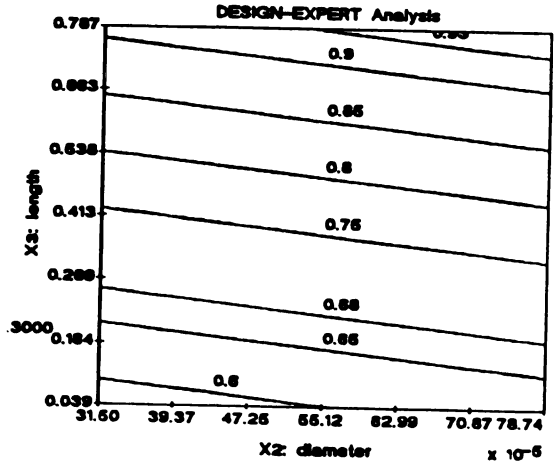
fiber strength=60ksi



fiber strength=80ksi



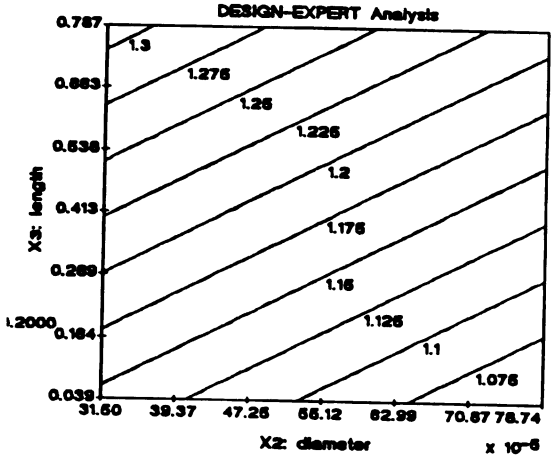
fiber strength=100ksi



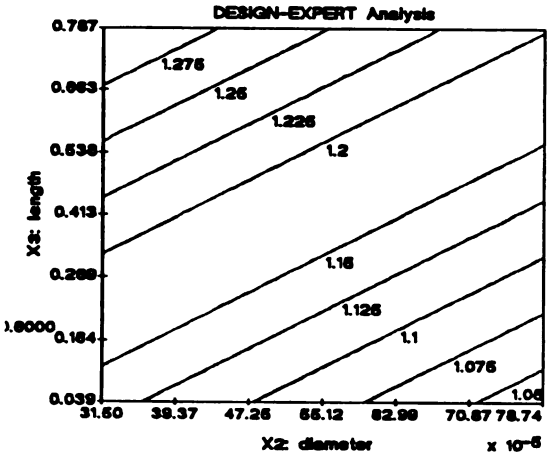
fiber strength=120ksi

FIGURE 8.19

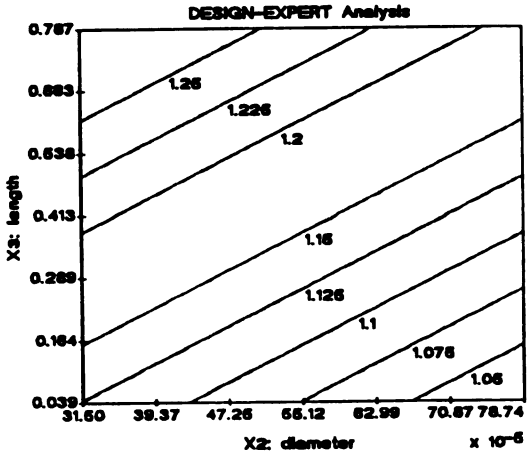
Combined Effects of Carbon Fiber Length, Diameter, and Strength on Peak Toughness (Units are based on KIPS and INCHES system; numbers on countour lines are peak toughness values in 10^{-3} ksi).



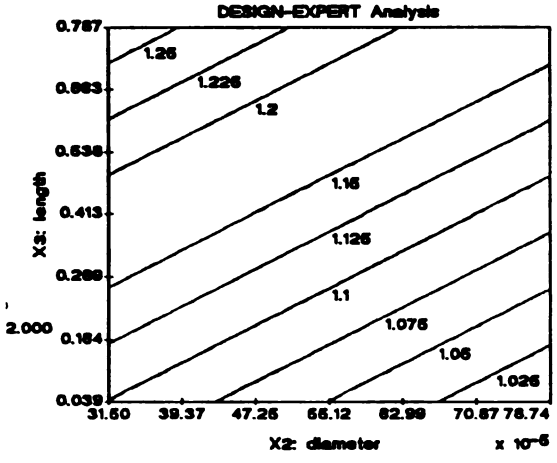
TAU = .2 ksi



TAU = .6 ksi



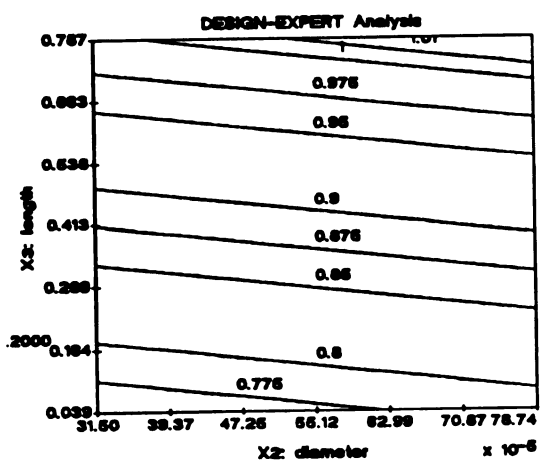
TAU = 1 ksii



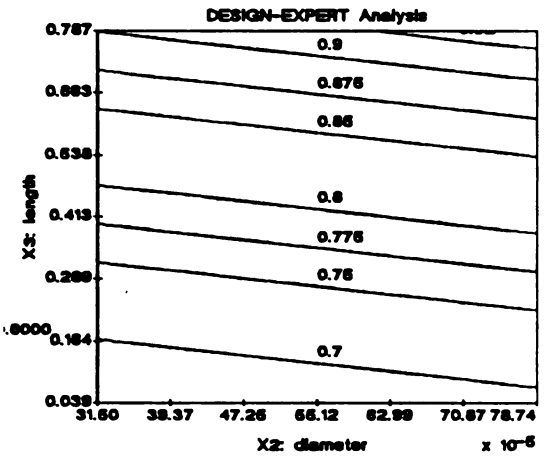
TAU = 2 ksi

FIGURE 8.20

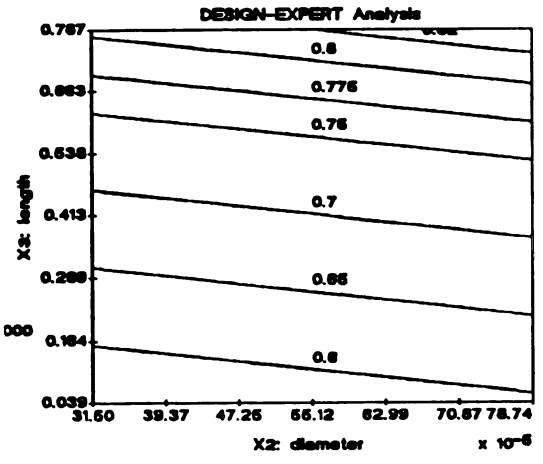
Combined Effects of Carbon Fiber Length, Diameter, and Interfacial Shear Strength on Peak Stress (Units are based on KIPS and INCHES system; numbers on countour lines are peak stress values in ksi).



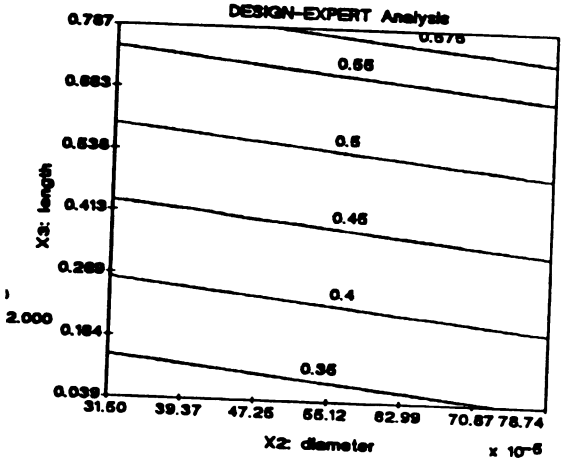
TAU = .2 ksi



TAU = .6 ksi

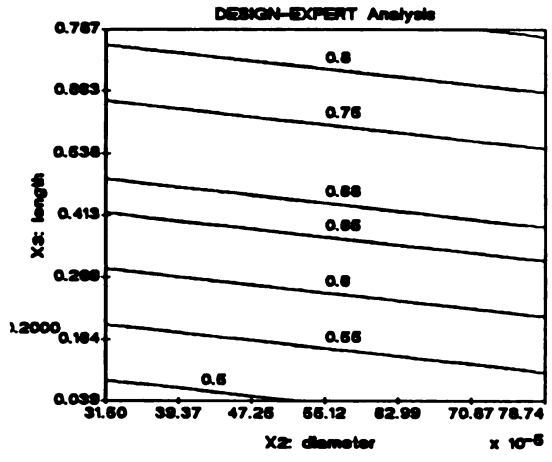


TAU = 1 ksi

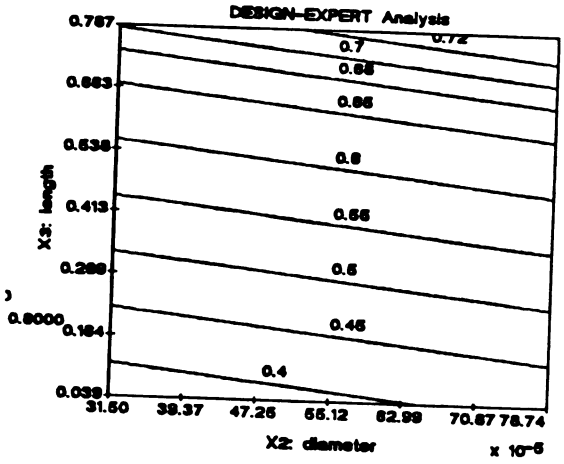


TAU = 2 ksi

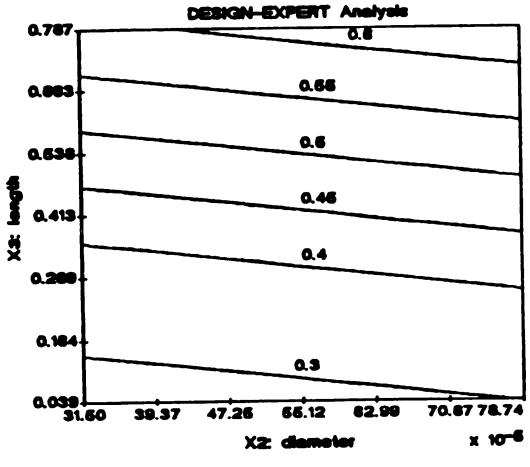
FIGURE 8.21 Combined Effects of Carbon Fiber Length, Diameter, and Interfacial Shear Strength on Peak Strain (Units are based on KIPS and INCHES system; numbers on countour lines are peak strain values in 10^{-3}).



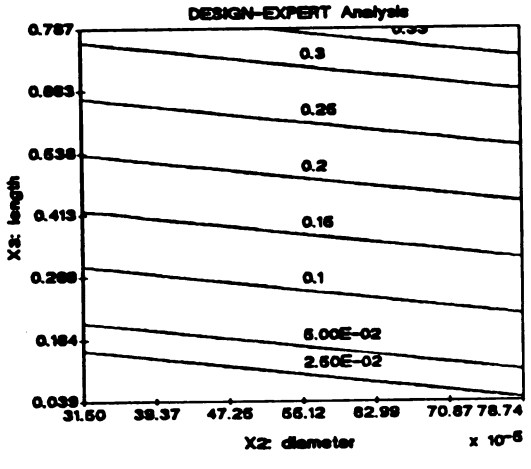
TAU = .2 ksi



TAU = .6 ksi



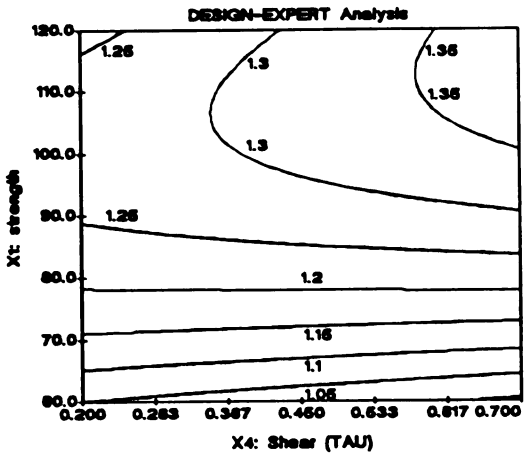
TAU = 1 ksi



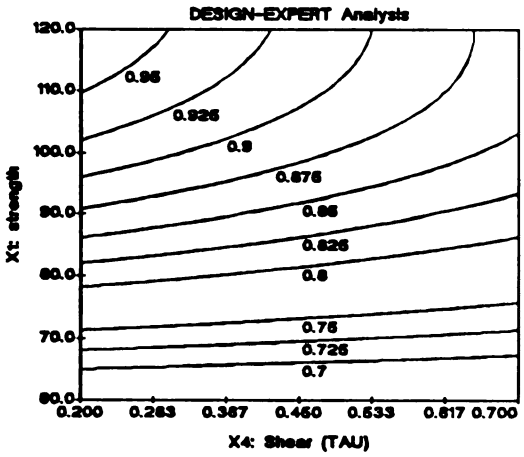
TAU = 2 ksi

FIGURE 8.22

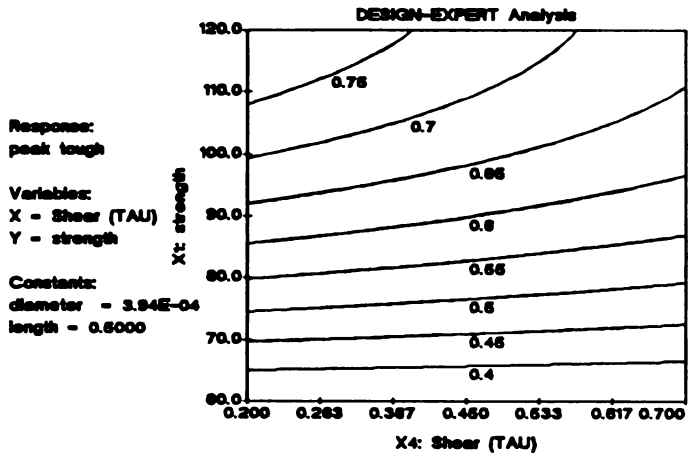
Combined Effects of Carbon Fiber Length, Diameter, and Interfacial Shear Strength on Peak Toughness (units are based on KIPS and INCHES system: numbers on countour lines are peak toughness values in 10^{-3} ksi).



(a) Peak Stress (ksi)



(b) Peak Strain (10^{-3})

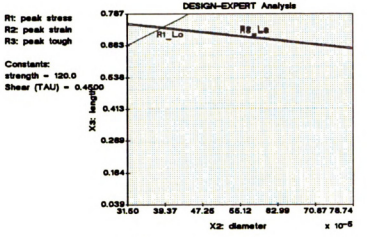


(c) Toughness (10^{-3} ksi)

FIGURE 8.23

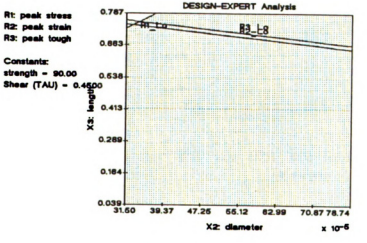
Combined Effects of Carbon Fiber Strength and Interfacial Shear Strength on Peak Stress, Peak Strain, and Toughness (Units are based on KIPS and INCHES system; numbers on countour lines are peak stress values (a), peak strain values (b), and toughness).

Response	Units	Lo
peak stress	ksi	1.350
peak strain	10-3	1.010
peak tough	10-3 ksi	0.850



(a) Strength=120 ksi

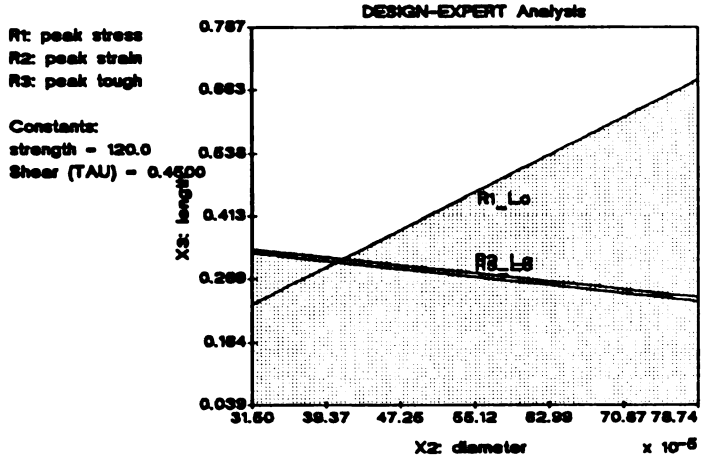
Response	Units	Lo
peak stress	ksi	1.255
peak strain	10-3	0.880
peak tough	10-3 ksi	0.670



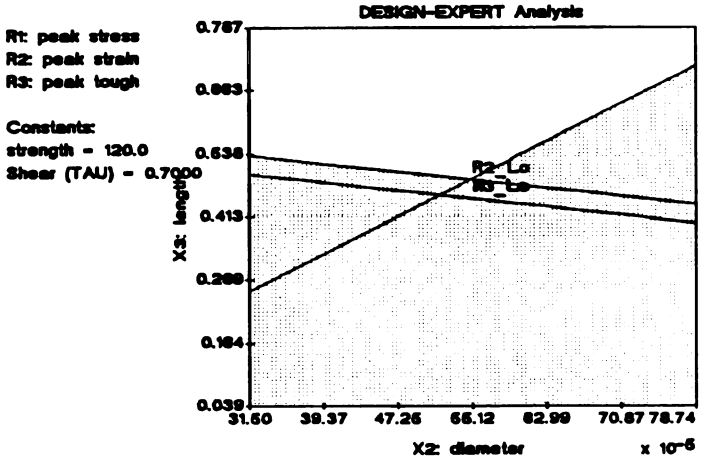
(b) strength = 90 ksi

FIGURE 8.24 Effects of Carbon fiber Strength on Optimum Material Performance.

Response	Units	Lo
R1: peak stress	ksi	1.255
R2: peak strain	10-3	0.880
R3: peak tough	10-3 ksi	0.670



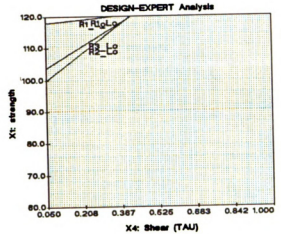
(a) Shear = .45 ksi



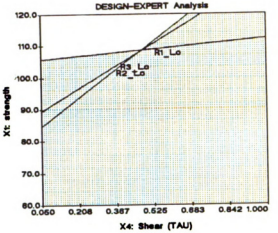
(b) Shear = .7 ksi

FiGURE 8.25 Effects of Interfacial Shear Strength on Optimum Carbon Fiber Size Ranges.

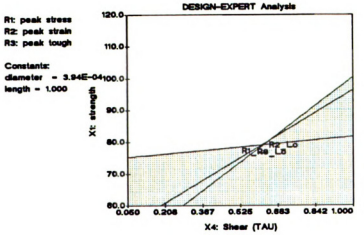
Response	Units	Lo
R1: peak stress	ksi	1.255
R2: peak strain	10-3	0.880
R3: peak tough	10-3 ksi	0.670



(a) Length = .3 in.



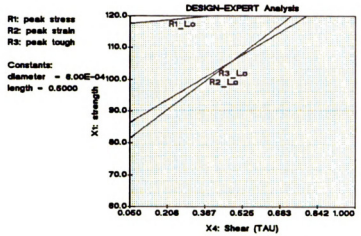
(b) Length = .5 in.



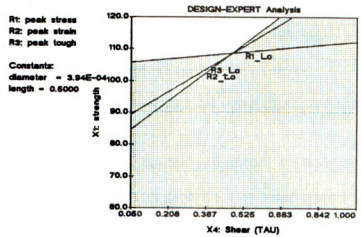
(c) Length = 1 in.

FIGURE 8.26 Effects of Carbon Fiber Length on Optimum Ranges of Fiber Strength and Interfacial Shear Strength.

Response	Units	Lo
R1: peak stress	ksi	1.255
R2: peak strain	10-3	0.880
R3: peak tough	10-3 ksi	0.670



(a) Diameter = .0006 in.



(b) Diameter = 0.000394 in.

FIGURE 8.27 Effects of Carbon Fiber Diameter on Optimum Ranges of Fiber Strength and Shear Strength.

8.3.2 Optimization with respect to steel fiber

In this section, the use of the model is demonstrated through the collection of necessary data that was processed with the optimization software 'Design-Expert' (Reference 7.7) and analyzed in order to answer the following types of questions:

What steel fiber properties should be used to maximize the cement composite performance?

Are there some fiber properties that allow the composite material performance to be doubled, tripled,...?

The analysis is based on the steel fiber matrix presented in Chapter 7.

8.3.2.1 Fiber length, fiber diameter, and fiber strength effects

The fiber length, fiber diameter, and fiber strength are varied, in this investigation, within the commonly used ranges, as suggested by ASTM A820 and the steel fiber industry.

Fiber length (Lf): from 0.25 inches to 1.5 inches.

Fiber Diameter (Df): from .005 inches to .04 inches.

Fiber strength (SIGULT): from 50 ksi to 130 ksi

Modulus of elasticity of fiber: fixed at 29,000 ksi

Interfacial Shear Strength (TAU): fixed at .6 ksi

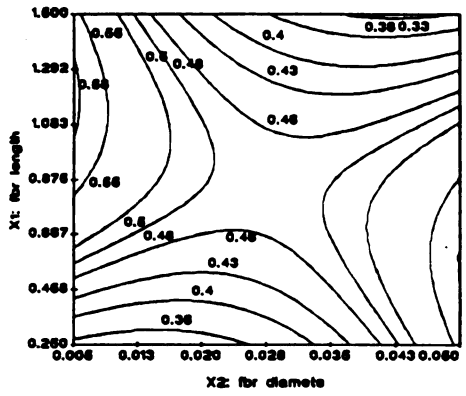
The data produced by the model, for use in the optimization process, are shown in Table 8.2.

The results of the optimization are shown in Figures 8.28 through 8.30

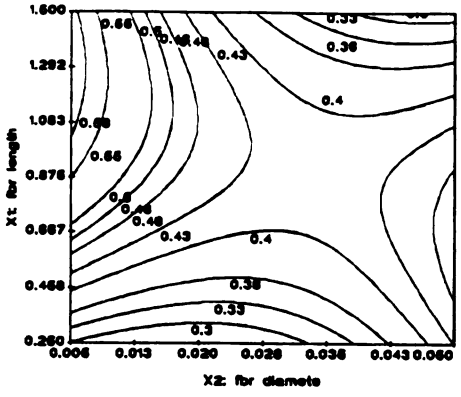
Figures 8.28, 8.29 and 8.30 show the combined effects of the fiber length, fiber diameter and fiber strength on peak stress, peak strain, and total toughness, respectively. These Figures show that the highest values of peak stress, peak strain, and total toughness are achieved for the larger fiber lengths and strengths and the smaller fiber diameters.

Table 8.2: Data produced by the model, for the purpose of optimization of steel fiber cement composites with respect of fiber length, diameter, and strength.

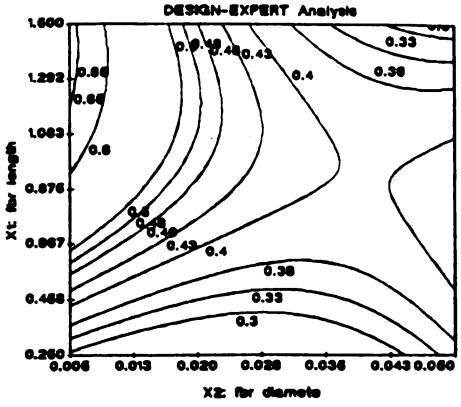
Fiber length	Fiber diamete	Fiber strengt	Peak Stress	Peak Strain	Peak Togh	Total Togh
inches	inches	ksi	ksi	10-3	10-3 Ksi	10-3 ksi
0.2500	5.00000E-03	300.00	0.4410	0.1030	0.0230	0.8490
0.8750	2.75000E-02	175.00	0.4430	0.1030	0.0230	0.4210
0.2500	5.00000E-02	300.00	0.4400	0.1020	0.0230	0.0730
1.5000	5.00000E-02	300.00	0.4370	0.1010	0.0220	0.4210
0.8750	2.75000E-02	175.00	0.4430	0.1030	0.0230	0.9730
0.8750	2.75000E-02	175.00	0.4430	0.1030	0.0230	0.9730
0.8750	1.62500E-02	175.00	0.4050	0.0940	0.0200	0.3980
0.2500	5.00000E-03	50.00	0.4450	0.1030	0.0240	0.7770
1.1875	2.75000E-02	175.00	0.4120	0.0960	0.0190	0.3680
0.8750	2.75000E-02	175.00	0.3450	0.0803	0.0139	0.7060
0.8750	2.75000E-02	175.00	0.4870	0.1131	0.0276	1.5010
0.8750	2.75000E-02	112.50	0.4400	0.1020	0.0230	0.4370
0.8750	3.87500E-02	175.00	0.4100	0.2550	0.1130	0.4020
1.5000	5.00000E-02	50.00	0.4160	0.0970	0.0200	3.7550
0.5625	2.75000E-02	175.00	0.3990	0.0930	0.0200	0.5660
0.2500	5.00000E-02	50.00	0.4360	0.2050	0.0720	0.1480
0.8750	2.75000E-02	175.00	0.4970	0.1155	0.0288	0.7100
1.5000	5.00000E-03	300.00	1.2630	1.2450	1.1810	6.8400
1.5000	5.00000E-03	50.00	0.4730	0.1320	0.0370	0.3720
0.8750	2.75000E-02	237.50	0.4400	0.1020	0.0230	0.4370
0.8750	4.25000E-02	112.50	0.4600	0.1070	0.0250	0.2680
0.8750	4.25000E-02	237.50	0.4600	0.1070	0.0250	0.2680



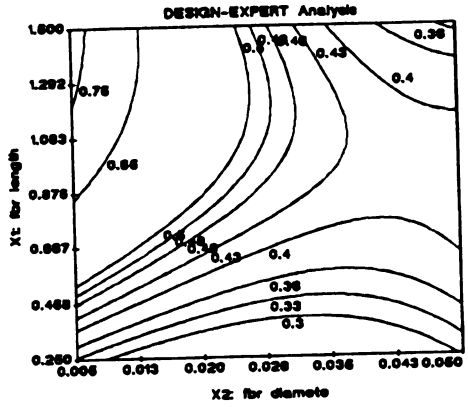
fiber strength=50ksi



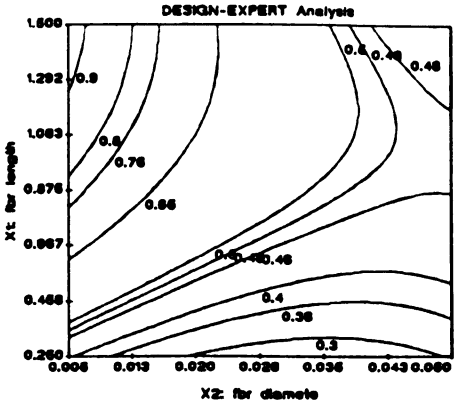
fiber strength=100ksi



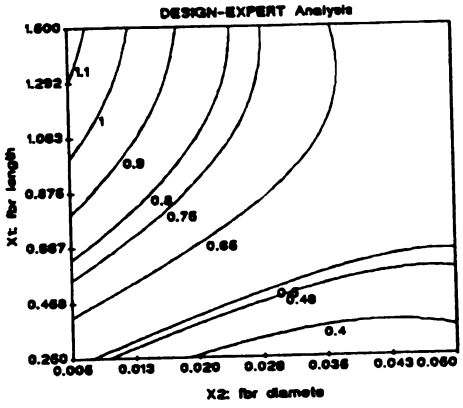
fiber strength=150ksi



fiber strength=200ksi



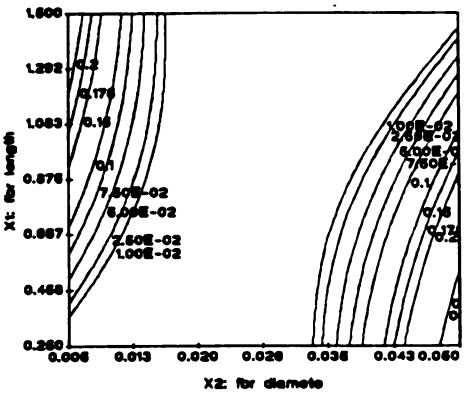
fiber strength=250ksi



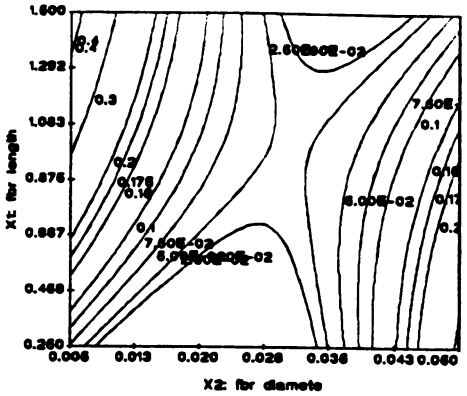
fiber strength=300ksi

FIGURE 8.28

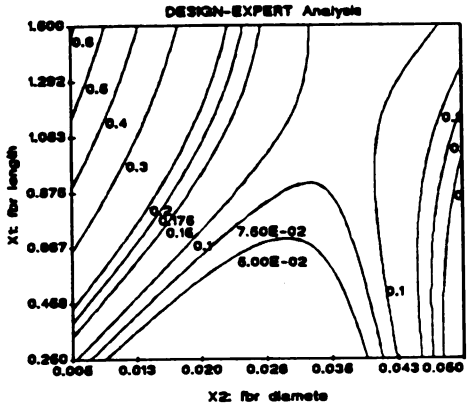
Combined Effects of Steel Fiber Length, Diameter, and Strength on Peak Stress (Units are based on KIPS and INCHES system; numbers on countour lines are peak stress values in ksi).



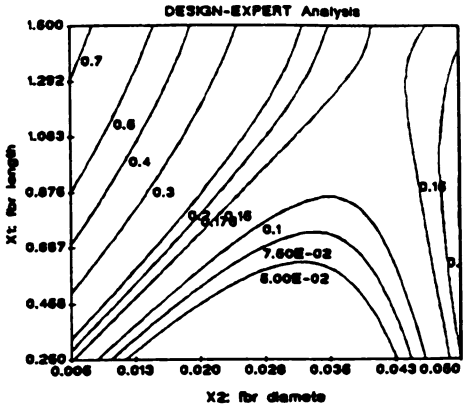
fiber strength=50ksi



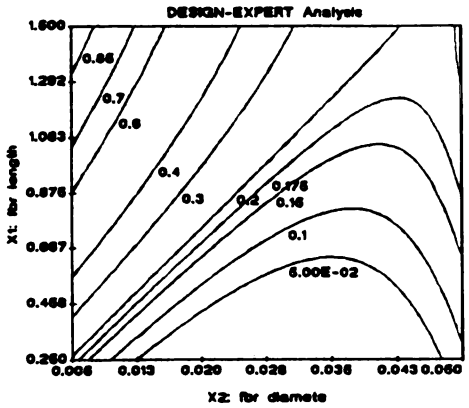
fiber strength=100ksi



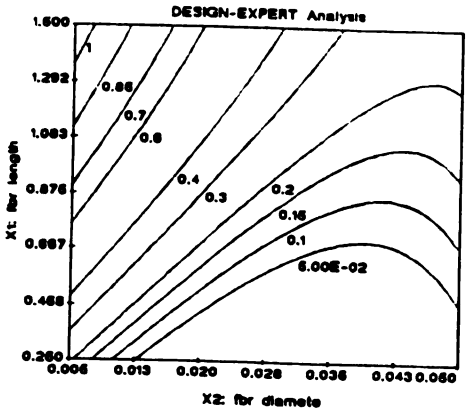
fiber strength=150ksi



fiber strength=200ksi

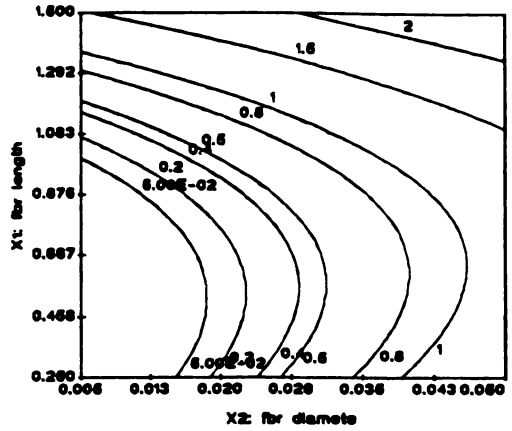


fiber strength=250ksi

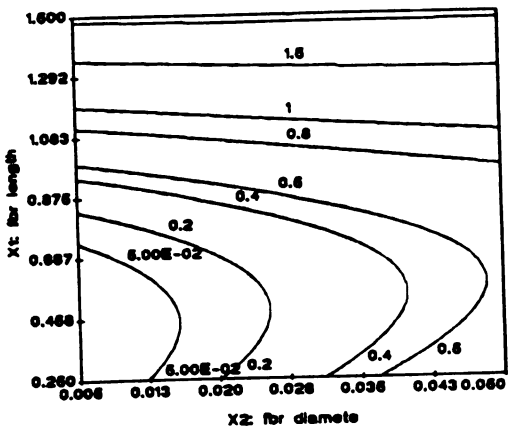


fiber strength=300ksi

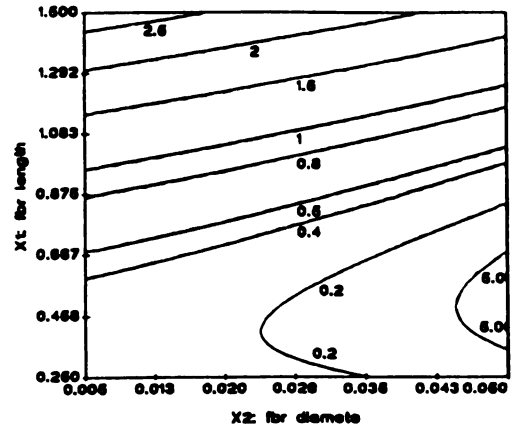
FIGURE 8.29 Combined Effects of Steel Fiber Length, Diameter, and Strength on Peak Strain (Units are based on KIPS and INCHES system; numbers on countour lines are peak strain values in (10-3)).



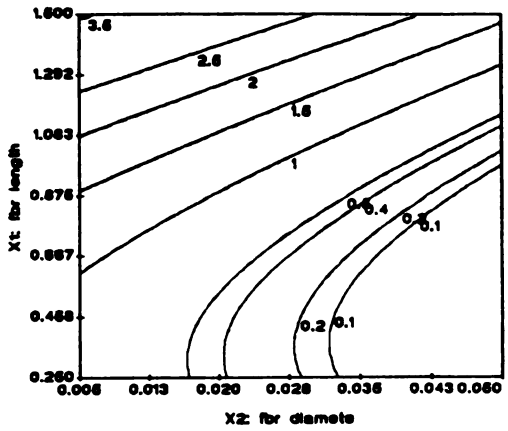
fiber strength=50ksi



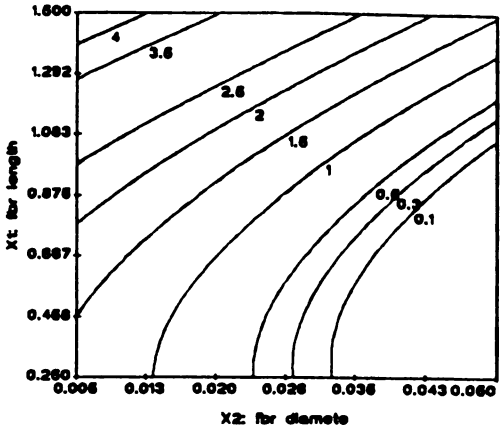
fiber strength=100ksi



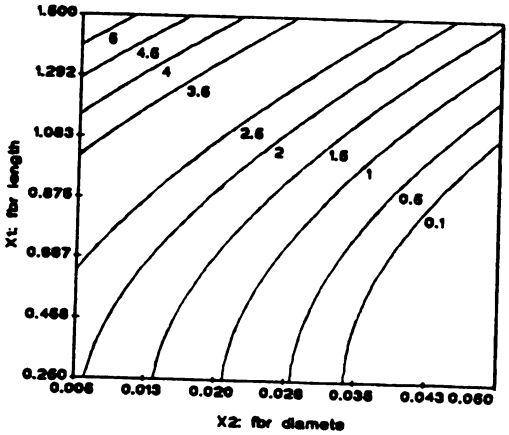
fiber strength=150ksi



fiber strength=200ksi



fiber strength=250ksi



fiber strength=300ksi

FIGURE 8.30 Combined Effects of Steel Fiber Length, Diameter, and Strength on Tota Toughness (Units are based on KIPS and INCHES system; numbers on countour lines are total toughness values in 10-3 ksi).

8.3.2.2 Steel Fiber aspect ratio and strength effects

The data used in the previous section was converted as shown in Table 8.3, in order to study the effects of fiber aspect ratio (fiber length devided by fiber diameter) on the composite material performance. The processed results are shown in Figures 8.31 through 8.34. Figures 8.31 through 8.34 show that the best material performance is achieved with higher strength fibers at higher aspect ratios.

Figure 8.35 shows the optimum ranges of fiber strength and fiber aspect ratio that produce three different levels of the composite performance. The performance is quantified in terms of the peak stress, peak strain, and toughness. Figure 8.35 indicates that there are obviously smaller ranges to choose from as we require higher material performance. Also, Figure 8.35 indicates that the best performance is achieved when high strength fibers are used in combination with high aspect ratio.

Table 8.3: Data produced by the model for the purpose of optimization of steel fiber cement composites with respect to fiber aspect ratio and fiber strength.

Aspect Ratio	Fiber Strength	Peak stress	peak Strain	Peak Toghnes	Total toghnes
Lf/df	ksi	Ksi	10-3	10-3ksi	10-3ksi
31.82	112.50	0.4400	0.1030	0.0230	0.8490
31.82	175.00	0.4430	0.1030	0.0230	0.4210
31.82	175.00	0.4430	0.1020	0.0230	0.0730
31.82	175.00	0.4430	0.1010	0.0220	0.4210
43.18	175.00	0.4120	0.1030	0.0230	0.9730
31.82	175.00	0.4870	0.1030	0.0230	0.9730
53.85	175.00	0.4050	0.0940	0.0200	0.3980
30.00	300.00	0.4370	0.1030	0.0240	0.7770
50.00	300.00	0.4410	0.0960	0.0190	0.3680
22.58	175.00	0.4100	0.0803	0.0139	0.7060
50.00	50.00	0.4450	0.1131	0.0276	1.5010
31.82	175.00	0.3450	0.1020	0.0230	0.4370
5.00	300.00	0.4400	0.2550	0.1130	0.4020
20.59	237.50	0.4600	0.0970	0.0200	3.7550
20.59	112.50	0.4600	0.0930	0.0200	0.5660
31.82	237.50	0.4400	0.2050	0.0720	0.1480
300.00	50.00	0.4730	0.1155	0.0288	0.7100
300.00	300.00	1.2630	1.2450	1.1810	6.8400
31.82	175.00	0.4970	0.1320	0.0370	0.3720
5.00	50.00	0.4360	0.1020	0.0230	0.4370
20.45	175.00	0.3990	0.1070	0.0250	0.2680
30.00	50.00	0.4160	0.1070	0.0250	0.2680

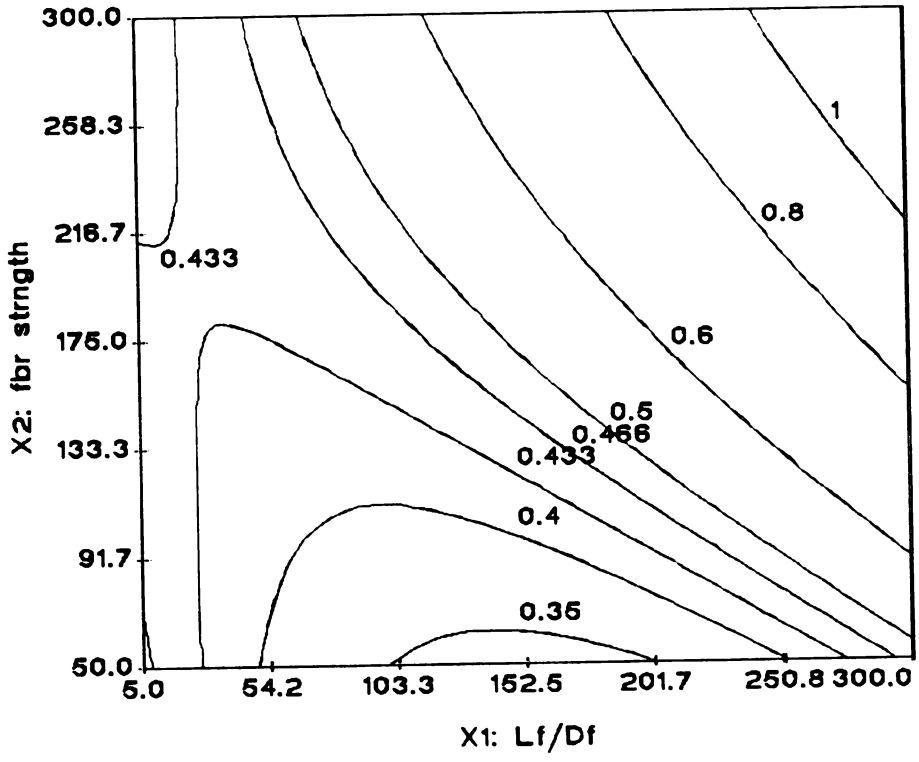


FIGURE 8.31 Combined Effects of Steel Fiber aspect ratio, and Strength on Peak Stress (Units are based on KIPS and INCHES system; countour lines represent peak stresses in ksi).

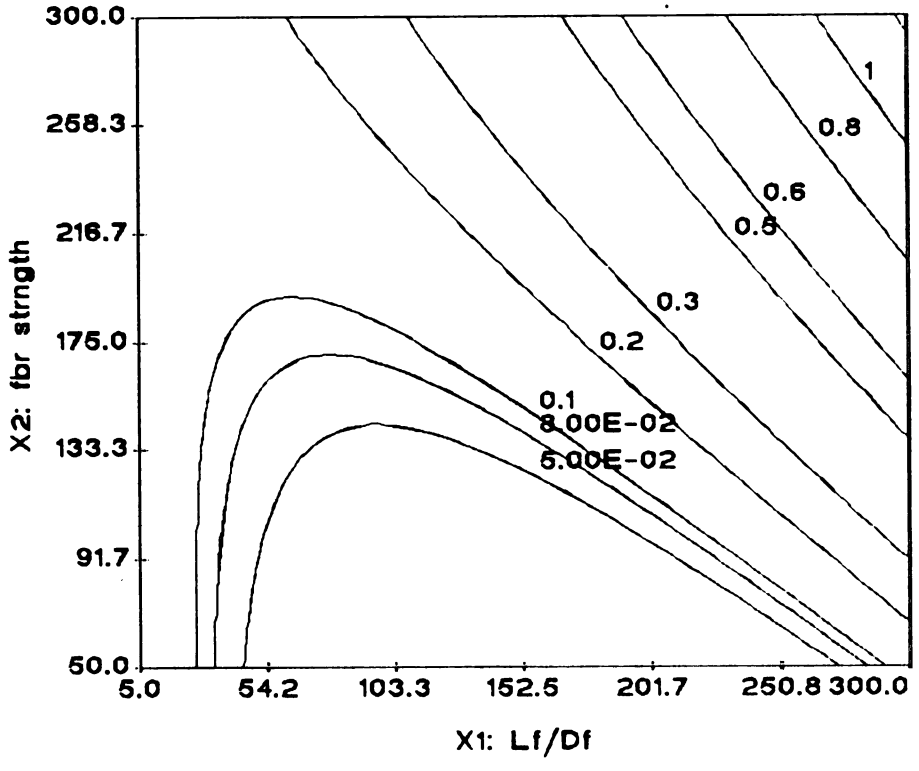


FIGURE 8.32 Combined Effects of Stell Fiber aspect ratio, and Strength on Peak Strain (Units are based on KIPS and INCHES system; countour lines represent strains in 10-3).

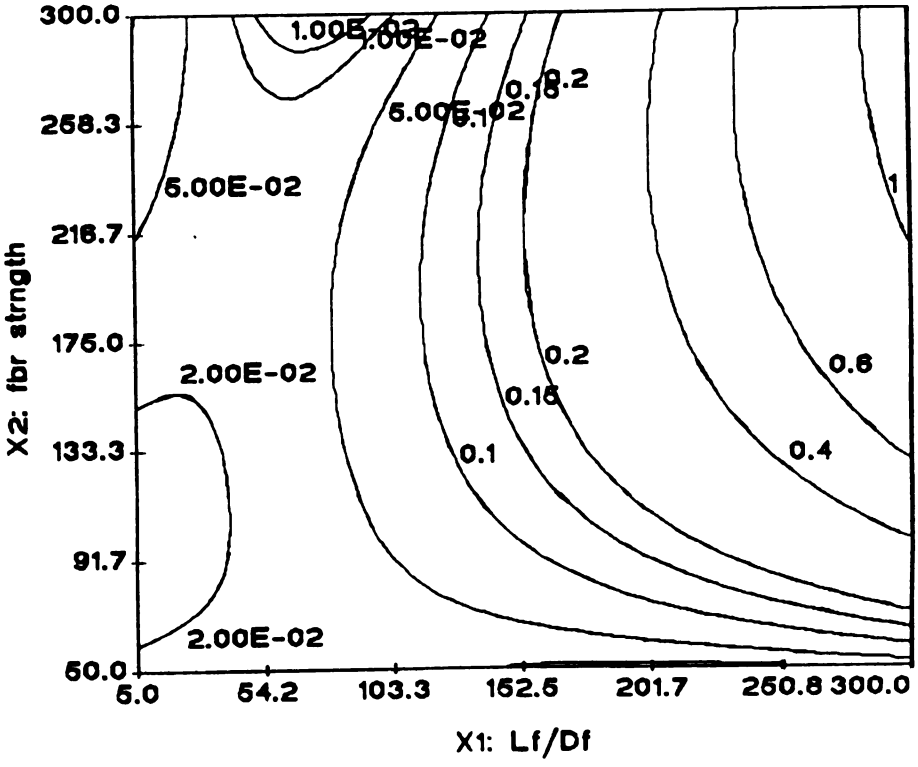


FIGURE 8.33 Combined Effects of Steel Fiber Aspect Ratio, and Strength on Peak Toughness (Units are based on KIPS and INCHES system; countour lines represent peak toughness values in 10-3 ksi).

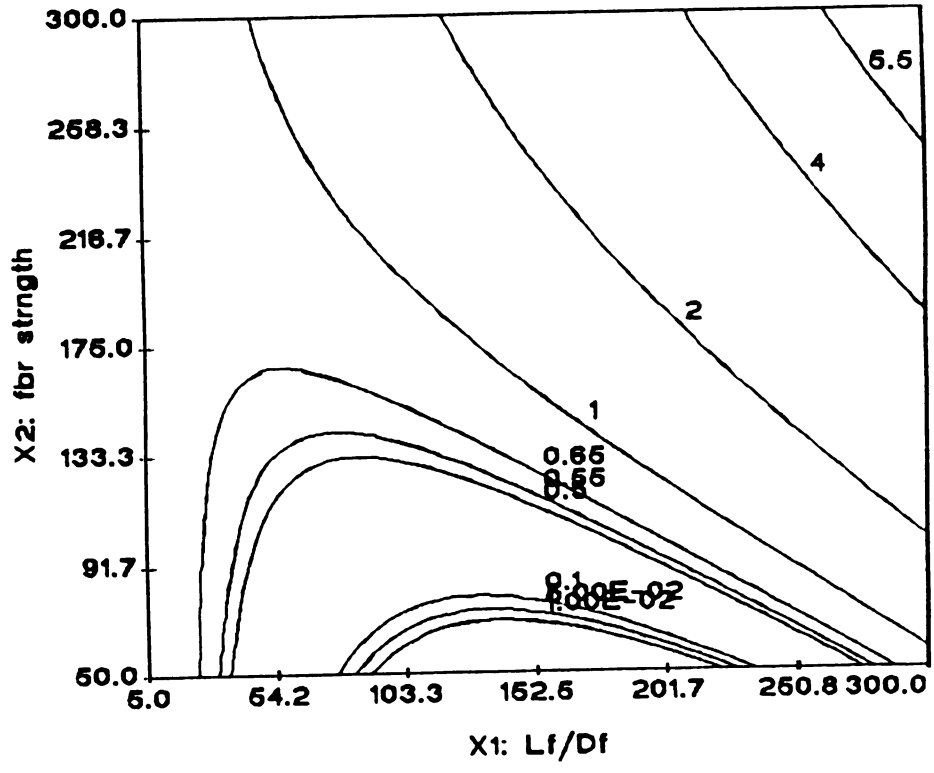
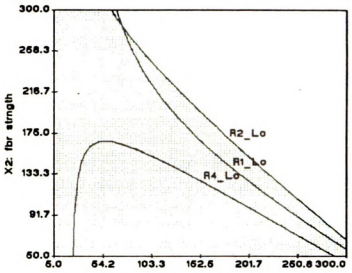
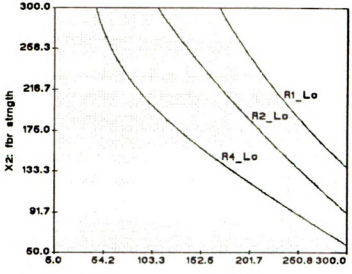


FIGURE 8.34 Combined Effects of Steel Fiber Aspect Ratio, and Strength on Total Toughness (Units are based on KIPS and INCHES system; countour lines represent total toughness valies in 10-3 ksi).

(a) Actual Experimental Results



(b) 1.5 Times the experimental results



(c) Twice the Experimental results

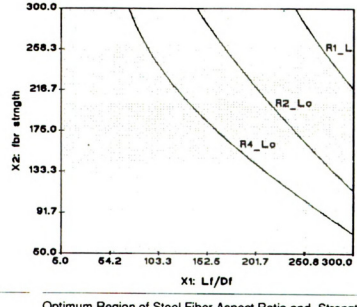


FIGURE 8.35

Optimum Region of Steel Fiber Aspect Ratio and Strength that gives (a) one time, (b) 1.5 times, and (c) 2 times the experimental results (Units are based on KIPS and INCHES system).

8.4 Application of the model to Cellulosic (wood) Fiber Reinforced Cement Composites

8.4.1 General

Cellulosic fibers are natural organic fibers characterized by relatively low cost when compared with man-made fibers. There are many different types of cellulosic fibers, depending on their origin. Some typical engineering properties of wood fibers are as follows:

Modulus of elasticity = 10,295 ksi

Tensile strength = 130.5 ksi

Interfacial bond strength = .030 - .090 ksi

Depending on the trees from which they are derived two types of wood fibers are distinguished: (1) softwood fibers; and (2) hardwood fibers. Typical geometries of both softwood and hardwood fibers are shown in Table 8.4. When used in cement materials, the wood fiber volume fraction usually ranges from 6% to 20%.

Table 8.4: Length and Diameter Ranges of Softwood and Hardwood Fibers.

	Softwood	Hardwood
Length	3 to 5 mm (.11811 to .1969 inches)	1/3 to 1/2 that of softwood
Diameter	30 to 45 μm (0.0011811 to .0017717 inches)	about 1/2 that of softwood

Based on the above fiber characteristics, considering the lack of tension test data on wood fiber cement composites in the literature, the model was used to generate the following information regarding the tensile behavior of wood fiber reinforced cement composites:

(1) Effects of fiber content on the stress-strain curves of softwood fiber reinforced cement composites. The fiber volume fractions considered were 0%, 10%, and 20%. The interfacial shear strength was fixed at an average value of .060 ksi. The fiber di-

ameter and length were .15 inches and .0015 inches, respectively.

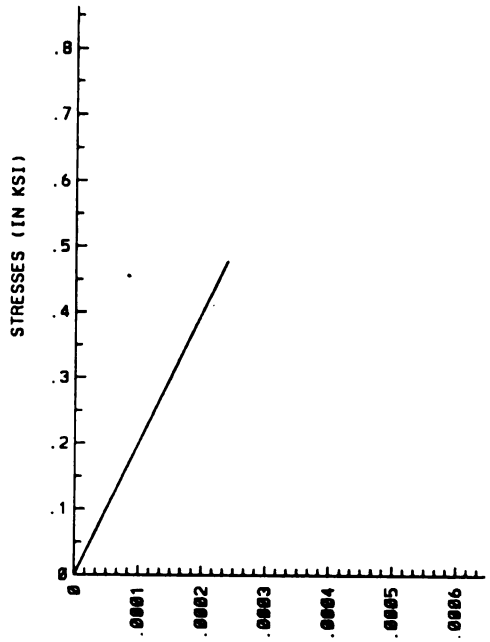
(2) Effects of the interfacial shear strength on the stress-strain curves of softwood fiber reinforced cement composites. The shear strengths considered were 0.03 ksi, 0.06 ksi, and 0.09 ksi. The fiber volume fraction was 10%. The fiber diameter and length were as in the previous case.

(3) Effects of fiber content on the stress-strain curves of hardwood fiber reinforced cement composites. All the parameters were the same as in case (1), except that a length of 0.06 inches and a diameter of 0.00075 inches were used.

8.4.2 Results

As expected, a considerable increase in all aspects of the stress-strain characteristics was noticed as either softwood or hardwood fiber content was increased (see Figures 8.36, and 8.37). However, softwood improvements were more pronounced than those due to hardwood (Figure 8.38).

Figure 8.39 shows the improvements in the stress-strain curves characteristics as the interfacial shear strength of softwood fibers increases within the range specified above. Higher interfacial shear strengths are observed to increase both the tensile strength and toughness of the composites.



(a) Vf=0%

Data Input

Fiber type: Softwood

Fiber Modulus: 10,295 ksi

Fiber Length: 0.15 inches

Fiber Diameter: 0.0015 inches

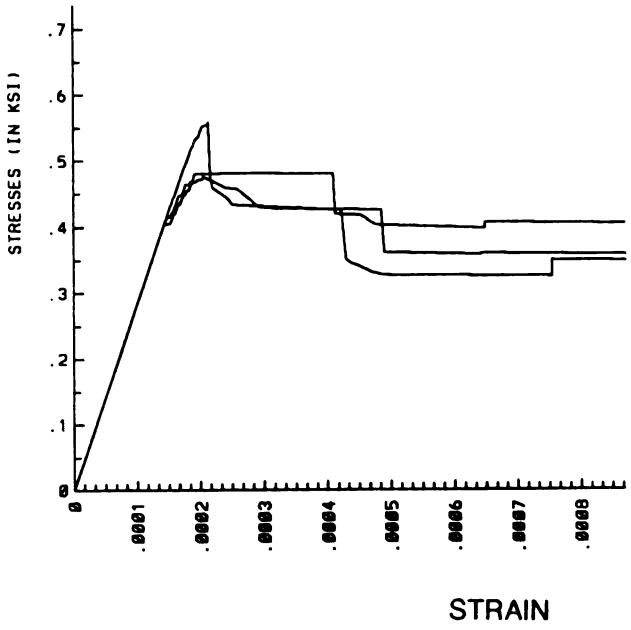
Fiber Strength: 130.0 ksi

Matrix Modulus: 2,000 ksi

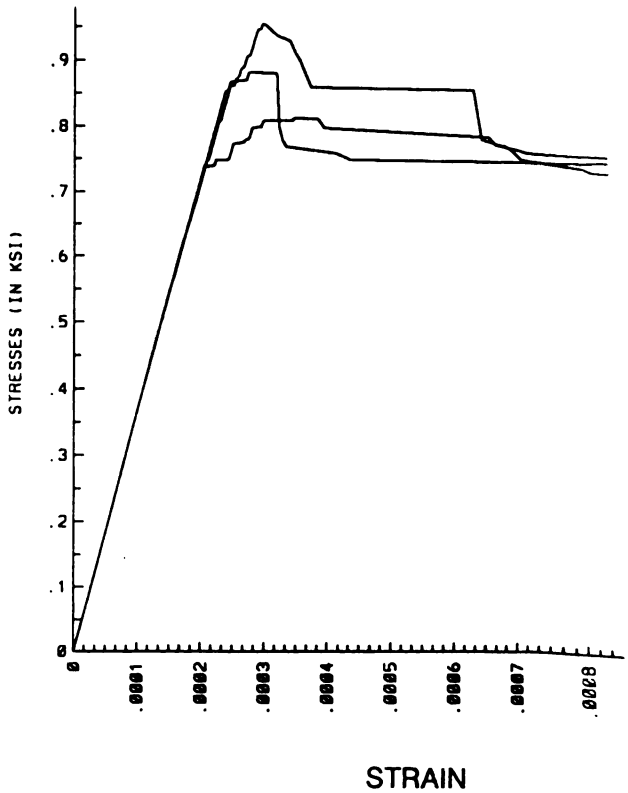
Fracture Toughness: 0.1 k(in)3/2

TAU: .06 ksi

Variable: fiber Content (vf)

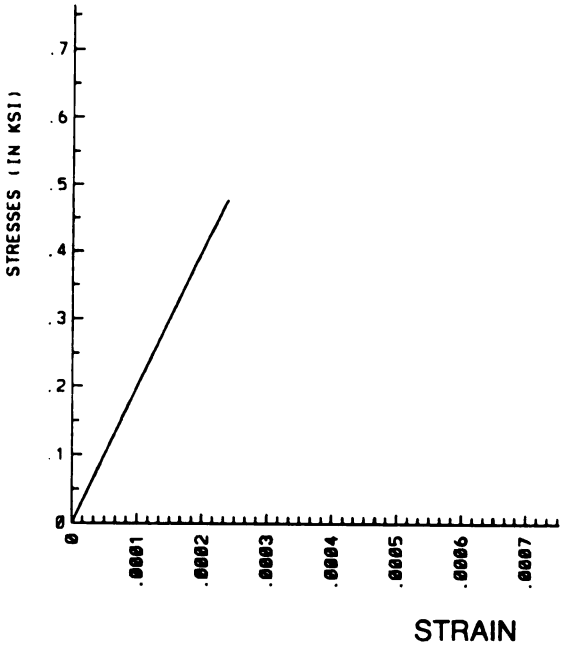


(b) Vf=10%



(c) Vf=20%

FIGURE 8.36 Effects of Fiber Content on Softwood Fiber Cement Composites Stress-Strain Curves.



(a) Vf=0%

Data input

Fiber type: Softwood

Fiber Modulus: 10,295 ksi

Fiber Length: 0.15 inches

Fiber Diameter: 0.0015 inches

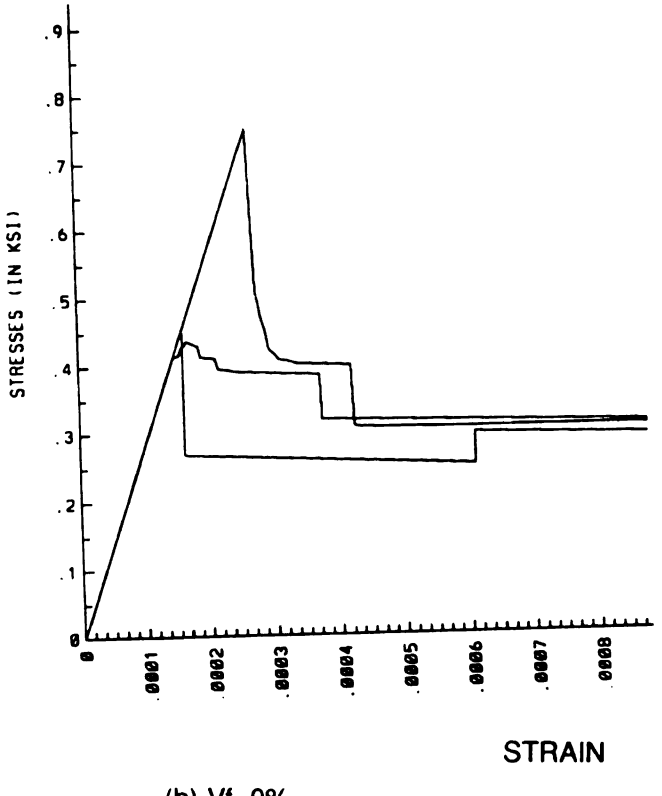
Fiber Strength: 130.0 ksi

Matrix Modulus: 2,000 ksi

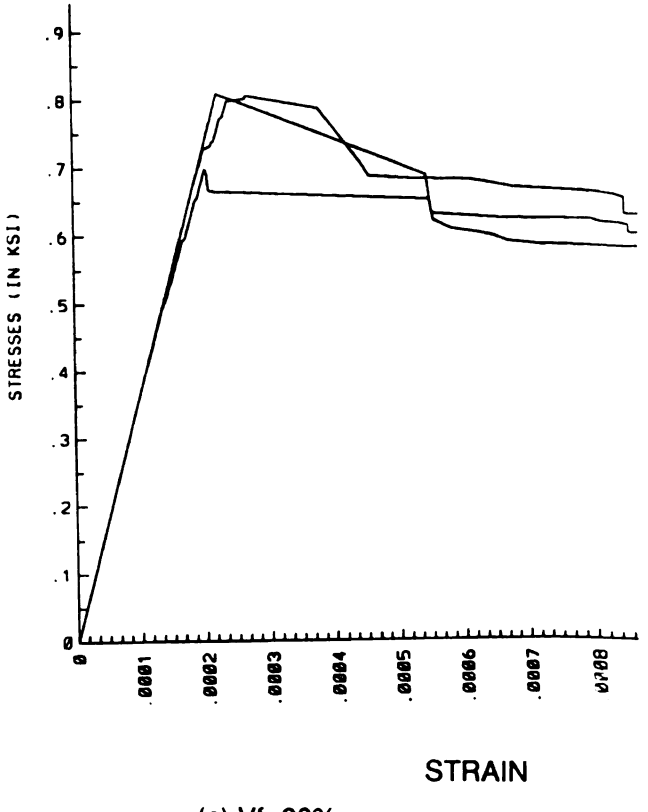
Fracture Toughness: 0.1 k(in)3/2

TAU: .06 ksi

Variable: fiber Content (vf)



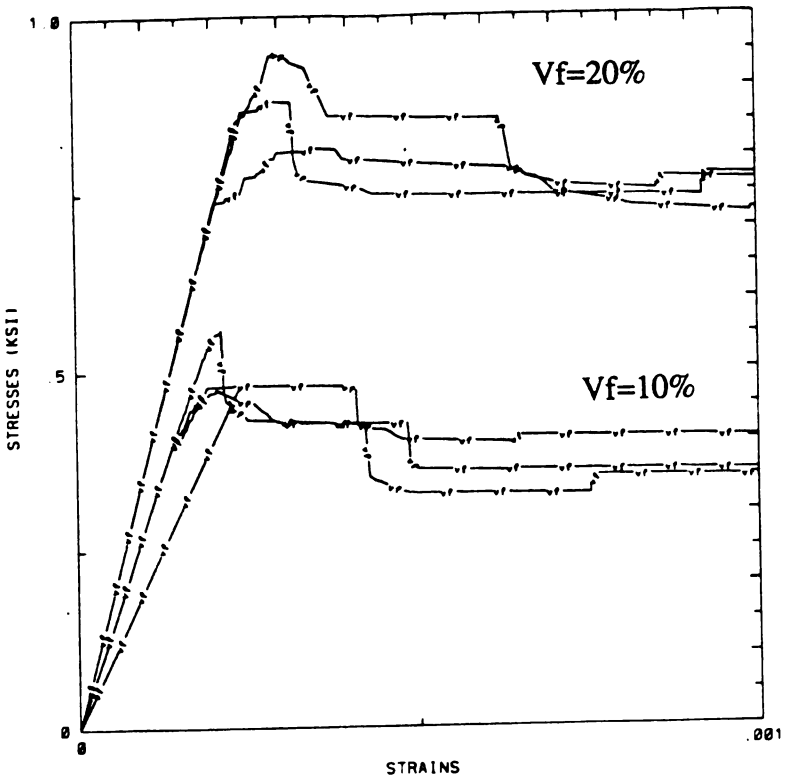
(b) Vf=0%



(c) Vf=20%

FIGURE 8.37 Effects of Fiber Content on Hardwood Fiber Cement Composites Stress Strain Curves.

Softwood



Hardwood

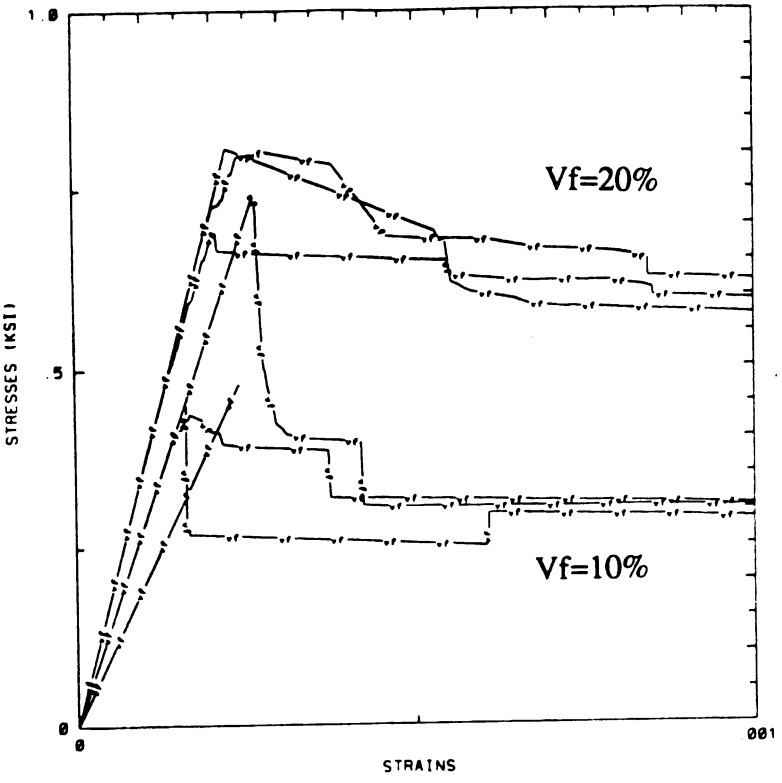
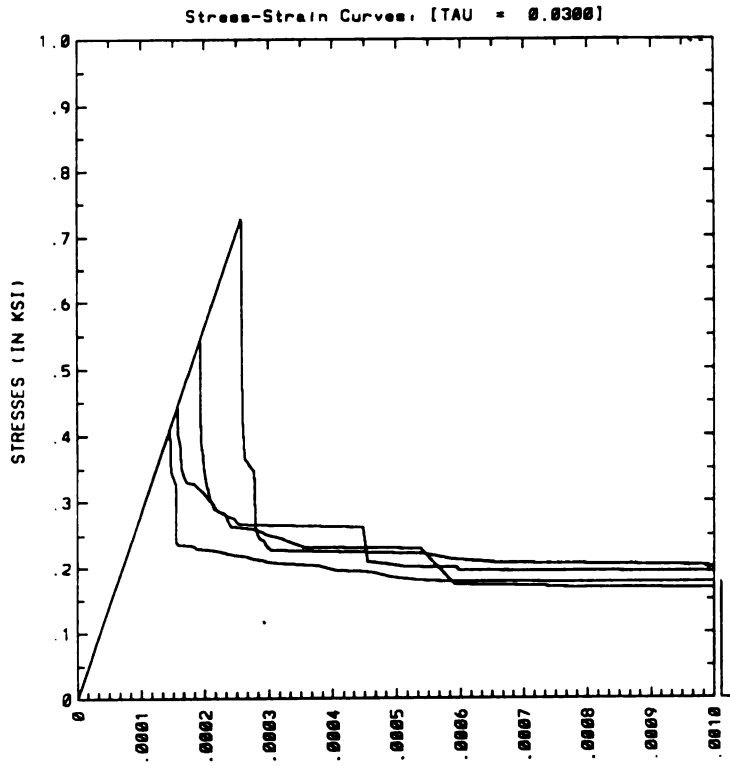


FIGURE 8.38 Comparison Between Softwood and Hardwood Fiber Reinforced Cement Composites Stress-Strain Curves.



Data Input

Fiber type: Softwood

Fiber Modulus: 10,295 ksi

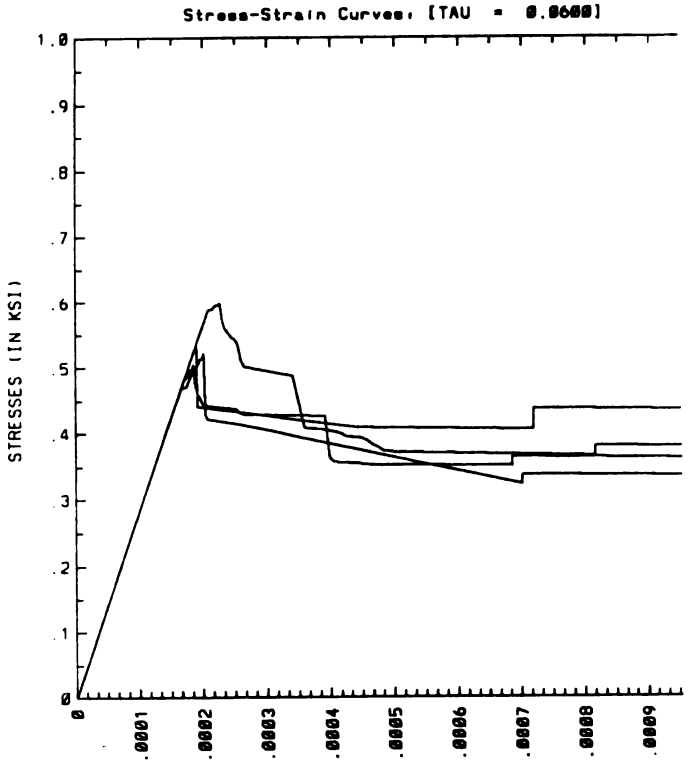
Fiber Length: 0.15 inches

Fiber Diameter: 0.0015 inches

Fiber Strength: 130.0 ksi

Matrix Modulus: 2,000 ksi

Fracture Toughness: 0.1 k(in)3/2



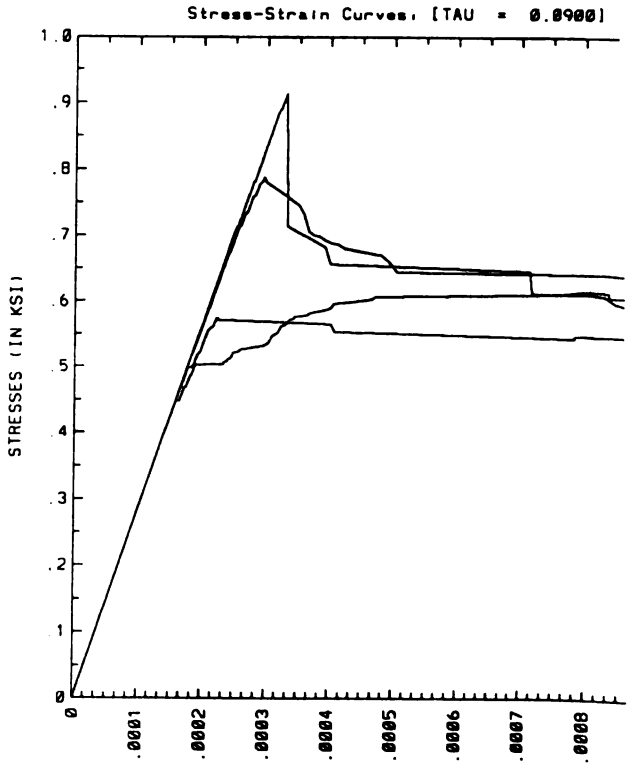


FIGURE 8.39 Effects of Interfacial Shear Strength on Softwood Fiber Cement Composites Stress-Strain Curves.

CHAPTER 9

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

9.1 Summary

This study presented a new approach to modeling the mechanics of the tensile behavior of fiber reinforced cement-based composites. The model predicts the tensile stress-strain curves of cement composites using general information regarding the material such as the fiber properties, the matrix properties, and the fiber-matrix interaction characteristics.

The study was motivated by the following facts:

- Despite the massive research that is going on throughout the world on cement based materials, relatively little is known about the mechanics of behavior of these materials (when compared with polymers, ceramics, and metals).
- Cement-based materials are evolving rapidly with advancements in technology; material models can thus help in the development and evaluation of new cement-based materials.
- Nowadays, fiber reinforcement constitutes a very active research area in concrete technology; experimental developments in this area need to be complemented with analytical investigations.
- In general, this model helps the researcher to systematically organize his or her theories about cement composites and deduce logical conclusions.
- Experimenting with a computer model costs less than experimenting with actual cement-based materials. Also, model experiments can be accomplished faster and easier.

A systematic approach was used in this investigation consisting of the following

stages:

(1) System Analysis: At this stage, the cement system is defined in terms of an input (tensile test conditions), a system (fiber reinforced cement-based specimen), and an output (stress-strain curve). Also, different system variables, elements, and the relationships are identified at this stage, the purpose of which was to relate the input and the cement material mechanisms of action in a way that the output (stress-strain curve) is predictable. In general, the information needed was a full understanding of the structure of cement-based materials, and a theory (fracture mechanics) that best describes the changes in the material structure and load resistance capacity as the tensile test is carried on.

(2) Model Synthesis: At this stage, the analysis accomplished in the previous stage is organized into logical structures and flow charts, and finally transformed into a computer program. Also, at this stage decisions regarding the hardware (computer systems, output devices,...), and software (programming language, and other tools) were made.

(3) Model Verification: This stage is concerned with checking and debugging the computer program of stage (2). The purpose of this stage is to make sure that the program gives the intended correct results.

(4) Model Validation: This stage establishes the degree of correlation between the model and the actual system by comparing the available actual system data with the results predicted by the model.

(5) Model Analysis (or Simulation): In this stage, experiments with the verified and validated model are carried out.

An introduction to the basic concepts of linear elastic fracture mechanics (LEFM) was presented, along with a thorough review of the literature regarding the applicability of LEFM to cement composites.

The analysis stage was accomplished by considering the following factors:

- The material structure of cement composites: The modelled structure recognizes cracks as an inherent characteristic of cement composites.
- Solution for the stress intensity factors of multi-cracked specimens: The solution is derived for an infinite plate with multiple cracks. This solution is based on the integral equations method. The stress intensity factors were modified by a geometry factor

to obtain the solution of the infinite plate adjusted for application to finite bodies.

- Fiber-matrix interaction: The mechanisms of fiber bridging of cracks is modelled using: (1) equilibrium of forces along the axis of each fiber, and (2) displacements compatibility between fibers and cracks.

- The stress-strain curve was modelled by considering the stages that the material undergoes as the input tensile displacement is increased. The stresses are computed as the average stresses (load divided by area). The strains are computed in two parts: one part is the linear component and is based on the average stress and the composite modulus of elasticity; the second strain component is due to the opening of the cracks as the load is applied, and it is based on the areas of the opened cracks. The stress-strain curve can be described in the following stages: (a) STAGE0: preload condition (stress=0, and strain=0); (b) STAGE1: in this stage, the aggregate interfacial cracks propagate to their maximum length possible at interface zones which depends on the average aggregate size; (c) STAGE*: This point on the stress-strain curve is characterized by the fact that no cracks have yet started propagating into the matrix; (d) STAGE2: During this stage, the matrix has just reached its breaking limit, that is, at least one interfacial crack has started propagating into the matrix; (e) STAGE3 (Prepeak): In this stage, fiber reinforcement enters into the picture by toughening the matrix through the bridging process; this stage is characterized by an increase in the material load resistance with increasing deformation; (f) STAGE4 (Peak): At this point, the material has reached its maximum capacity, and its load resistance can not increase any more; (g) STAGE5 (Postpeak): This stage is characterized by a drop in the load resistance with increasing deformation.

In the Synthesis phase of the modelling process, the theories outlined in the analysis stage were translated into flow charts and then into FORTRAN codes.

The model validation was done by statistically comparing eight experimental stress-strain curves to the results produced by the model. For this purpose, some unspecified fundamental properties of the tested materials were selected based on an optimization process aimed at reproducing the experimental stress-strain curves by the model. The desired optimum values of these fundamental material properties were all within acceptable ranges; a phenomenon which supports the validity of the model. During the comparison process, the stress-strain curves were represented in terms of three basic parameters: the peak stress, the strain at the peak stress, and the toughness (com-

puted as the area underneath the stress-strain curve). The comparison of these parameters was established by comparing the means of the previous parameters using the statistical T-Test method. The experimental results were comparable to the results produced by the model at a confidence level of 95%, with the model using input variables within acceptable ranges for the specific test conditions considered Also, in the validation phase of the model, the stability of the model with increasing number of cracks was established. It was concluded that the model outputs approach some limiting values as the number of cracks increases, and that a minimum of five to nine cracks will produce similar results as any higher number of cracks. It was also noticed that acceptable model results could be achieved with a number of cracks that is less than five.

The use of the model was demonstrated through the following case studies:

(1) Parametric studies with respect to steel and carbon fiber: In this case study, the effects of the composite material characteristics on the tensile stress-strain curve were verified. The composite characteristics are: fiber content (Vf), matrix fracture toughness (Kc), fiber length (Lf), Fiber diameter (Df), fiber-matrix bond strength (TAU), fiber ultimate strength (SIGULT), fiber modulus of elasticity (MODF), and matrix modulus of elasticity (MOD0). The trends in the variation of stress-strain curves were found to agree with what is established in the experimental state-of-the-art.

(2) Optimization of the composite performance with respect to steel and carbon fiber properties: In this application, the model was used to produce necessary data that were analyzed using an optimization software. The purpose of the analysis was to identify the fiber properties that produce the best overall composite characteristics. The fiber properties were their length, diameter, strength, modulus of elasticity, and the interfacial bond strength between fibers and matrix. The composite performance was quantified in terms of the peak tensile stress, the strain at the peak stress, and the material toughness (defined as the area underneath the stress-strain curve). It was concluded that the best performance is always characterized by thinner, longer, and stronger fibers. It was also concluded that there is an optimum value of interfacial bond strength that produces the best composite performance.

(3) Finally, the model was applied to cellulosic wood fiber-cement composites. This application was motivated by the lack of theoretical research information in this area, and its aim was to study the effects of fiber content and interfacial bond strength on the stress-strain curve characteristics of the composite. Two types of cellulosic wood fibers were used: softwood and hardwood. The ranges of the fiber content and interfacial shear

bond strength were within commonly used values. It was concluded that higher fiber contents and interfacial bond strengths improved the composite material performance. Also, it was concluded that softwood performance was relatively better than that of hardwood.

9.2 Conclusions

This research presented a systematic approach to the understanding of the tensile mechanical behavior of fiber reinforced cement-based composites. The approach is based on the following concepts:

(1) Detailed and realistic modelling of the structure of the cement composite and the interaction among the different composite constituents as the tensile mechanical test is carried on. The composite constituents are mainly: the matrix, fibres, cracks, and fine aggregates.

(2) Linear elastic fracture mechanics (LEFM) failure criteria were modified in a way that is compatible with the tensile behavior of cement composites. The modified LEFM criteria can be summarized as follows: (a) The basic fracture toughness component is due to the matrix (assumed linear); (b) The fine aggregates cause an in increase in the basic fracture toughness; (c) The fibers alter the stress intensity factors and not the fracture toughness by their crack-arrest action.

The review of literature concerned with the structure of cement based materials and LEFM applicability to cement composites revealed that cracks are inherent characteristics of cement composites and that fracture mechanics failure criteria are suitable approaches for explaining the mechanical behavior of cement composites. Also, the literature revealed that direct applications of LEFM to concrete and FRC in general are not certain.

The proposed model is a valid model for predicting the stress-strain curve of cement-based fiber reinforced materials in tension. The model characteristics are:

- A realistic representation of the structure of cement-based materials by considering multiple cracks.
- Recognizing the inherent variations between specimens by considering stochastic methods to generate each stress-strain curve.
- Linear Elastic Fracture Mechanics (LEFM) can be used to predict the stress-strain curve of fiber reinforced cement materials, based on the fracture toughness of the

paste only, and by incorporating the effects of the other constituents, such as fibers and aggregates, indirectly.

The use of the model was demonstrated through three case studies: (1) parametric studies with respect to the model input variables; (2) optimization of the cement composite performance with respect to carbon and steel fiber properties; and (3) application of the model to cellulosic wood fibers.

The results of the case studies provided the following benefits:

(1) Provided new insights into the behavior of fiber reinforced cement composites.

(2) established guidelines for refining the composite design to optimize their performance characteristics.

(3) Supported and reinforced the validation process of the model.

9.3 Recommendations

It is recommended that this model be used to establish relationships between the composite characteristics and the tensile stress-strain curve. These relations can be used as aids in the design and optimization process of fiber reinforced cement-based composites.

Also, it is recommended that further investigations be carried out along the steps and guidelines outlined in this work, by considering the following points:

- Improving the stress intensity factor computation techniques.
- improving the modeling process of the structure of the material, by considering different shapes of cracks, or by considering 3-dimensional cracks.
- Developing similar models for flexual, compression, and in general for any combined type of loading.
- Extending the approach to account for any type of fibers and cement-based matrices.

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Appendix A:

Program Source Code

APPENDEX A: Program Source Code

```
      PROGRAM FRCSIM1
c     this program is set for maximum number of 10 cracks (NC)
c     an maximum # of 20 integration points (M)


      IMPLICIT DOUBLE PRECISION (A - H , O - Z)


      DOUBLE PRECISION X(40),Y(40),TABLE(50,50),R(50,50),TEMP2(50)
+ ,BT(50),ME,TE1(10,10),TE2(10,10),TE3(10,10),AT(50),
+ ALPH(12)

      INTEGER NNN(50),DA,DB,DI,DE,C(50,50)
      CHARACTER*40 DSCRPT(50),NAMEA,NAMEB
      CHARACTER*2 DEC(3,12),REL(3,12)
      LOGICAL FLAG
      CHARACTER*20 FTYPE,FILE

      DOUBLE PRECISION MOD,MOD0,MODF,VARTEMP(10)
      DOUBLE PRECISION PSALL(10,10),P11ALL(10,10),PKALL(10,10)
+     ,EKALL(10,10),PFLALL(10,10),EFLALL(10,10),PLTALL(10,10)
+ ,TOGH1(10,10),TOGH2(10,10),E11ALL(10,10),ESALL(10,10),
+ ELTALL(10,10)
      INTEGER UN(10)
      CHARACTER*20 FIL(10)
      CHARACTER*9 HD
      CHARACTER*50 VAR,BUFF
      CHARACTER*60 TITLE
      COMMON/FBRDAT/F,MODF,FBL,FSPACE,AF,DF
      COMMON/MTRXDAT/TKI0,TKIC,W,H,D,MOD0,MOD,TAU

      COMMON/RSLTS1/P11,E11,PS,ES
      COMMON/RSLTPPK/PR,EPR,PPEAK,EPEAK
      COMMON/RSLTPOST/PPOST(2000),EPOST(2000),PFAIL,EFAIL
      COMMON/RSLTULT/PULT,EULT
      COMMON/SEED/ISEED
      COMMON/FRAC/IFRAC
      COMMON/CONTROLS/P1,NS1,DPMAX,DPMIN,NMAX,NMIN,MAXFLAG
      COMMON/MTRXNU/ANU
      COMMON/BNCM/NC,M
      COMMON/TOLS1/TOLS,TOL1
      COMMON/FSULT/SIGULT,FDMG
      COMMON/B4/W2,H2,D2
      COMMON/B10/IFLAG10
```

```
      COMMON/FIBFORC/FBRFRC(10)
      COMMON/CRKLOC/XBEG(10),XEND(10),YBEG(10),YEND(10),AA(10)
+ ,ALPHA(10)

      COMMON/FLAGPOST/JFLAG,CODP,NCRIT
      COMMON/COUNT/ICOUNT
      COMMON/FILELBL/NOUT,NSUM,NCONF,NFBR,NCOUNT

      COMMON/EPSIL/EPS
      COMMON/FILE/IFILE
      COMMON/FIBEFF/EFCT
      common/codpost/ipost,epeak2

      OPEN(51,FILE='frc2.dat',STATUS='OLD')


      READ(51,*)TITLE
      READ(51,*)NMAT,NTEST,NRAND
      READ(51,*)FTYPE,F,MODF,FBL,DF,IFBFLAG,SIGULT,FDMG
      PI=3.141592654
      READ(51,*)ISEED1,NL
      READ(51,*)P1,NS1,DPMAX,DPMIN,NMAX,NMIN,MAXFLAG
      READ(51,*)DPP,NLP
      READ(51,*)NBOND,NVOID,M
      READ(51,*)MOD0,TKI0,TAU,W,H,D,AGGRAD,AGGVOL
      aggrad=0.0
      READ(51,*)TOLS,TOL1
      READ(51,*)ITERPOST
      READ(51,*)NVAR,VAR,VARMIN,DELVAR
      READ(51,*)IFILE,ISTAT
      READ(51,*)ALTAU
      READ(51,*)CONFLEV
      READ(51,*)EFCT
      READ(51,*)EPSMAX

      WW=W

      ISEED=ISEED1

      IF(IFILE.EQ.1) OPEN(50,FILE='SUMALL',STATUS='NEW')


      IF(ISTAT.EQ.1) THEN
      OPEN(21,FILE='peak2.dat',STATUS='NEW')
      OPEN(22,FILE='togh12.dat',STATUS='NEW')
      OPEN(23,FILE='togh22.dat',STATUS='NEW')
```

```
OPEN(24,FILE='stpeak2.dat',STATUS='NEW')
ENDIF


IF(IFILE.EQ.1) THEN
OPEN(49,FILE='STRSVAR',STATUS='NEW')
OPEN(48,FILE='STRNVAR',STATUS='NEW')
ENDIF

IF(ISTAT.EQ.1) THEN
WRITE(21,*)NVAR
WRITE(22,*)NVAR
WRITE(23,*)NVAR
WRITE(24,*)NVAR
ENDIF


DO 1002 IVAR=1,NVAR

II=IVAR-1

IF(VAR.EQ.'NRAND')THEN
NRAND=INT(VARMIN)+II*INT(DELVAR)
VARTEMP(IVAR)=NRAND

ELSEIF(VAR.EQ.'F')THEN
F=VARMIN+II*DELVAR
PRINT*,'IVAR=',IVAR,'F=',F

VARTEMP(IVAR)=F

ELSEIF(VAR.EQ.'MODF')THEN
MODF=VARMIN+II*DELVAR
VARTEMP(IVAR)=MODF

ELSEIF(VAR.EQ.'FBL')THEN
FBL=VARMIN+II*DELVAR
VARTEMP(IVAR)=FBL

ELSEIF(VAR.EQ.'DF')THEN
DF=VARMIN+II*DELVAR
VARTEMP(IVAR)=DF

ELSEIF(VAR.EQ.'SIGULT')THEN
SIGULT=VARMIN+II*DELVAR
VARTEMP(IVAR)=SIGULT
```

```
ELSEIF(VAR.EQ.'FDMG')THEN
FDMG=VARMIN + II*DELVAR
VARTEMP(IVAR)=FDMG

ELSEIF(VAR.EQ.'DPMAX')THEN
DPMAX=VARMIN+II*DELVAR
VARTEMP(IVAR)=DPMAX

ELSEIF(VAR.EQ.'DPMIN')THEN
DPMIN=VARMIN+II*DELVAR
VARTEMP(IVAR)=DPMIN

ELSEIF(VAR.EQ.'DPP')THEN
DPP=VARMIN+II*DELVAR
VARTEMP(IVAR)=DPP

ELSEIF(VAR.EQ.'NC')THEN
NBOND=INT(VARMIN)/2 + II*INT(DELVAR)/2
NVOID=NBOND
NC=NVOID+NBOND
VARTEMP(IVAR)=NC

ELSEIF(VAR.EQ.'M')THEN
M=INT(VARMIN)+II*INT(DELVAR)
VARTEMP(IVAR)=M

ELSEIF(VAR.EQ.'MOD0')THEN
MOD0=VARMIN+II*DELVAR
VARTEMP(IVAR)=MOD0

ELSEIF(VAR.EQ.'TKI0')THEN
TKI0=VARMIN+II*DELVAR
VARTEMP(IVAR)=TKI0

ELSEIF(VAR.EQ.'TAU')THEN
TAU=VARMIN+II*DELVAR
VARTEMP(IVAR)=TAU

ELSEIF(VAR.EQ.'TOL')THEN
TOLS=VARMIN+II+DELVAR
TOL1=TOLS
VARTEMP(IVAR)=TOLS

ELSE
ENDIF
```

```
      WRITE(BUFF,992)IVAR
992   FORMAT('OUT',I1)
      NOUT=30+IVAR
      IF(IFILE.EQ.1) OPEN(NOUT,FILE=BUFF,STATUS='NEW')

      WRITE(BUFF,993)IVAR
993   FORMAT('SUM',I1)
      NSUM=40+IVAR
      IF(IFILE.EQ.1) OPEN(NSUM,FILE=BUFF,STATUS='NEW')

      WRITE(BUFF,994)IVAR
994   FORMAT('CONF',I1)
      NCONF=50+IVAR
      IF(IFILE.EQ.1) OPEN(NCONF,FILE=BUFF,STATUS='NEW')

      WRITE(BUFF,995)IVAR
995   FORMAT('FBR',I1)
      NFBR=60+IVAR
      IF(IFILE.EQ.1) OPEN(NFBR,FILE=BUFF,STATUS='NEW')

      WRITE(BUFF,996)IVAR
996   FORMAT('COUNT',I1)
      NCOUNT=70+IVAR
      IF(IFILE.EQ.1) OPEN(NCOUNT,FILE=BUFF,STATUS='NEW')



      AF=PI*DF**2/4.0

      NC=NBOND+NVOID
      MOD=MODF*F+(1-F)*MOD0
      CALL KIAGG(TKI0,TKIC,B,AGGRAD,AGGVOL)
      CALL FBSPACE(IFBFLAG)
      DLP=FSPACE*NLP
      NBS=4
      W2=W
      H2=H
      D2=D
      IFRAC=0


      CALL OUTPUT0(TITLE,NTEST,NMAT,NRAND,B)

      IF(ISTAT.EQ.1) THEN
      WRITE(BUFF,17)IVAR,VAR,VARTEMP(IVAR)
```

```
 17     FORMAT(' TREATMENT LEVEL:',I2,' ',A5,'=',F8.5)
        WRITE(21,19)NRAND,BUFF
        WRITE(22,19)NRAND,BUFF
        WRITE(23,19)NRAND,BUFF
        WRITE(24,19)NRAND,BUFF
 19     FORMAT(I3,A50)
        ENDIF



        TAU1=TAU


        DO 10 JSIM=1,NRAND

        ipost=0
        TAU=TAU1

        CALL FRCINIT(NC,M,NBS)
        IF(NTEST.EQ.1)CALL SIM1(NBOND,NVOID,W,H,D,JSIM)



        STRAIN=0.
        ICOUNT=1

        IF(IFILE.EQ.1) THEN
        DO 99 KK=1,NC

        WRITE(NCONF,*)XBEG(KK),YBEG(KK),XEND(KK),YEND(KK)
        WRITE(NFBR,*)STRAIN,FBRFRC(KK)

 99     CONTINUE
        ENDIF

        IFRAC=0
        IFLAG10=0

        UN(JSIM)=80+(IVAR-1)*NRAND+JSIM
        WRITE(BUFF,997)IVAR,JSIM
 997    FORMAT('PLOT',I1,I1)

        IF(IFILE.EQ.1) OPEN(UNIT=UN(JSIM),FILE=BUFF,STATUS='NEW')

C       IF(NTEST.EQ.2)CALL SIM2
C       IF(NTEST.EQ.3)CALL SIM3
```

```
C       IF(NTEST.EQ.4)CALL SIM4
C       CALL FRCINIT(NC,M,NBS)
        CALL OUTPUT1(UN(JSIM))
        IFLAG10=0
        P100=P1
        JFLAG=0
        CALL AS1(P100,NC,AA)
        CALL FILL0S(NL,MOD,ES,UN(JSIM))
        SS=PS/W/D
        IF(IFILE.EQ.1)write(nout,*)SS,ES
        IF(IFILE.EQ.1)WRITE(UN(JSIM),*)ES,SS
        CALL FILLS1(NS1,W,D,UN(JSIM))
        S11=P11/W/D
        IF(IFILE.EQ.1)write(nout,*)S11,E11
        IF(IFILE.EQ.1)WRITE(UN(JSIM),*)E11,S11
        IFLAG10=1

        ICOUNT=ICOUNT+1

        IF(IFILE.EQ.1)THEN
        DO 1001 I11=1,NC
        WRITE(NFBR,*) E11,FBRFRC(I11)
1001    CONTINUE
        ENDIF

        PRINT*,'***** WORKING ... ON MATERIAL # ',IVAR
        PRINT*,' ... ON SPECIMEN # ',JSIM
        PRINT*,'TAU AT PREPEAK STAGE = ',TAU

        CALL PREPEAK(TKIC,NC,W,D,NPRE,UN(JSIM))
        epeak2=epeak

        IF(IFILE.EQ.1) THEN
        DO 98 KK=1,NC

        WRITE(NCONF,*)XBEG(KK),YBEG(KK),XEND(KK),YEND(KK)

98      CONTINUE
        ENDIF

        IFRAC=1

        TAU=TAU1
        PRINT*,'***** '
        PRINT*,'PREPEAK IS DONE'
```

```
      ipost=1
      CALL POST(DPP,DLP,W,D,TKIC,NPOST,UN(JSIM))
      PRINT*,'******'
      PRINT*,'POST-PEAK 1 IS DONE'

      IF(IFILE.EQ.1) THEN
      DO 97 KK=1,NC

      WRITE(NCONF,*)XBEG(KK),YBEG(KK),XEND(KK),YEND(KK)

 97   CONTINUE
      WRITE(NCONF,*)XBEG(NCRIT),YBEG(NCRIT),XEND(NCRIT),YEND(NCRIT)
      ENDIF

      JFLAG=1
      TAU=TAU1*ALTAU
      CALL POST2(H,W,D,UN(JSIM),MOD,P11,ITERPOST,TOGH3,epsmax)

      PRINT*,'******'
      PRINT*,'POST-PEAK 2 IS DONE'
      PRINT*,'******'
      PRINT*,'******'
      IF(IFILE.EQ.1) THEN
      DO 96 KK=1,NC
      WRITE(NCONF,*)XBEG(KK),YBEG(KK),XEND(KK),YEND(KK)
 96   CONTINUE
      WRITE(NCONF,*)XBEG(NCRIT),YBEG(NCRIT),XEND(NCRIT),YEND(NCRIT)
      ENDIF

CCC   CALL OUTPUT2
C     CALL PLOT(NL,NS1,NPRE,NPOST)

C NOTE THE FOLLOWING ARRAYS CONTAIN STRESSES & NOT LOADS
      SSS=PS/W/D
      PSALL(IVAR,JSIM)=SSS
      ESALL(IVAR,JSIM)=ES
      SS11=P11/W/D
      P11ALL(IVAR,JSIM)=SS11
      E11ALL(IVAR,JSIM)=E11
      SSPK=PPEAK/W/D
      PKALL(IVAR,JSIM)=SSPK
      EKALL(IVAR,JSIM)=EPEAK

c     PFAIL=PPEAK
```

```
c       EFAIL=EPEAK

        SSFL=PFAIL/W/D
        PFLALL(IVAR,JSIM)=SSFL
        EFLALL(IVAR,JSIM)=EFAIL

        SSULT=PULT/W/D
        PLTALL(IVAR,JSIM)=SSULT
        ELTALL(IVAR,JSIM)=EULT

        TOGH1(IVAR,JSIM)=ES*SSS/2. + (E11-ES)*(SSS+(SS11-SSS)/2.)
+ + (EPEAK-E11)*(SS11+(SSPK-SS11)/2.)*1.2
        TOGH2(IVAR,JSIM)=TOGH1(IVAR,JSIM) + TOGH3

        IF(IFILE.EQ.1)WRITE(NCOUNT,*)ICOUNT

10      CONTINUE

        TAU=TAU1

        IF(ISTAT.EQ.1) THEN
        WRITE(21,*)(PKALL(IVAR,IJK),IJK=1,NRAND)
        WRITE(22,*)(TOGH1(IVAR,IJK),IJK=1,NRAND)
        WRITE(23,*)(TOGH2(IVAR,IJK),IJK=1,NRAND)
        WRITE(24,*)(EKALL(IVAR,IJK),IJK=1,NRAND)
        ENDIF


        IF(NRAND.GT.1) THEN
        CALL STAT(PSALL,NRAND,PSMEAN,PSS2,PSST,IVAR)
        CALL STAT(ESALL,NRAND,ESMEAN,ESS2,ESST,IVAR)
        CALL STAT(P11ALL,NRAND,P11MEAN,P11S2,P11ST,IVAR)
        CALL STAT(E11ALL,NRAND,E11MEAN,E11S2,E11ST,IVAR)
        CALL STAT(PKALL,NRAND,PKMEAN,PKS2,PKST,IVAR)
        CALL STAT(EKALL,NRAND,EKMEAN,EKS2,EKST,IVAR)
        CALL STAT(PFLALL,NRAND,PFLMEAN,PFLS2,PFLST,IVAR)
        CALL STAT(EFLALL,NRAND,EFLMEAN,EFLS2,EFLST,IVAR)
        CALL STAT(PLTALL,NRAND,PLTMEAN,PLTS2,PLTST,IVAR)
        CALL STAT(ELTALL,NRAND,ELTMEAN,ELTS2,ELTST,IVAR)

        ENDIF

        PSMIN=PSMEAN-PSST
        PSMAX=PSMEAN+PSST
        ESMIN=ESMEAN-ESST
        ESMAX=ESMEAN+ESST
```

```
P1MIN=P11MEAN-P11ST
P1MAX=P11MEAN+P11ST
E1MIN=E11MEAN-E11ST
E1MAX=E11MEAN+E11ST

PKMIN=PKMEAN-PKST
PKMAX=PKMEAN+PKST
EKMIN=EKMEAN-EKST
EKMAX=EKMEAN+EKST

PFLMIN=PFLMEAN-PFLST
PFLMAX=PFLMEAN+PFLST
EFLMIN=EFLMEAN-EFLST
EFLMAX=EFLMEAN+EFLST

PLTMIN=PLTMEAN-PLTST
PLTMAX=PLTMEAN+PLTST
ELTMIN=ELTMEAN-ELTST
ELTMAX=ELTMEAN+ELTST

IF(IFILE.EQ.1) THEN
WRITE(50,*)ESMIN,ESMAX,PSMIN,PSMAX,ESMEAN,PSMEAN
WRITE(50,*)E1MIN,E1MAX,P1MIN,P1MAX,E11MEAN,P11MEAN
WRITE(50,*)EKMIN,EKMAX,PKMIN,PKMAX,EKMEAN,PKMEAN
WRITE(50,*)EFLMIN,EFLMAX,PFLMIN,PFLMAX,EFLMEAN,PFLMEAN
WRITE(50,*)ELTMIN,ELTMAX,PLTMIN,PLTMAX,ELTMEAN,PLTMEAN

WRITE(49,*)VARTEMP(IVAR),PSMIN,PSMEAN,PSMAX,PSST
WRITE(49,*)VARTEMP(IVAR),P1MIN,P11MEAN,P1MAX,P11ST
WRITE(49,*)VARTEMP(IVAR),PKMIN,PKMEAN,PKMAX,PKST
WRITE(49,*)VARTEMP(IVAR),PFLMIN,PFLMEAN,PFLMAX,PFLST
WRITE(49,*)VARTEMP(IVAR),PLTMIN,PLTMEAN,PLTMAX,PLTST


WRITE(48,*)VARTEMP(IVAR),ESMIN,ESMEAN,ESMAX,ESST
WRITE(48,*)VARTEMP(IVAR),E1MIN,E11MEAN,E1MAX,E11ST
WRITE(48,*)VARTEMP(IVAR),EKMIN,EKMEAN,EKMAX,EKST
WRITE(48,*)VARTEMP(IVAR),EFLMIN,EFLMEAN,EFLMAX,EFLST
WRITE(48,*)VARTEMP(IVAR),ELTMIN,ELTMEAN,ELTMAX,ELTST



write(nout,100)
WRITE(NSUM,100)
```

```
100         FORMAT('1',//,25X,'S U M M A R Y O F R E S U L T S',//,
 + 18X,'STRESSES (KSI)',18X,'STRAINS',//,
 + 12X,'SS',7X,'S11',5X,'SPEAK',7X,'ES',10X,'E11',8X,'EPEAK',
 +         /)

          WRITE(NSUM,199)TITLE
199       FORMAT('0',//,25X,A40,//)

          DO 91 I=1,NRAND
          write(nout,101)PSALL(IVAR,I),P11ALL(IVAR,I),PKALL(IVAR,I),
 + ESALL(IVAR,I),E11ALL(IVAR,I),EKALL(IVAR,I)
          WRITE(NSUM,101)PSALL(IVAR,I),P11ALL(IVAR,I),PKALL(IVAR,I),
 + ESALL(IVAR,I),E11ALL(IVAR,I),EKALL(IVAR,I)
91        CONTINUE

          HD='MEAN'
          write(nout,102)HD,PSMEAN,P11MEAN,PKMEAN,ESMEAN,E11MEAN,EKMEAN
          WRITE(NSUM,102)HD,PSMEAN,P11MEAN,PKMEAN,ESMEAN,E11MEAN,EKMEAN

          HD='VARIANCE'
          write(nout,102)HD,PSS2,P11S2,PKS2,ESS2,E11S2,EKS2
          WRITE(NSUM,102)HD,PSS2,P11S2,PKS2,ESS2,E11S2,EKS2

          HD='ST. DEV.'
          write(nout,102)HD,PSST,P11ST,PKST,ESST,E11ST,EKST
          WRITE(NSUM,102)HD,PSST,P11ST,PKST,ESST,E11ST,EKST

102       FORMAT('0',/,1X,A8,3(2X,F7.5),3(2X,E10.3))
101       FORMAT('0',10X,3(F7.5,2X),3(E10.3,2X))

          ENDIF

1002      CONTINUE

 if(nvar.gt.1)then
C Start of statistical hypothesis test and anova

          OPEN(52,FILE='report2.stat',RECL=130,STATUS='NEW')

          WRITE(52,901)
901       FORMAT('1',//,125('*'),/,'*',123X,'*',/,'*',50X,
 + 'G E N E R A L D A T A',50X,'*',/,'*',123X,'*',/,125('*'),
 + 3(/,'*',123X,'*'),/)

          WRITE(52,902)TITLE,NMAT,NTEST,NRAND
902       FORMAT('0','*',7X,'TITLE: ',A30,5X,'MTR.-ID.(NMAT): ',
```

```
     + I2,5X,'TEST-ID.(ITEST): ',I2,5X,'NUMB.-OF-SPEC.(NRAND):',I2,
     + 3X,'*',2(/,'*',123X,'*'))

               WRITE(52,903)FTYPE,F,MODF,FBL,DF,SIGULT,FDMG,IFBFLAG
903            FORMAT(' ','*',4X,'FIBER CHARACTERISTICS INFORMATION',86X,'*',/,
     +         '*',4X,35('='),84X,'*',/,'*',123X,'*',/,
     + '*',7X,'FIBER TYPE',4X,'CONTENT (VF%)',4X,'MODULUS',4X,'LENGTH',
     + 4X,'DIAMETER',4X,'ULT. STRENGHT',4X,'DAMG. PORTION',4X,
     + 'SAPACING FLAG',5X,'*',/,'*',123X,'*',/,'*',7X,A10,
     + 4X,F13.8,2X,F11.4,2X,F6.4,2X,F10.8,
     + 2X,F15.6,4X,F13.10,8X,I2,12X,'*',/,'*',123X,'*',/)

               WRITE(52,904)MOD0,TKI0,TKIC,TAU,ALTAU,NBOND,NVOID,NC,M
904            FORMAT('0','*',4X,'MATRIX CHARACTERISTICS INFORMATION',85X,'*',/,
     + '*',4X,35('='),84X,'*',/,'*',123X,'*',/,'*',7X,'MTRX.-MOD.',4X,
     + 'MTRX.-FRAC.-TOGH.',4X,
     + 'TOT.-FRAC.-TOGH',4X,'FIB.-MTRX-BOND',4X,'REDC.TAU',4X
     + ,'NUMBER OF CRACKS',4X,'#INTEG-PNTS',/,
     + '*',7X,'MOD0',10X,'TKI0',17X,'TKIC',15X,'TAU',15X,'ALTAU',7X,
     + 'NBOND ','NVOID ','NC',10X,'M',/,'*',123X,'*',/,
     +         '*',7X,F10.4,3X,F10.5,10X,F10.5,9X,F10.6,10X,F6.4,5X,I3,3X,
     + I3,3X,I2,10X,I2,/,'*',123X,'*',/)

               WRITE(52,9005)W,D,H,AGGVOL,AGGRAD
9005 FORMAT('0','*',18X,' SPECIMEN DIMENTIONS',24X,'AGGREGATE CONTENT'
     +,/,20X,20('='),24X,17('='),//,10X,'WIDTH(IN.)',5X,'DEPTH(IN.)',
     +5X,'HEIGHT(IN.)',9X,'VOLUME FRACTION',4X,'RADIUS (SIZE)',/,
     +12X,'( W )',10X,'( D )',10X,'( H )',14X,'(AGGVOL)',12X,'(AGGRAD)'
     + ,/,10X,3(F10.6,5X),5X,2(F15.10,5X))

               WRITE(52,905)ISEED1,NL,P1,NS1,DPMAX,DPMIN,NMAX,NMIN,MAXFLAG
     + ,DPP,NLP,TOLS
905            FORMAT('0','*',4X,'PROGRAM CONTROL DATA',/,
     + '*',4X,21('='),//,'*',7X,'ISEED',5X,'NL',5X,'P1',5X,'NS1',5X,
     + 'DPMAX',
     + 5X,'DPMIN',5X,'NMAX',5X,'NMIN',5X,'MAXFLAG',5X,'DPP',5X,'NLP',
     + 5X,'TOLERANCE',/,'*',/,'*',7X,I5,5X,I2,2X,F8.5,2X,I3,2X,
     + F9.5,2X,F8.5,2X,
     + I4,5X,I4,5X,I5,5X,F9.5,2X,I3,5X,F10.8,/,'*',123X,'*',/)

               WRITE(52,906)NVAR,VAR,VARMIN,DELVAR,ITERPOST,IFILE,ISTAT
906 FORMAT('0','*',4X,'DATA CONTROLLING THE TREATMENT VARIABLE AND'
     + ,' OUTPUT CONTROL FLAGS',/,'*',4X,66('='),2(/,'*'),7X,
     + '# TREATS',2X,
     + 'TREAT. VAR.',2X,'LOWEST TREAT. VALUE',2X,'TREAT. INCREMNT',
     + 2X,'#POST PEK PNTS',2X,'OUTPT FILES FLAG',2X,
```

```
     + 'STAT. REPORT FLAG',/,'*',7X,'(NVAR)',4X,'(VAR)',8X,'(VARMIN)'
     + ,13X,
     + '(DELVAR)',9X,'(ITERPOST)',7X,'IFILE=0 NO, 1YES',1X,
     + 'ISTAT=0 NO,1 YES',2(/,'*'),7X,I3,7X,A5,8X,F16.8,5X,
     + F16.8,1X,I5,
     + 20X,I2,15X,I2,/,'*',123X,'*',/)

               WRITE(52,907)VAR,NVAR,NRAND
907            FORMAT('1',//,10X,'VARIABLE DEFINING TREATMENTS: ',A10,
     + 5X,'NUMBER OF TREATMENTS: ',I2,5X,
     + 'NUMBER OF SAMPLES PER TREATMENT: ',I2,//)


               WRITE(52,908)
908 FORMAT('0',27X,'|',24('-'),'D E P E N D E N T V A R I A B L E S'
     + ,23('-'),'|')

               WRITE(52,909)
909            FORMAT('0',1X,'LEV',1X,'TRET-VALUE',1X,
     + 'STRESS A*',1X,'STRAIN A*',1X,'STRESS A1',1X,'STRAIN A1',
     + 1X,'PEAK STRS',
     + 1X,'PEAK STRN',1X,'ULT-STRESS',1X,'ULT-STRAIN',1X,
     + 'TOUGHNESS1',1X,'TOUGHNESS2',/,
     + 2X,3('='),11(1X,10('=')),//)


               DO 119 I=1,NVAR
               DO 117 J=1,NRAND
               WRITE(52,910)I,VARTEMP(I),PSALL(I,J),ESALL(I,J),P11ALL(I,J)
     + ,E11ALL(I,J),PKALL(I,J),EKALL(I,J),PLTALL(I,J),ELTALL(I,J),
     + TOGH1(I,J),TOGH2(I,J)
117            CONTINUE
119            CONTINUE

910            FORMAT(' ',1X,I3,1X,11(F10.7,1X))


               REWIND 21
               REWIND 22
               REWIND 23
               REWIND 24


               JFILE=21
               FILE='PEAK.DAT'
               NEXT=10002
```

```
            GO TO 11000


10002       JFILE=22
            FILE='TOGH1.DAT'
            NEXT=10003
            GO TO 11000


10003       JFILE=23
            FILE='TOGH2.DAT'
            NEXT=10004
            GO TO 11000

10004       JFILE=24
            FILE='STPEAK.DAT'
            NEXT=0
            GO TO 11000



******* 1 *****READ DATA ******************

11000       CONTINUE

c read # of treatment levels (or variables)
            READ(JFILE,*)NTREAT
            DO 75 I=1,NTREAT
C read description of treatment and number of entries for each treat.
            READ(JFILE,76)NNN(I),DSCRPT(I)
76          FORMAT(I3,A20)
c read entries values for each treatment
            READ(JFILE,*)(TABLE(I,J),J=1,NNN(I))
75          CONTINUE



****** 3 ********* TEST INVOLVING TWO MEAN *****************



            write(52,191)file
191         format('1',//,125('*'),/,'***** COMPARISON OF MEANS:',
 + 'for file: ',a20,/,125('*'),/)

            PP=CONFLEV
```

```
            WRITE(52,291)INT(PP)
291         FORMAT(76X,'|',37('-'),'|',/,
 + 76X,'|','SMALLEST SIGNIFICANCE TO REJECT NULL |',/,
 + 76X,'|','HYPOTHESES(NL)&ACCEPT ALTERNATE (AL) |',/,
 + '|',6('-'),2('|',5('-'),'|',7('-'),'|',7('-')),
 + 4('|',7('-')),3('|',9('-')),'|',15('-'),/,
 + '|INDXES|SAMPL|MEAN(X)| STD(X)|SAMPL|MEAN(Y)| STD(Y)|',
 + 'MEAN OF|STD.ERR|'
 + ,' T-TEST|T-TEST |NL:X-Y>=0|NL:X-Y<=0|NL:X-Y= 0|'
 + ,I2,'%CONF. INTRVL',/,
 + '| X Y |SIZ:X|',2(7X,'|'),'SIZ:Y|',2(7X,'|'),' (X-Y) |',
 + ' (X-Y) | D.O.F |VAL(T=)|AL:X-Y <0|AL:X-Y >0|AL:X-Y<>0|',
 + ' ON DIFFERENCE',2(/,'|',6X,'|',2(5X,'|',7X,'|',7X,'|'),
 + 4(7X,'|'),3(9X,'|')))
```

```
c read treatment numbers to be studied

            DO 19000 IVAR2=1,(NVAR-1)
            DO 19001 IVAR3=(IVAR2+1),NVAR

            IX=IVAR2
            IY=IVAR3
            N1=NNN(IX)
            N2=NNN(IY)
            DO 78 I=1,N1
            X(I)=TABLE(IX,I)
78          CONTINUE
            DO 79 I=1,N2
            Y(I)=TABLE(IY,I)
79          CONTINUE

            HV=0.

C calculate mean, std. dev. for 1rst variable
            CALL SUB29000(X,AMEAN,STD,N1)
            AM1=AMEAN
            S1=STD
C calculate mean, std. dev. for 2nd variable
            CALL SUB29000(Y,AMEAN,STD,N2)
```

```
            AM2=AMEAN
            S2=STD
            D1=1
            D2=N1+N2-2
            P=(100+PP)/2.
            CALL SUB33500(P,F,D1,D2,A)
            T=SQRT(F)
            Z=AM1-AM2-HV
            SS=SQRT((((N1-1)*S1**2+(N2-1)*S2**2)/D2)*(N1+N2)/(N1*N2))
            Z=Z/SS
            F=Z*Z
            CALL SUB34000(A,D1,D2,F)
            DELM=AM1-AM2

C

            TE1(IVAR2,IVAR3)=A/2.
            IF(DELM.GT.HV)TE1(IVAR2,IVAR3)=1-A/2.
            TE2(IVAR2,IVAR3)=A/2.
            IF(DELM.LT.HV)TE2(IVAR2,IVAR3)=1-A/2.
            TE3(IVAR2,IVAR3)=A

            ALW=DELM-SS*T
            UP=DELM+SS*T

            WRITE(52,292)IVAR2,IVAR3,N1,AM1,S1,N2,AM2,S2,DELM,SS,
     + INT(D2),Z,TE1(IVAR2,IVAR3),TE2(IVAR2,IVAR3),
     + TE3(IVAR2,IVAR3),ALW,UP

292 FORMAT('|',1X,I1,1X,I1,2X,'|',2(1X,I3,1X,'|',F7.4,'|',F7.4,'|')
     + ,2(F7.4,'|'),1X,I5,1X,'|',F7.3,3('|',1X,F7.4,1X),'|',
     + F7.4,'_',F7.4)



19001       continue
19000       continue



            ALPH(1)=.40
            ALPH(2)=.35
            ALPH(3)=.30
            ALPH(4)=.25
            ALPH(5)=.20
```

```
            ALPH(6)=.15
            ALPH(7)=.1
            ALPH(8)=.05
            ALPH(9)=.02
            ALPH(10)=.01
            ALPH(11)=.005
            ALPH(12)=.001

            WRITE(52,19007)(INT(100*ALPH(I1)),I1=1,10),
     + (INT(100*ALPH(I2)),I2=1,10)
     + ,(INT(100*ALPH(I3)),I3=1,10)

19007       FORMAT(//,2X,'D',5X,'|',' For a given significance',
     + 'level (40% to 1%) do we reject (R)',
     + ' or accept (A) the',/,2X,'E T',3X,'|',
     + 'null hypotheses shown below, and what kind of relation',
     + ' is valid between the 2 treatmment indeces',/,2x,'C A',3x,
     + '|',93('_'),/,2x,'I B',3x,'|','NULL HYPOTHESES:',
     + ' MEAN(X-Y)>=0||'
     + ,'NULL HYPOTHESES: MEAN(X-Y)<=0||NULL HYPOTHESES:',
     + ' MEAN(X-Y) =0||'
     + ,/,2X,'S L',3X,'|','ALTR HYPOTHESES: MEAN(X-Y) <0||'
     + ,'ALTR HYPOTHESES: MEAN(X-Y) >0||',
     + 'ALTR HYPOTHESES: MEAN(X-Y)<>0||',/,2X,'I E',3X,'|',
     + /,2X,'O',5X,
     + '|',' SIGNIFICANCE LEVEL (%) ||',
     + ' SIGNIFICANCE LEVEL (%) ||'
     + ,' SIGNIFICANCE LEVEL (%) ||',/,100('_'),/,
     + '|INDXES|',3(10(I2,'|'),'|'),/,100('_'))

            DO 19002 IVAR2=1,(NVAR-1)
            DO 19003 IVAR3=(IVAR2+1),NVAR

            DO 19004 IHYP=1,3
            DO 19004 ISIG=1,12
            DEC(IHYP,ISIG)=' A'
19004       CONTINUE

            DO 19005 ISIG=1,12
            REL(1,ISIG)='NS'
            REL(2,ISIG)='<='
            REL(3,ISIG)=' ='

            IF(ALPH(ISIG).GT.TE1(IVAR2,IVAR3)) THEN
            DEC(1,ISIG)=' R'
            REL(1,ISIG)=' <'
```

```
            ENDIF

            IF(ALPH(ISIG).GT.TE2(IVAR2,IVAR3)) THEN
            DEC(2,ISIG)=' R'
            REL(2,ISIG)='NS'
            ENDIF

            IF(ALPH(ISIG).GT.TE3(IVAR2,IVAR3)) THEN
            DEC(3,ISIG)=' R'
            REL(3,ISIG)='<>'
            ENDIF
19005       CONTINUE

            WRITE(52,19006)IVAR2,IVAR3,(DEC(1,ISIG1),ISIG1=1,10),
     + (DEC(2,ISIG2),ISIG2=1,10),(DEC(3,ISIG3),ISIG3=1,10),
     + (REL(1,ISIG4),ISIG4=1,10),(REL(2,ISIG5),ISIG5=1,10),
     + (REL(3,ISIG6),ISIG6=1,10)

19006       FORMAT('|',1X,I1,1X,I1,2X,'|',3(10(A2,'|'),'|'),
     + /,'|rition|',3(10(A2,'|'),'|'))

19003       CONTINUE
19002       CONTINUE


********** 5 ******* HYPOTHESES TESTS INVOLVING TWO VARIANCES **********

15000       CONTINUE

********* 6 ******** ONE-WAY ANOVA ************************

16000       CONTINUE
            write(52,521)FILE
521         FORMAT('0',/,125('*'),/,'***** ONE-WAY ANOVA ******',
     + ' FILE: ',A10,/,125('*'),/)
            DO 81 I=1,2
            DO 81 J=1,NTREAT
            R(I,J)=0
81          CONTINUE
            NA=0
            T=0
            T2=0
            DO 82 I=1,NTREAT
            DO 82 J=1,NNN(I)
            R(1,I)=R(1,I)+TABLE(I,J)
            R(2,I)=R(2,I)+1
```

```
            NA=NA+1
            T=T+TABLE(I,J)
            T2=T2+TABLE(I,J)*TABLE(I,J)
 82         CONTINUE
            T=T*T/REAL(NA)
            T2=T2-T
            TC=0
            D1=NTREAT-1
            D2=NA-D1-1

            DO 30 I=1,NTREAT
            TC=TC+(R(1,I)/R(2,I))*R(1,I)
            R(1,I)=R(1,I)/R(2,I)
 30         CONTINUE

            TC=TC-T
            SE=T2-TC

            TEMP=D2*SE
            IF(TEMP.EQ.0)THEN
            F=1.0E20
            ELSE
            F=(TC/REAL(D1))/(SE/REAL(D2))
            ENDIF
 C calculate significance level

            CALL SUB34000(A,D1,D2,F)
            write(52,522)
522         FORMAT('0','treatment index',5x,' ------- description ------',
+ 5x,' mean ',5x,'Number of samples',/)

            DO 40 I=1,NTREAT
            write(52,523)I,DSCRPT(I),R(1,I),NNN(I)
40          CONTINUE
523         format('0',7x,i2,11x,a28,5x,f10.6,10x,i2)

            write(52,*)' '
write(52,*)'SOURCE ---- SUM OF ------------------- DEG. OF'
+,"------MEAN ------------ F STAT ---------------- SMLEST SIG.'
write(52,*)'OF ERROR---- SQUARS ------------------- FRDM. '
+,"  ------SQURS REJECT NULL'
write(52,*)'======== ====== ======='
+,'  ==== ====== ==========='
            write(52,*)' '
            TEMP=TC/D1
            write(52,*)'BTWN.TRTS',TC,int(D1),TEMP,F,A
```

```
            TEMP=SE/D2
            write(52,*)'WTHN.TRTS',SE,int(D2),TEMP
            write(52,*)' (error)'
            NTOT=D1+D2
            write(52,*)'-----------------------------------------------------'
            write(52,*)'TOTAL ',T2,NTOT
            write(52,*)' '
            write(52,*)' TOTAL NUMBER OF DATA ENTRIES = ',NA


            IF(NEXT.EQ.10002) GO TO 10002
            IF(NEXT.EQ.10003) GO TO 10003
            IF(NEXT.EQ.10004) GO TO 10004

*************************************************************
 endif
18000       STOP
            END

*********************************************************
*********************************************************
            SUBROUTINE SUB33500(P,F,D1,D2,A)
            IMPLICIT DOUBLE PRECISION (A - H , O - Z)

C binary search for F value matching probability

            P=(100-P)/100.
            B1=10.

C  Find F upper bound

            DO 1 LL=1,10
                        F=B1
                        CALL SUB34000(A,D1,D2,F)
                        IF(A.LT.P) THEN
                        B1=B1*10
                        GO TO 19
                        ENDIF
                        B1=B1*10
1           CONTINUE
19          CONTINUE
            AL1=.05
            B1=1024
            DO 2 LL=1,100
                        F=(AL1+B1)/2.
                        CALL SUB34000(A,D1,D2,F)
```

```
                    IF(ABS(A-P).LT.0.001) GO TO 5
                    IF(A.GT.P)THEN
                    AL1=F
                    ELSE
                    B1=F
                    ENDIF
2           CONTINUE
5           CONTINUE
            RETURN
            END

*************************************************************
*************************************************************

            SUBROUTINE SUB34000(A,D1,D2,F)

            IMPLICIT DOUBLE PRECISION (A - H , O - Z)
C Calculate F probabilities


            IF((D1*D2*F).LE.0) THEN
            A=1.
            GO TO 6
            ENDIF
            IF(F.LT.1) GO TO 4
            V1=D1
            V2=D2
            F1=F
            GO TO 3
4           V1=D2
            V2=D1
            F1=1/F
3           V3=2./(9.*V1)
            V4=2./(9.*V2)
            ZZ=ABS(((1.-V4)*F1**(1./3.)-1+V3)/SQRT(V4*F1**(2./3.)+V3))
            IF(V2.LT.4.) ZZ=ZZ*(1.+.08*ZZ**4/V2**3)


            A=.5/(1.+ZZ*(.196854+ZZ*(.115194+ZZ*(.000344+ZZ*.019527))))**4

            IF(F.LT.1) A = 1-A

6           RETURN
            END

*************************************************************
```

```
*****************************************

      SUBROUTINE SUB29000(X,AMEAN,STD,NN)
      IMPLICIT DOUBLE PRECISION (A - H , O - Z)

C compute Mean, standard dev.

      DOUBLE PRECISION X(NN)

      AMEAN=0.
      STD=0.

      DO 1 I=1,NN
      AMEAN=AMEAN + X(I)
      STD=STD+X(I)*X(I)
1     CONTINUE
      AMEAN=AMEAN/REAL(NN)
      STD=SQRT((STD-AMEAN*AMEAN*NN)/(NN-1))

      RETURN
      END

*********************************


C     STOP
C     END

*****************************************************************

      SUBROUTINE STAT(Y,N,AMEAN,S2,S,IVAR)
      IMPLICIT DOUBLE PRECISION (A - H , O - Z)
      DOUBLE PRECISION Y(10,10)
      AMEAN=0
      S2=0
      S=0

      DO 1 I=1,N
      AMEAN=AMEAN+Y(IVAR,I)
1     CONTINUE
      AMEAN=AMEAN/REAL(N)

      DO 2 I=1,N
      S2=S2+(Y(IVAR,I)-AMEAN)**2
2     CONTINUE
      S2=S2/REAL(N-1)
```

```
      S=SQRT(S2)

C     RETURN
      END

*************************************************************************
      SUBROUTINE FRCINIT(NC,M,NBS)
      IMPLICIT DOUBLE PRECISION (A - H , O - Z)
      INTEGER ACTNC(10),ACTNCALL(10)
      CHARACTER*2 ITYPE(10),INSTBL(10)
      COMMON/B2/A(200,200),B(200),X(200)
      COMMON/CRKTYP/ITYPE,INSTBL
      COMMON/NF/NFGRPA(10),NFGRPB(10)
      COMMON/FIBFORC/FBRFRC(10)
      COMMON/ACTIVE/NACT,ACTNC,NACTALL,ACTNCALL
      COMMON/XFBR/NFTOTAL(10),XNEW(10,2000)
      common/tem/temp
      temp=0.0
      JJ=2*NC*M
      DO 10 I=1,NC
      DO 110 J=1,2000
      XNEW(I,J)=0
110   CONTINUE
      ACTNC(I)=0
      ACTNCALL(I)=0
      NFGRPA(I)=0
      NFGRPB(I)=0
      FBRFRC(I)=0.0
      ITYPE(I)='IN'
      INSTBL(I)='ST'
10    CONTINUE
      NACT=0
      NACTALL=0
      DO 20 J=1,JJ
      B(J)=0
      DO 30 K=1,JJ
      A(J,K)=0
30    CONTINUE
20    CONTINUE
      RETURN
      END
*************************************************************************
      SUBROUTINE FBSPACE(IFBFLAG)
      IMPLICIT DOUBLE PRECISION (A - H , O - Z)
      DOUBLE PRECISION MODF
      COMMON/FBRDAT/F,MODF,FBL,FSPACE,AF,DF
```

```
      COMMON/FILELBL/NOUT,NSUM,NCONF,NFBR,NCOUNT
      COMMON/FILE/IFILE

C F is NOT a %, rather it is the actual fiber volume fraction (e.g. .03 not
c 3%.
      FACT=1.
      IF(IFBFLAG.EQ.1)THEN
      FSPACE=13.8*DF/SQRT(100*F)*FACT
      ELSEIF(IFBFLAG.EQ.2)THEN
      FSPACE=(AF*FBL/F)**(1.0/3.)
      ELSE
      ENDIF

      IF(IFILE.EQ.1) THEN
      write(nout,*)' '
      write(nout,*)'AVERAGE FIBER SPACE=FSPACE=',FSPACE
      write(nout,*)' '
      ENDIF

      RETURN
      END
*************************************************************************
      SUBROUTINE OUTPUT0(TITLE,NTEST,NMAT,NRAND,B)
      IMPLICIT DOUBLE PRECISION (A - H , O - Z)
      DOUBLE PRECISION MOD0,MOD
      CHARACTER*60 TITLE
      COMMON/MTRXDAT/TKI0,TKIC,W,H,D,MOD0,MOD,TAU
      COMMON/FILELBL/NOUT,NSUM,NCONF,NFBR,NCOUNT
      COMMON/FILE/IFILE

      IF(IFILE.EQ.1) THEN

      IF(NTEST.EQ.1)THEN
      write(nout,100)TITLE,NTEST,NMAT,NRAND
100   FORMAT('1',//25X,'T E N S I O N T E S T S I M U L A T I O N'
+ //25X,A60,//25X,'NTEST= ',I1,2X,'NMAT= ',I1,2X,'NRAND= ',I3,//)
      IF(NMAT.EQ.0)WRITE(NOUT,101)
      IF(NMAT.EQ.1)WRITE(NOUT,102)
101   FORMAT('0',25X,'*** NO FIBERS AND NO COARSE AGGREGATE ARE USED'//)
102   FORMAT('0',25X,'*** FIBERS ARE USED,NO COARSE AGGREGATE IS USED'//)
      ELSE
      IF(NTEST.EQ.2)THEN
      ELSE
      IF(NTEST.EQ.3)THEN
      ELSE
      IF(NTEST.EQ.4)THEN
```

```
            ENDIF
            ENDIF
            ENDIF
            ENDIF
            write(nout,103)TKI0,B,TKIC
  103       FORMAT('1',//25X,'T O U G H N E S S O F M A T E R I A L',
     + /25X,40('*'),//25X,'PASTE TOUGHNESS, AS INPUT,= TKI0= ',F20.10/
     + 25X,'FACTOR OF AGGREGATE EFFECT ON TOUGHNESS=B= ',F20.10/
     + 25X,'MODIFIED TOUGHNESS=TKIC=',F20.10/,70('*'))

            ENDIF

            RETURN
            END
 ************************************************************************
            SUBROUTINE OUTPUT1(N)
            IMPLICIT DOUBLE PRECISION (A - H , O - Z)
            COMMON/FILELBL/NOUT,NSUM,NCONF,NFBR,NCOUNT
            COMMON/FILE/IFILE

            IF(IFILE.EQ.1) THEN

            write(nout,100)
  100       FORMAT('1',//)
            write(nout,*)'=============================================='
            write(nout,*)'==  ==='
            write(nout,*)'== S T R E S S S T R A I N V A L U E S ==='
            write(nout,*)'==  ==='
            write(nout,*)'=============================================='
            write(nout,*)' '
            S0=0
            E0=0
            write(nout,*)S0,E0
            WRITE(N,*)E0,S0

            ENDIF

            RETURN
            END
 ************************************************************************
            SUBROUTINE SIM1(NBOND,NVOID,W,H,D,JSIM)
            IMPLICIT DOUBLE PRECISION (A - H , O - Z)
            DOUBLE PRECISION L(10),L2(10),ALPHA2(10)
            COMPLEX Z0(10),Z02(10)
            COMMON/CRKLOC/XBEG(10),XEND(10),YBEG(10),YEND(10),L,
     + ALPHA(10)
```

```
      COMMON/BNCM/NC,M
      COMMON/CNBS/NBS,XB1(4),XE1(4),YB1(4),YE1(4)
      COMMON/SEED/ISEED
      COMMON/A2A3/A2(324),A3(100)
      COMMON/B1/M2,N2,Z0,L2,ALPHA2
      COMMON/FILELBL/NOUT,NSUM,NCONF,NFBR,NCOUNT
      COMMON/FILE/IFILE


      DO 10 I=1,324
C     XAGG(I)=RANDOM(ISEED)
C     YAGG(I)=RANDOM(ISEED)/4.0
      A2(I)=0.5*(RANDOM(ISEED)*0.006)
10    CONTINUE
      DO 20 I=1,NBOND
      Z0(I)=CMPLX(RANDOM(ISEED)*w,RANDOM(ISEED)*h)
      L(I)=0.5*(0.018+RANDOM(ISEED)*0.002)
      ALPHA(I)=0.
      XBEG(I)=REAL(Z0(I))-L(I)
      XEND(I)=REAL(Z0(I))+L(I)
      YBEG(I)=AIMAG(Z0(I))
      YEND(I)=AIMAG(Z0(I))

      Z02(I)=Z0(I)
      L2(I)=L(I)
      ALPHA2(I)=ALPHA(I)

20    CONTINUE
      NC=NBOND+NVOID

      N2=NC
      M2=M

      NBS=4
      DO 11 I=1,100
      A3(I)=0.5*(0.006*RANDOM(ISEED))
11    CONTINUE
      DO 30 I=NBOND+1,NC
      Z0(I)=CMPLX(RANDOM(ISEED)*w,RANDOM(ISEED)*h)
      L(I)=0.5*(0.01+0.03*RANDOM(ISEED))
      ALPHA(I)=0.
      XBEG(I)=REAL(Z0(I))-L(I)
      XEND(I)=REAL(Z0(I))+L(I)
      YBEG(I)=AIMAG(Z0(I))
      YEND(I)=AIMAG(Z0(I))
```

```
            Z02(I)=Z0(I)
            L2(I)=L(I)
            ALPHA2(I)=ALPHA(I)

 30         CONTINUE
C
            IF(IFILE.EQ.1)THEN

            write(nout,500)JSIM
500         FORMAT('1',//,25X,'RESULTS OF SIMULATION OF SPECIMEN#',2X,I2,///)
            write(nout,501)
501         FORMAT('0',25X,' *** SPECIMEN GEOMETRY ***',//)
            write(nout,502)H,W,D
502         FORMAT('0',24X,'H = HEIGHT = ',F6.4,'INCHES',
 +/,25X,'W = WIDTH = ',F6.4,'INCHES',
 +/,25X,'D = DEPTH = ',F6.4,'INCHES',//)

            write(nout,503)NBOND,NVOID,NC
503         FORMAT('0',25X,'INITIAL SIMULATED CRACKS CONFIGURATION',//,
 + 25X,'NUMBER OF BOND CRACKS = NBOND = ',I3,/,
 + 25X,'NUMBER OF VOID CRACKS = NVOID = ',I3,/,
 + 25X,'TOTAL NUMBER OF CRACKS = NC = ',I3,//)

            write(nout,504)
504         FORMAT('0',2X,' I ',8X,'Z0',9X,'XBEG',4X,'XEND',4X,'YBEG',
 + 4X,'YEND',5X,'L',6X,'ALPHA',//)

            DO 59 I=1,NC
 WRITE(NOUT,505)I,Z0(I),XBEG(I),XEND(I),YBEG(I),YEND(I),L(I)
 + ,ALPHA(I)
59          CONTINUE
505         FORMAT('0',2X,I3,8(2X,F6.4))
C
            ENDIF

            RETURN
            END
*******************************************************************************
            FUNCTION RANDOM(IDUM)
            IMPLICIT DOUBLE PRECISION (A - H , O - Z)

C FUNCTION RAN3(IDUM)
C IMPLICIT REAL*4(M)
C PARAMETER (MBIG=4000000.,MSEED=1618033.,MZ=0.,FAC=2.5E-7)
 PARAMETER (MBIG=1000000000,MSEED=161803398,MZ=0,FAC=1.E-9)
 DIMENSION MA(55)
```

```
      DATA IFF /0/
      IF(IDUM.LT.0.OR.IFF.EQ.0)THEN
      IFF=1
      MJ=MSEED-IABS(IDUM)
      MJ=MOD(MJ,MBIG)
      MA(55)=MJ
      MK=1
      DO 11 I=1,54
      II=MOD(21*I,55)
      MA(II)=MK
      MK=MJ-MK
      IF(MK.LT.MZ)MK=MK+MBIG
      MJ=MA(II)
   11 CONTINUE
      DO 13 K=1,4
      DO 12 I=1,55
      MA(I)=MA(I)-MA(1+MOD(I+30,55))
      IF(MA(I).LT.MZ)MA(I)=MA(I)+MBIG
   12 CONTINUE
   13 CONTINUE
      INEXT=0
      INEXTP=31
      IDUM=1
      ENDIF
      INEXT=INEXT+1
      IF(INEXT.EQ.56)INEXT=1
      INEXTP=INEXTP+1
      IF(INEXTP.EQ.56)INEXTP=1
      MJ=MA(INEXT)-MA(INEXTP)
      IF(MJ.LT.MZ)MJ=MJ+MBIG
      MA(INEXT)=MJ
      RAN3=MJ*FAC
      RANDOM=RAN3
      RETURN
      END

*************************************************************************
            SUBROUTINE KIAGG(TKI0,TKIC,B,AGGRAD,AGGVOL)
            IMPLICIT DOUBLE PRECISION (A - H , O - Z)
            DOUBLE PRECISION A(0:7)
            PARAMETER(PI=3.141592654)

            R0=AGGRAD
            V=AGGVOL

            IF(R0.NE.0) THEN
```

```
            A(0)=1.4555
            A(1)=2.1395
 A(2)=-1.1783
            A(3)=0.51965
            A(4)=-0.13085
            A(5)=0.018143
 A(6)=-0.001290
            A(7)=0.000036645
            C=0.5*SQRT(2*PI/3.0/V)*R0-R0
            B=0.0
            DO 10 I=0,7
            B=B+A(I)*(R0/C)**I
 10         CONTINUE
 c          B=1+(B-1.)/4.
            B=sqrt(B)
            ELSE
            B=1.
            ENDIF

            TKIC=TKI0*B
            RETURN
            END
*************************************************************************
            SUBROUTINE AS1(PP,NC,A)
            IMPLICIT DOUBLE PRECISION (A - H , O - Z)
            DOUBLE PRECISION MOD,MOD0,SRT(10),SLT(10),A(10)
            INTEGER ACTNC(10),ACTNCALL(10)
            COMMON/RSLTS1/P11,E11,PS,ES
            COMMON/MTRXDAT/TKI0,TKIC,W,H,D,MOD0,MOD,TAU
            COMMON/ACTIVE/NACT,ACTNC,NACTALL,ACTNCALL
            COMMON/DELEF/DE
            COMMON/TOLS1/TOLS,TOL1
            COMMON/B99/F
            COMMON/B100/SIFRP(10),SIFLP(10)
            COMMON/FILELBL/NOUT,NSUM,NCONF,NFBR,NCOUNT
            COMMON/FLAGPOST/JFLAG,CODP,NCRIT
            COMMON/FILE/IFILE

            F=0
            IFLAG=0
            P=PP
            CALL SIF(P)
            CALL CRIT(TKIC)
            IF(NACT.EQ.0) GO TO 10
            IF(NACT.GT.0) GO TO 20
```

```
10      IFLAG=0
        PMINUS=PP
11      IF(IFLAG.EQ.0) P=2*P
        IF(IFLAG.EQ.1) P=P+(PPLUS-PMINUS)/2.0
12      CALL SIF(P)
        CALL CRIT(TKIC)
C
        IF(NACT.EQ.0) THEN
                      PMINUS=P
                      GO TO 11
        ELSE
                      PPLUS=P
                      R1=RATIO1(PPLUS,PMINUS)
                      IF(R1.LE.TOL1) THEN
                                     P11=PPLUS

        DO 99 II=1,NC
        SRT(II)=SIFRP(II)
        SLT(II)=SIFLP(II)
99      CONTINUE

                                     GO TO 30
                      ELSE
                                     P=P-(PPLUS-PMINUS)/2.0
                                     IFLAG=1
                                     GO TO 12
                      ENDIF
        ENDIF
20      IFLAG=0
        PPLUS=PP
21      IF(IFLAG.EQ.0) P=P/2.0
        IF(IFLAG.EQ.1) P=P-(PPLUS-PMINUS)/2.0
22      CALL SIF(P)
        CALL CRIT(TKIC)
        IF(NACT.GT.0) THEN
                      PPLUS=P
                      GO TO 21
        ENDIF
        IF(NACT.EQ.0) THEN
                      PMINUS=P
                      R1=RATIO1(PPLUS,PMINUS)
                      IF(R1.LE.TOL1) THEN
                                     P11=PPLUS
                                     GO TO 30
                      ELSE
                                     P=P+(PPLUS-PMINUS)/2.0
```

```
                                    IFLAG=1
                                    GO TO 22
                        ENDIF
              ENDIF
30            CONTINUE


              MAX=1
              IF(NACT.EQ.0) THEN
              DO 2001 I19=2,NC
              IF(A(I19).GT.A(MAX)) MAX=I19
2001          CONTINUE
              NCRIT=MAX
              ELSE
              NCRIT=ACTNC(NACT)
              ENDIF

              CALL EFRAC(P11,E11)
C

              IF(IFILE.EQ.1)write(nout,*)'A1 IS FOUND: P11 & E11 ARE:',P11,E11
C
              P=P11
              CALL ELIN(EL,P)
              CALL EFRAC(P,EF)
              RS=RATIOS(EL,EF)
C             RS=DE/E11
              IF(RS.LE.TOLS) THEN
                        PS=P
                        GO TO 60
              ELSE
                        GO TO 40
              ENDIF
C
40            CONTINUE
              DELE=EF-EL
              DELP=DELE*W*D*MOD
              P=P-DELP
C
              CALL SIF(P)
              CALL CRIT(TKIC)
              CALL ELIN(EL,P)
              CALL EFRAC(P,EF)
C             RS=RATIOS(EL,EF)
              RS=DE/E11
              IF(RS.LE.TOLS) THEN
```

```
                    PS=P
                    GO TO 60
                    ELSE
                                GO TO 40
        ENDIF
C
 60     CONTINUE
        ES=(EL+EF)/2
C
        I99=IFILE
        IF(I99.EQ.1)write(nout,*)'POINT A* IS FOUND: PS & ES ARE: ',PS,ES
C

        DO 100 JJ=1,NC
        SIFRP(JJ)=SRT(JJ)
        SIFLP(JJ)=SLT(JJ)
100     CONTINUE

        RETURN
        END
*************************************************************************
        FUNCTION RATIO1(PPLUS,PMINUS)
        IMPLICIT DOUBLE PRECISION (A - H , O - Z)
        RATIO1=ABS(PPLUS-PMINUS)/PPLUS
        RETURN
        END
*************************************************************************
        FUNCTION RATIOS(EL,EF)
        IMPLICIT DOUBLE PRECISION (A - H , O - Z)
        RATIOS =2*ABS(EL-EF)/ABS(EF+EL)
        RETURN
        END
*************************************************************************
        SUBROUTINE ELIN(EL,P)
        IMPLICIT DOUBLE PRECISION (A - H , O - Z)
        DOUBLE PRECISION MOD0,MOD,MODF
        COMMON/MTRXDAT/TKIO,TKIC,W,H,D,MOD0,MOD,TAU
        COMMON/FBRDAT/F,MODF,FBL,FSPACE,AF,DF
C       M=METHD
C       IF(M.EQ.1) GO TO 1
C       IF(M.EQ.2) GO TO 2
 1      MOD=MODF*F+(1-F)*MOD0
        GO TO 3
 2      CONTINUE
 3      CONTINUE
        EL = P/W/D/MOD
```

```
      RETURN
      END
*************************************************************************
      SUBROUTINE EFRAC(P,EF)
      IMPLICIT DOUBLE PRECISION (A - H , O - Z)
      DOUBLE PRECISION SUMCOD(324),MOD,MOD0
      CHARACTER*2 ITYPE(10),INSTBL(10)
      COMMON/CRKTYP/ITYPE,INSTBL
      COMMON/MTRXDAT/TKI0,TKIC,W,H,D,MOD0,MOD,TAU
      COMMON/CRKLOC/XBEG(10),XEND(10),YBEG(10),YEND(10),A(10),
     + ALPHA(10)
      COMMON/BNCM/NC,M
      COMMON/A2A3/A2(324),A3(100)
      COMMON/FRAC/IFRAC
      COMMON/RSLTPPK/PR,EPR,PPEAK,EPEAK
      COMMON/DELEF/DE
      COMMON/RSLTS1/P11,E11,PS,ES
      COMMON/FIBFORC/FBRFRC(10)
      P1=P
      IF(IFRAC.EQ.1) P1=PPEAK
      E1=P1/W/D/MOD
      E2=0
      EA2=0
      EA3=0
      PI=3.141592654

      DO 10 I=1,NC

C     P5=P-FBRFRC(I)*A(I)*D*2
      P5=P
      IF(IFRAC.EQ.1) P5=PPEAK
      IF(P5.LT.0) P5=0
                  SUMCOD(I)=2*P5*A(I)**2*PI/W/D/MOD
                  IF(ITYPE(I).EQ.'IN') THEN
                              E2=E2+SUMCOD(I)/H/W
                  ELSE
                              E2=E2+SUMCOD(I)/H/W/2.0
                  ENDIF
 10   CONTINUE
C
C NOTE: THE 1.1 FACTOR BELOW ACCOUNTS FOR THE STRAIN EFFECTS OF CRACKS
C THAT WER NOT EXPLICITLY USED HERE.
C
      EF=E1+E2*1.1
      DE=E2*1.1
      RETURN
```

```
      END
*****************************************************************
      SUBROUTINE FILL0S(NL,MOD,ES,NN)
      IMPLICIT DOUBLE PRECISION (A - H , O - Z)
      DOUBLE PRECISION SL(100),EL(100),MOD
      COMMON/FILELBL/NOUT,NSUM,NCONF,NFBR,NCOUNT
      COMMON/FILE/IFILE


      DE=ES/(NL+1)

      IF(IFILE.EQ.1)THEN
      DO 10 I=1,NL
      EL(I)=I*DE
      SL(I)=EL(I)*MOD
      WRITE(nout,*)SL(I),EL(I)
      WRITE(NN,*)EL(I),SL(I)
10    CONTINUE
      ENDIF

      RETURN
      END
*****************************************************************
      SUBROUTINE FILLS1(NS1,W,D,NN)
      IMPLICIT DOUBLE PRECISION (A - H , O - Z)
      DOUBLE PRECISION SS1(100),ES1(100)
      COMMON/RSLTS1/P11,E11,PS,ES
      COMMON/FILELBL/NOUT,NSUM,NCONF,NFBR,NCOUNT
      COMMON/FILE/IFILE

      DPS1=(P11-PS)/(NS1+1)
      IF(IFILE.EQ.1) THEN
      DO 10 I=1,NS1
      PS1=PS+I*DPS1
      SS1(I)=PS1/W/D
      CALL EFRAC(PS1,ES1(I))
      WRITE(nout,*)SS1(I),ES1(I)
      WRITE(NN,*)ES1(I),SS1(I)
10    CONTINUE
      ENDIF

      RETURN
      END
*****************************************************************
      SUBROUTINE PREPEAK(TKIC,NC,W,D,NPRE,NNN)
      IMPLICIT DOUBLE PRECISION (A - H , O - Z)
```

```
      INTEGER ACTNC(10),ACTNCALL(10),ACTNCT(10),ACALLT(10)
      CHARACTER*2 ITYPE(10),ITYPTEMP(10),INSTBL(10),INSTEMP(10)
      DOUBLE PRECISION XBEGTEMP(10),XENDTEMP(10),YBEGTEMP(10),
+ YENDTEMP(10),
+ AATEMP(10),SPR,MODF,NGA(10),NGB(10),NTL(10)
+ ,XNEWTEMP(10,2000),FBRTEMP(10)
      COMMON/CRKLOC/XBEG(10),XEND(10),YBEG(10),YEND(10),AA(10),
+ ALPHA(10)


      COMMON/COUNT/ICOUNT
      COMMON/RSLTS1/P11,E11,PS,ES
      COMMON/FBRDAT/F,MODF,FBL,FSPACE,AF,DF
      COMMON/CONTROLS/P1,NS1,DPMAX,DPMIN,NMAX,NMIN,MAXGLAG
      COMMON/ACTIVE/NACT,ACTNC,NACTALL,ACTNCALL
      COMMON/RSLTPPK/PR,EPR,PPEAK,EPEAK
      COMMON/FLAGP/IFLAGP
      COMMON/DELTA/DEL
      COMMON/NF/NFGRPA(10),NFGRPB(10)
      COMMON/NEW/NEWF(2000),NRANK(2000),NSIDE(2000)
      COMMON/XFBR/NFTOTAL(10),XNEW(10,2000)
      COMMON/B99/FF
      COMMON/FIBFORC/FBRFRC(10)
      COMMON/CRKTYP/ITYPE,INSTBL
      COMMON/B3/SIFR(10),SIFL(10)
      COMMON/FLAGPOST/JFLAG,CODP,NCRIT
      COMMON/FILELBL/NOUT,NSUM,NCONF,NFBR,NCOUNT
      COMMON/FILE/IFILE
      common/maxi/amax

      IF(F.LE.0.00001) THEN
      PPEAK=P11
      EPEAK=E11
      GO TO 9999
      ENDIF

      FF=1.
      amax=1
      delmin=w/100.
      del=nmin*fspace

      amax=del/delmin
      del=del/real(amax)
      print*,'fspace= ',fspace

      print*,'del = ',del
```

```
      IF(IFILE.EQ.1)WRITE(nout,*)' '
      IF(IFILE.EQ.1)WRITE(nout,*)'** PREPEAK LOAD, STRESS, AND STRAIN **'
      IF(IFILE.EQ.1)WRITE(nout,*)' '
      I=0
      NPRE=0
      PR=P11
      ki=0
      kflag=0
1     I=I+1

      if(i.gt.100) then
      kflag=1
      ki=ki+1
      endif
      if(mod(ki,5).eq.0) kflag=0

      PR=PR+DPMIN
      SPR=PR/W/D
      IFLAGP=1
      CALL FIBER(PR)
      CALL SIF(PR)
      CALL CRIT(TKIC)

      IF(NACT.EQ.0) THEN
                    NPRE=NPRE+1
                    CALL EFRAC(PR,EPR)
      IF(IFILE.EQ.1)WRITE(nout,*) I,SPR,EPR
      if(kflag.eq.0.AND.IFILE.EQ.1)WRITE(NNN,*)EPR,SPR

      IF(KFLAG.EQ.0) ICOUNT=ICOUNT+1

      IF(KFLAG.EQ.0.AND.IFILE.EQ.1) THEN
                    DO 1001 I11=1,NC
      WRITE(NFBR,*)EPR,FBRFRC(I11)
1001                CONTINUE

      ENDIF

                    GO TO 1
C     ELSE
C     IF(NACT.EQ.1)THEN
C     K=ACTNC(NACT)
C     IF(INSTBL(K).EQ.'LE')DS=ABS(SIFL(K)-TKIC)
C     IF(INSTBL(K).EQ.'RI')DS=ABS(SIFR(K)-TKIC)
C     if(instbl(k).eq.'ri')then
```

```
C       dsr=abs(sifr(k)-tkic)
C       dsl=abs(sifl(k)-tkic)
C       ds=amin1(dsr,dsl)
C       endif


C       IF(DS.LE.(TKIC/200))GO TO 3
C       ELSE
C       CALL OPTIM1(PR,TKIC)
C       ENDIF
        ENDIF
3       CONTINUE
        NACTTEMP=NACT
        NALLT=NACTALL
        DO 25 II=1,NACT
        ACTNCT(II)=ACTNC(II)
25      CONTINUE
        DO 26 J=1,NACTALL
        ACALLT(J)=ACTNCALL(J)
26      CONTINUE
        DO 101 K=1,NC
        XBEGTEMP(K)=XBEG(K)
        XENDTEMP(K)=XEND(K)
        YBEGTEMP(K)=YBEG(K)
        YENDTEMP(K)=YEND(K)
        AATEMP(K)=AA(K)
        ITYPTEMP(K)=ITYPE(K)
        INSTEMP(K)=INSTBL(K)
        NGA(K)=NFGRPA(K)
        NGB(K)=NFGRPB(K)
        NTL(K)=NFTOTAL(K)
        FBRTEMP(K)=FBRFRC(K)
        DO 99 KK=1,1000

        XNEWTEMP(K,KK)=XNEW(K,KK)
99      CONTINUE
101     CONTINUE
5       CONTINUE
        DO 20 J=1,NACT
        JJ=ACTNC(J)
        ILGFLAG=0
        CALL INCLENG(JJ,ILGFLAG,W)
        call crktype(jj,w)

        IF(ILGFLAG.EQ.1) THEN
        NCRIT=JJ
```

```
      GO TO 6
      ENDIF

20    CONTINUE
      call crktype(jj,w)
      IFLAGP=0
      CALL FIBER(PR)
      CALL SIF(PR)
      CALL CRIT(TKIC)
      IF(NACT.EQ.0) THEN

                  CALL EFRAC(PR,EPR)
      IF(IFILE.EQ.1)WRITE(nout,*)I,SPR,EPR
                  IF(IFILE.EQ.1)WRITE(NNN,*)EPR,SPR


                  ICOUNT=ICOUNT+1

      IF(KFLAG.EQ.0.AND.IFILE.EQ.1) THEN
                  DO 1002 I11=1,NC
      WRITE(NFBR,*)EPR,FBRFRC(I11)
1002              CONTINUE

      ENDIF

                  GO TO 1
      ELSE
      GO TO 5
      ENDIF
6     CONTINUE
      NPRE=I-1
      PPEAK=PR
      DO 23 J=1,NC
      XBEG(J)=XBEGTEMP(J)
      XEND(J)=XENDTEMP(J)
      YBEG(J)=YBEGTEMP(J)
      YEND(J)=YBEGTEMP(J)
      AA(J)=AATEMP(J)
      ITYPE(J)=ITYPTEMP(J)
      INSTBL(J)=INSTEMP(J)
      NFGRPA(J)=NGA(J)
      NFGRPB(J)=NGB(J)
      NFTOTAL(J)=NTL(J)
      FBRFRC(J)=FBRTEMP(J)
      DO 123 JJ=1,1000
      XNEW(J,JJ)=XNEWTEMP(J,JJ)
```

```
123         CONTINUE
 23         CONTINUE
            NACT=NACTTEMP
            NACTALL=NALLT
            DO 27 II=1,NACT
            ACTNC(II)=ACTNCT(II)
27          CONTINUE
            DO 28 J=1,NACTALL
            ACTNCALL(J)=ACALLT(J)
28          CONTINUE
            CALL EFRAC(PPEAK,EPEAK)
            SPEAK=PPEAK/W/D
            IF(IFILE.EQ.1)WRITE(nout,*)' '
            IF(IFILE.EQ.1)WRITE(nout,*)'PEAK LOAD=',PPEAK,'PEAK STRESS=',SPEAK
            IF(IFILE.EQ.1)WRITE(nout,*)'PEAK STRAIN=',EPEAK
            IF(IFILE.EQ.1)WRITE(nout,*)'PEAK CONDITION REACHED AT ITERATION:',I
            IF(IFILE.EQ.1)WRITE(nout,*)' '
            IF(IFILE.EQ.1)WRITE(NNN,*)EPEAK,SPEAK


            ICOUNT=ICOUNT+1

            IF(IFILE.EQ.1) THEN
            DO 1003 I11=1,NC
            WRITE(NFBR,*)EPEAK,FBRFRC(I11)
1003        CONTINUE
            ENDIF

9999        RETURN
            END
*************************************************************************
            SUBROUTINE INCLENG(J,ILGFLAG,W)
            IMPLICIT DOUBLE PRECISION (A - H , O - Z)
            double precision L(10)
            COMPLEX Z0(10)
            CHARACTER*2 ITYPE(10),INSTBL(10),T,S
            COMMON/CRKTYP/ITYPE,INSTBL
            COMMON/CRKLOC/XBEG(10),XEND(10),YBEG(10),YEND(10),AA(10)
+ ,ALPHA(10)
            COMMON/B1/M3,N3,Z0,L,ALPHA2(10)
            COMMON/DELTA/DEL
            COMMON/XFBR/NFTOTAL(10),XNEW(10,2000)
            ILGFLAG=0
            T=ITYPE(J)
            S=INSTBL(J)
            IF(T.EQ.'IN'.AND.S.EQ.'LE')XBEG(J)=XBEG(J)-DEL
```

```
IF(T.EQ.'IN'.AND.S.EQ.'RI')XEND(J)=XEND(J)+DEL
IF(T.EQ.'IN'.AND.S.EQ.'RL')THEN
XBEG(J)=XBEG(J)-DEL
XEND(J)=XEND(J)+DEL
ENDIF

IF(T.EQ.'ER'.AND.S.EQ.'LE') then
XBEG(J)=XBEG(J)-DEL
xend(j)=w
endif


IF(T.EQ.'EL'.AND.S.EQ.'RI') then
Xend(J)=Xend(J)+DEL
xbeg(j)=0
endif

IF(T.EQ.'IN')THEN
AA(J)=(XEND(J)-XBEG(J))/2.0
IF(AA(J).GE.0.9*(W/2.)) ilgflag=1
ELSE
AA(J)=XEND(J)-XBEG(J)
IF(AA(J).GE.0.9*W) ILGFLAG=1
ENDIF

if(aa(j).gt.w) print*,'error: aa(j) > w'


if(t.eq.'in')then
R1=(XBEG(J)+XEND(J))/2.
A1=(YBEG(J)+YEND(J))/2.
Z0(J)=CMPLX(R1,A1)
endif


if(t.eq.'el') then
r1=0
a1=(ybeg(j)+yend(j))/2.
z0(j)=cmplx(r1,a1)
endif

if(t.eq.'er') then
r1=xend(j)
a1=(ybeg(j)+yend(j))/2.
z0(j)=cmplx(r1,a1)
endif
```

```
            if(t.eq.'in') then
            DO 99 JF=1,NFTOTAL(J)
            IF(S.EQ.'RI')XNEW(J,JF)=XNEW(J,JF)-DEL/2
            IF(S.EQ.'LE')XNEW(J,JF)=XNEW(J,JF)+DEL/2
99          CONTINUE
            endif

            RETURN
            END
*********************************************************************
            SUBROUTINE OPTIM1(P,TKIC)
            IMPLICIT DOUBLE PRECISION (A - H , O - Z)
            CHARACTER*2 ITYPE,INSTBL
            INTEGER ACTNC(10),ACTNCALL(10)
            COMMON/CONTROLS/P1,NS1,DPMAX,DPMIN,NMAX,NMIN,MAXFLAG
            COMMON/ACTIVE/NACT,ACTNC,NACTALL,ACTNCALL
            COMMON/CRKTYP/ITYPE(10),INSTBL(10)
            COMMON/B3/SIFR(10),SIFL(10)
            D=DPMAX-DPMIN
            I=1
            P=P+D/2**I
 1 CALL FIBER(P)
            CALL SIF(P)
            CALL CRIT(TKIC)
            IF(NACT.EQ.0)THEN
                        I=I+1
                        P=P+D/2**I
                        GO TO 1
            ELSE
            IF(NACT.EQ.1) THEN
            K=ACTNC(NACT)
            IF(INSTBL(K).EQ.'LE') DS=ABS(SIFL(K)-TKIC)
            IF(INSTBL(K).EQ.'RI') DS=ABS(SIFR(K)-TKIC)
            if(instbl(k).eq.'ri') then
            dsl=abs(sifl(k)-tkic)
            dsr=abs(sifr(k)-tkic)
            ds=dmin1(dsl,dsr)
            endif
             IF(DS.LE.(TKIC/200.)) GO TO 2
                        IF(I.GE.MAXFLAG) GO TO 2
                        ELSE
                        IF(I.GE.MAXFALG) GO TO 2
                        I=I+1
                        P=P-D/2**I
                        GO TO 1
```

```
            ENDIF
            ENDIF
 2          CONTINUE
            RETURN
            END
*************************************************************************
C           SUBROUTINE OPTIM2(P,NACTS,TKIC)
C           INTEGER ACTNC(20),ACTNCALL(20)
C           COMMON/CRKLOC/XBEG(20),XEND(20),YBEG(20),YEND(20),L(20),ALPHA(20)
C           COMMON/CONTROLS/P1,NS1,DPMAX,DPMIN,NMAX,NMIN,MAXFLAG
C           COMMON/FBRDAT/F,MODF,FBL,FSPACE,AF,DF
C           COMMON/ACTIVE/NACT,ACTNC,NACTALL,ACTNCALL
C           DELMAX=NMAX*FSPACE
C           DELMIN=NMIN*FSPACE
C           D=DELMAX-DELMIN
C           N1=NACTS
C           I=1
C           DO 10 J=1,N1
C           L(ACTNC(J))=L(ACTNC(J))-D/2
C10         CONTINUE
C           CALL FIBER
C           CALL SIF(P)
C           CALL CRIT(TKIC)
C           IF(NACT.EQ.0) THEN
C           IF(I.GE.MAXFLAG) GO TO 2
C
C           ENDIF
C
C
C           RETURN
C           END
*************************************************************************
            SUBROUTINE FIBER(P)
            IMPLICIT DOUBLE PRECISION (A - H , O - Z)
            CHARACTER*2 ITYPE(10),INSTBL(10)
            INTEGER LBLPB(2000),LBLPLL(10,2000),LBLAB(2000),
     + IFLAG(2000),LABOUT(2000),ACTNC(10),
     + ACTNCALL(10),LBLB(10,2000)
     DOUBLE PRECISION FORCEA(2000),FORCEB(2000),
     + ENBDLA(10,2000),
     + XA(2000),COD(2000),XNEWB(10,2000),
     + X(2000),ENBDLB(10,2000),MOD,MOD0,MODF
            COMMON/FBRDAT/F,MODF,FBL,FSPACE,AF,DF
            COMMON/MTRXDAT/TKI0,TKIC,W,H,D,MOD0,MOD,TAU
            COMMON/CONTROLS/P1,NS1,DPMAX,DPMIN,NMAX,NMIN,MAXFLAG
            COMMON/SEED/ISEED
```

```
      COMMON/BNCM/NC,M2
      COMMON/CRKTYP/ITYPE,INSTBL

      COMMON/ACTIVE/NACT,ACTNC,NACTALL,ACTNCALL
      COMMON/FLAGP/IFLAGP
      COMMON/NF/NFGRPA(10),NFGRPB(10)
      COMMON/FSULT/SIGULT,FDMG
      COMMON/NEW/NEWF(2000),NRANK(2000),NSIDE(2000)
      COMMON/XFBR/NFTOTAL(10),XNEW(10,2000)
      COMMON/FLAGPOST/JFLAG,CODP,NCRIT
      common/tem/temp
      common/codpost/ipost,epeak

      temp=0.0
      SIG=P/W/D
      EF=MODF
      DMG=FDMG*FBL/2.
      ALPHA = 4.*TAU/MODF/DF
      FULT = SIGULT * AF
      IF(IFLAGP.EQ.1) THEN
      NCR=NACTALL
      ELSE
      NCR=NACTALL
      ENDIF

c     IF(JFLAG.EQ.1) NCR=1

      DO 10 I=1,NCR
      DO 99 IJK=1,2000
      FORCEA(IJK)=0
      FORCEB(IJK)=0
99    CONTINUE
      IF(IFLAGP.EQ.1)THEN
      NNC=ACTNCALL(I)
      ELSE
 NNC=ACTNCALL(I)
      ENDIF

c     IF(JFLAG.EQ.1)NNC=NCRIT

      NABRKN = 0
      NAPLL = 0
      NATOB = 0
      NBPULL = 0
      NR=0
      DO 16 II1=1,1000
```

```
      NEWF(II1)=0
      NSIDE(II1)=0
      NRANK(II1)=0
16    CONTINUE
      IF(JFLAG.EQ.1)GO TO 500
      IF(IFLAGP.EQ.1) GO TO 500
      IF(ITYPE(NNC).EQ.'IN'.AND.INSTBL(NNC).EQ.'RL') THEN
      NFGRPA(NNC)=NFGRPA(NNC)+NMIN+NMIN
      DO 18 J=1,NMIN
      JJ=NFGRPA(NNC)-NMIN-NMIN+J
      NR=NR+1
      NRANK(JJ)=NR
      NEWF(JJ)=1
      NSIDE(JJ)=1
      ENBDLA(NNC,JJ)=RANDOM(ISEED)*FBL/2.
18    CONTINUE
      NR=0
      DO 19 J=1,NMIN
      JJ=NFGRPA(NNC)-NMIN+J
      NR=NR+1
      NRANK(JJ)=NR
      NEWF(JJ)=1
      NSIDE(JJ)=-1
      ENBDLA(NNC,JJ)=RANDOM(ISEED)*FBL/2.
19    CONTINUE
      ELSE
                  NFGRPA(NNC) = NFGRPA(NNC) + NMIN
                  DO 20 J=1, NMIN
                  JJ = NFGRPA(NNC)-NMIN+J
                  NR=NR+1
                  NRANK(JJ)=NR
                  NEWF(JJ)=1
                  ENBDLA(NNC,JJ) = RANDOM(ISEED)*FBL/2.
20                CONTINUE
                  ENDIF

500               NFTOTAL(NNC)=NFGRPA(NNC)+NFGRPB(NNC)

C                 CALL CRKTYPE(NNC,W)
                  DO 30 K=1, NFGRPA(NNC)
                  if(jflag.eq.0)then

                  CALL CRKOPEN(NNC,K,COD,SIG,MOD)
                  endif

c                 if(ipost.eq.1) cod(k)=epeak*h
```

```
                IF(JFLAG.EQ.1)COD(K)=CODP

                XA(K) = SQRT(COD(K)*EF*DF/4./TAU)
                IF(XA(K).LE.ENBDLA(NNC,K)) THEN
                FORCEA(K) = 4.*AF*TAU*XA(K)/DF
                        IF(FORCEA(K).GE.FULT)THEN
                        FORCEA(K) = 0.
                        NABRKN = NABRKN + 1
                        LBLB(NNC,NABRKN) = K
                        ENDIF
                ELSE
                X(K) = (COD(K)-ENBDLA(NNC,K))/(ALPHA*ENBDLA(NNC,K)-1)

                IF(X(K).LE.DMG)THEN
                NAPLL=NAPLL+1
                LBLPLL(NNC,NAPLL)=K
                FORCEA(K)=0.
                ELSE
                NATOB=NATOB+1
                LBLAB(NATOB)=K
                FORCEA(K)=4*TAU*AF*X(K)/DF
                ENDIF
                ENDIF
30      CONTINUE

        DO 40 M=1, NFGRPB(NNC)
        MM=NFGRPA(NNC)+M
        NEWF(MM)=0
        if(jflag.eq.0) then
        CALL CRKOPEN(NNC,MM,COD,SIG,MOD)
        endif

c       if(ipost.eq.1) cod(k)=epeak*h
        IF(JFLAG.EQ.1)COD(MM)=CODP

        X(M)=(-ENBDLB(NNC,M)+COD(MM))/(ALPHA*ENBDLB(NNC,M)-1)
        IF(X(M).LE.DMG)THEN
        NBPULL = NBPULL+1
        LBLPB(NBPULL)=M
        FORCEB(M)=0.
        ELSE
        FORCEB(M)=4.*AF*TAU*X(M)/DF
        ENDIF
40      CONTINUE
        CALL DISTRB(NNC,M2,FORCEA,FORCEB)
        DO 200 J1=1,NFGRPB(NNC)
```

```
      IFLAG(J1)=1
200   CONTINUE
      DO 201 J2=1,NBPULL
      DO 202 J3=1,NFGRPB(NNC)
      IF(LBLPB(J2).EQ.J3)IFLAG(J3)=0
202   CONTINUE
201   CONTINUE

      NAOUT=NABRKN+NAPLL+NATOB
      NFANEW=NFGRPA(NNC)-NAOUT

      ICOUNT=0
      DO 203 J4=1,NFGRPB(NNC)
      IF(IFLAG(J4).EQ.0) THEN
      ICOUNT=ICOUNT+1
      ELSE
      NWI=J4-ICOUNT
      ENBDLB(NNC,NWI)=ENBDLB(NNC,J4)
      XNEWB(NNC,NFANEW+NWI)=XNEW(NNC,NFGRPA(NNC)+J4)
      ENDIF
203   CONTINUE
      NFGRPB(NNC)=NFGRPB(NNC)-NBPULL
      NOLD=NFGRPB(NNC)
      NNEW=NOLD+NATOB

      NFA=NFANEW

      DO 204 KK=1,NATOB
      ENBDLB(NNC,NOLD+KK)=ENBDLA(NNC,LBLAB(KK))
      XNEW(NNC,NFA+NOLD+KK)=XNEW(NNC,LBLAB(KK))
204   CONTINUE
      NFGRPB(NNC)=NNEW
      NAOUT=NABRKN+NAPLL+NATOB

      IF(NABRKN.NE.0)THEN
      DO 101 I1=1,NABRKN
      LABOUT(I1)=LBLB(NNC,I1)
101   CONTINUE
      ENDIF

      IF(NAPLL.NE.0)THEN
      DO 102 I2=1,NAPLL
      LABOUT(NABRKN+I2)=LBLPLL(NNC,I2)
102   CONTINUE
      ENDIF
```

```
      IF(NATOB.NE.0)THEN
      DO 103 I3=1,NATOB
      LABOUT(NABRKN+NAPLL+I3)=LBLAB(I3)
103   CONTINUE
      ENDIF


      DO 104 I5=1,NFGRPA(NNC)
      IFLAG(I5)=1
104   CONTINUE

      DO 106 II=1,NAOUT
      DO 107 JJ=1,NFGRPA(NNC)
      IF(LABOUT(II).EQ.JJ) IFLAG(JJ)=0
107   CONTINUE
106   CONTINUE
      ICOUNT=0
      DO 108 KK=1,NFGRPA(NNC)
      IF(IFLAG(KK).EQ.0) THEN
      ICOUNT=ICOUNT+1
      ELSE
      NWI=KK-ICOUNT
      ENBDLA(NNC,NWI)=ENBDLA(NNC,KK)
      XNEW(NNC,NWI)=XNEW(NNC,KK)
      ENDIF
108   CONTINUE

      DO 999 J9=1,NOLD
      XNEW(NNC,NFANEW+J9)=XNEWB(NNC,NFANEW+J9)
999   CONTINUE

      NFGRPA(NNC)=NFGRPA(NNC)-NAOUT
      NFTOTAL(NNC)=NFGRPA(NNC)+NFGRPB(NNC)
10    CONTINUE
      RETURN
      END

C-----------------------------------------------------------------------
      SUBROUTINE CRKTYPE(NNC,W)
      IMPLICIT DOUBLE PRECISION (A - H , O - Z)
      DOUBLE PRECISION L(10),L2(10)
      COMPLEX Z0(10)
      CHARACTER*2 ITYPE(10),INSTBL(10)
      COMMON/CRKTYP/ITYPE,INSTBL
      COMMON/XFBR/NFTOTAL(10),XNEW(10,2000)
      COMMON/CRKLOC/XBEG(10),XEND(10),YBEG(10),YEND(10),L
```

```
     + ,ALPHA(10)
              COMMON/DELTA/DEL
              COMMON/FLAG/IFLAG
              COMMON/B1/M2,N2,Z0,L2,ALPHA2(10)
              XL=XBEG(NNC)
              XR=XEND(NNC)
              IFLAG=1

              IF(ITYPE(NNC).EQ.'IN'.AND.INSTBL(NNC).EQ.'RI')THEN

                            IF(XR.GE.W) THEN
              ITYPE(NNC)='ER'
                            DO 10 I=1,NFTOTAL(NNC)
                            D1=L(NNC)
                            XNEW(NNC,I)=D1-XNEW(NNC,I)
     10                     CONTINUE
                            L(NNC)=2*L(NNC)
                            ELSE
                            DO 15 I=1,NFTOTAL(NNC)
                            XNEW(NNC,I)=XNEW(NNC,I)
     15                     CONTINUE

                            ENDIF
              ENDIF
              IF(ITYPE(NNC).EQ.'IN'.AND.INSTBL(NNC).EQ.'LE')THEN
                            IF(XL.LE.0) THEN
                            ITYPE(NNC)='EL'
                            DO 11 I=1,NFTOTAL(NNC)
                            D1=L(NNC)
                            XNEW(NNC,I)=D1+XNEW(NNC,I)
     11                     CONTINUE

                            ENDIF
              ENDIF
              IF(ITYPE(NNC).EQ.'IN'.AND.INSTBL(NNC).EQ.'RL') THEN
                            IF(XL.GT.0.AND.XR.GE.W) THEN
                            ITYPE(NNC)='ER'
                            IFLAG=2
                            DO 12 I=1,NFTOTAL(NNC)
                            D1=L(NNC)
                            XNEW(NNC,I)=D1-XNEW(NNC,I)
     12                     CONTINUE
                            L(NNC)=2*L(NNC)
                            ELSEIF(XL.LT.0.0) THEN
                             ITYPE(NNC)='EL'
                            IFLAG=2
```

```
                    DO 13 I=1,NFTOTAL(NNC)
                    D1=L(NNC)
                    XNEW(NNC,I)=D1+XNEW(NNC,I)
13                  CONTINUE
                    L(NNC)=2.*L(NNC)
                    ELSE

                    ENDIF


          ENDIF
          L2(NNC)=L(NNC)
          RETURN
          END

C-------------------------------------------------------------------
          SUBROUTINE CRKOPEN(NNC,NFLBL,COD,SIG,E)
          IMPLICIT DOUBLE PRECISION (A - H , O - Z)
          CHARACTER*2 ITYPE(10),INSTBL(10)
          DOUBLE PRECISION COD(2000),MODF
          COMMON/CRKTYP/ITYPE,INSTBL
          COMMON/FLAGP/IFLAGP
          COMMON/CRKLOC/XBEG(10),XEND(10),YBEG(10),YEND(10),A(10)
+ ,ALPHA(10)
          COMMON/FBRDAT/F,MODF,FBL,FSPACE,AF,DF
          COMMON/NEW/NEWF(2000),NRANK(2000),NSIDE(2000)
          COMMON/DELTA/DEL
          COMMON/XFBR/NFTOTAL(10),XNEW(10,2000)
          COMMON/FLAG/IFLAG
          COMMON/FIBFORC/FBRFRC(10)

          ANEW=A(NNC)
          IF(IFLAGP.EQ.1) GO TO 100
          IF(ITYPE(NNC).EQ.'IN'.AND.INSTBL(NNC).EQ.'RI')THEN
          IF(NEWF(NFLBL).EQ.1)THEN
          XNEW(NNC,NFLBL)=A(NNC)-DEL+NRANK(NFLBL)*DEL/2.
          ENDIF
          ENDIF
C
          IF(ITYPE(NNC).EQ.'IN'.AND.INSTBL(NNC).EQ.'LE')THEN
          IF(NEWF(NFLBL).EQ.1)THEN

          XNEW(NNC,NFLBL)=-A(NNC)+DEL-NRANK(NFLBL)*DEL/2.
          ENDIF
          ENDIF
C
```

```
            IF(ITYPE(NNC).EQ.'IN'.AND.INSTBL(NNC).EQ.'RL')THEN
            IF(NEWF(NFLBL).EQ.1)THEN
            IF(NSIDE(NFLBL).EQ.1)THEN
            XNEW(NNC,NFLBL)=A(NNC)-DEL+NRANK(NFLBL)*DEL/2.
            ENDIF
            IF(NSIDE(NFLBL).EQ.-1)THEN
            XNEW(NNC,NFLBL)=-A(NNC)+DEL-NRANK(NFLBL)*DEL/2.
            ENDIF
            ENDIF
            ENDIF
C


            IF(ITYPE(NNC).EQ.'EL'.AND.INSTBL(NNC).EQ.'RI')THEN
            IF(NEWF(NFLBL).EQ.1)THEN
            XNEW(NNC,NFLBL)=A(NNC)-DEL+NRANK(NFLBL)*DEL
            ENDIF
            ENDIF
            IF(ITYPE(NNC).EQ.'ER'.AND.INSTBL(NNC).EQ.'LE')THEN
            IF(NEWF(NFLBL).EQ.1)THEN
            XNEW(NNC,NFLBL)=-A(NNC)+DEL-NRANK(NFLBL)*DEL
            ENDIF
            ENDIF

            IF(ITYPE(NNC).EQ.'ER'.AND.INSTBL(NNC).EQ.'RL')THEN
            IF(NEWF(NFLBL).EQ.1.AND.NSIDE(NFLBL).EQ.1)THEN
            XNEW(NNC,NFLBL)=-DEL+NRANK(NFLBL)*del
            ENDIF
            IF(NEWF(NFLBL).EQ.1.AND.NSIDE(NFLBL).EQ.-1)THEN
            XNEW(NNC,NFLBL)=-A(NNC)+DEL-NRANK(NFLBL)*del
            ENDIF
            ENDIF

C           IF(ITYPE(NNC).EQ.'EL'.AND.INSTBL(NNC).EQ.'RL')THEN
C           IF(NEWF(NFLBL).EQ.1.AND.NSIDE(NFLBL).EQ.1)THEN
C           XNEW(NNC,NFLBL)=A(NNC)-DEL+NRANK(NFLBL)*del
C           ENDIF
C           IF(NEWF(NFLBL).EQ.1.AND.NSIDE(NFLBL).EQ.-1)THEN
C           XNEW(NNC,NFLBL)=DEL-NRANK(NFLBL)*del
C           ENDIF
C           ENDIF

 100        CONTINUE

C
```

```
            SIG2=SIG
            COD(NFLBL)=4.*SIG2*SQRT(abs(ANEW**2-
     + XNEW(NNC,NFLBL)**2))/E


            IF(COD(NFLBL).LT.0.0) COD(NFLBL)=0.0
            IF(IFLAGP.EQ.1) GO TO 101
     101    CONTINUE
            RETURN
            END
    C-------------------------------------------------------------------
            SUBROUTINE DISTRB(NCRK,M,FORCEA,FORCEB)
            IMPLICIT DOUBLE PRECISION (A - H , O - Z)
            DOUBLE PRECISION FORCEA(2000),FORCEB(2000),MODF,MOD0,MOD
            CHARACTER*2 ITYPE(10),INSTBL(10)
            COMMON/NF/NFGRPA(10),NFGRPB(10)
            COMMON/MTRXDAT/TKI0,TKIC,W,H,D,MOD0,MOD,TAU
            COMMON/FBRDAT/F,MODF,FBL,FSPACE,AF,DF
            COMMON/B2/A(200,200),B(200),XX(200)
     COMMON/CRKLOC/XBEG(10),XEND(10),YBEG(10),YEND(10),AA(10)
     + ,ALPHA(10)
            COMMON/CRKTYP/ITYPE,INSTBL
            COMMON/FIBFORC/FBRFRC(10)
            COMMON/FIBEFF/EFCT
            common/flagpost/jflag,codp,ncrit
            common/tem/temp
            common/maxi/amax
            FBRFRC(NCRK)=0
            if(jflag.eq.1) then
            fraction=1.*(d/fspace)/real(amax)
            else

            FRACTION=1.0*(d/fspace)/real(amax)
            endif

            IF(ITYPE(NCRK).EQ.'IN')THEN
            FRACTION=FRACTION/2./AA(NCRK)/D
    C       FRACTION=FRACTION/AA(NCRK)/D
            ELSE
            FRACTION=FRACTION/AA(NCRK)/D
            ENDIF
            FBRFRC(NCRK)=0
            DO 10 I=1,NFGRPA(NCRK)
            FBRFRC(NCRK)=FBRFRC(NCRK)+FRACTION*FORCEA(I)
     10     CONTINUE
            DO 11 J=1,NFGRPB(NCRK)
```

```
            FBRFRC(NCRK)=FBRFRC(NCRK)+FRACTION*FORCEB(J)
11          CONTINUE
            FBRFRC(NCRK)=1.5*FBRFRC(NCRK)/0.90

            if(temp.lt.fbrfrc(ncrk)) ncrit=ncrk
            temp=fbrfrc(ncrk)

C           B((NCRK-1)*M+K)=FBRFRC(NCRK)
C12         CONTINUE
            RETURN
            END
*****************************************************************
            SUBROUTINE CRIT(TKIC)
            IMPLICIT DOUBLE PRECISION (A - H , O - Z)
            INTEGER ACTNC(10),ACTNCALL(10)
            CHARACTER*2 ITYPE(10),INSTBL(10)
            COMMON/CRKTYP/ITYPE,INSTBL
            COMMON/ACTIVE/NACT,ACTNC,NACTALL,ACTNCALL
            COMMON/B3/SIFR(10),SIFL(10)
            COMMON/BNCM/NC,M
            COMMON/B99/F
            COMMON/B100/SIFRP(10),SIFLP(10)
            COMMON/B10/IFLAG10
            NACT=0
            DO 10 I=1,NC

            SL=SIFL(I)
            SR=SIFR(I)
            SLP=F*SIFLP(I)
            SRP=F*SIFRP(I)

            IF(ITYPE(I).EQ.'IN')THEN
            IF(SIFL(I).GE.TKIC)THEN
            NACT=NACT+1
            ACTNC(NACT)=I
            IF(IFLAG10.EQ.1) CALL ALLACT(I)
             IF(SIFR(I).GE.TKIC)THEN
                          INSTBL(I)='RL'
             ELSE
                          INSTBL(I)='LE'
             ENDIF
            ELSE
             IF(SIFR(I).GE.TKIC)THEN
             INSTBL(I)='RI'
             NACT=NACT+1
             ACTNC(NACT)=I
            IF(IFLAG10.EQ.1) CALL ALLACT(I)
             ELSE
             INSTBL(I)='ST'
             ENDIF
            ENDIF
```

```
      ENDIF
      IF(ITYPE(I).EQ.'EL')THEN
                  IF(SIFR(I).GE.TKIC)THEN
                  INSTBL(I)='RI'
                  NACT=NACT+1
                  ACTNC(NACT)=I
      IF(IFLAG10.EQ.1) CALL ALLACT(I)
                  ELSE
                  INSTBL(I)='ST'
                  ENDIF
      ENDIF
      IF(ITYPE(I).EQ.'ER')THEN
                  IF(SIFL(I).GE.TKIC)THEN
                  INSTBL(I)='LE'
                  NACT=NACT+1
                  ACTNC(NACT)=I
      IF(IFLAG10.EQ.1) CALL ALLACT(I)
                  ELSE
                  INSTBL(I)='ST'
                  ENDIF
      ENDIF
10    CONTINUE

      DO 20 J=1,NC
      SIFLP(J)=SIFL(J)
      SIFRP(J)=SIFR(J)
20    CONTINUE

      RETURN
      END
*************************************************************************
      SUBROUTINE ALLACT(I)
      IMPLICIT DOUBLE PRECISION (A - H , O - Z)
      INTEGER ACTNC(10),ACTNCALL(10)
      COMMON/ACTIVE/NACT,ACTNC,NACTALL,ACTNCALL
      IF(NACTALL.NE.0)THEN
                  IFLAG=1
       DO 10 J=1,NACTALL
                  IF(I.EQ.ACTNCALL(J))THEN
                  IFLAG=0
                  GO TO 20
                  ELSE
                  IFLAG=1
                  ENDIF
10     CONTINUE
20    IF(IFLAG.EQ.1)THEN
      NACTALL=NACTALL+1
      ACTNCALL(NACTALL)=I
      ENDIF
      ELSE
      NACTALL=NACTALL+1
```

```
            ACTNCALL(NACTALL)=I
            ENDIF
            RETURN
            END
*********************************************************************
            SUBROUTINE POST2(H,W,D,NNN,MOD,P11,ITERPOST,TOGH3,epsmax)
            IMPLICIT DOUBLE PRECISION (A - H , O - Z)
            CHARACTER*2 ITYPE(10),INSTBL(10),ITYPE2(10),INSTBL2(10)
     + ,ITYPTEMP(10),INSTEMP(10)
            DOUBLE PRECISION L0(10),L1(10),SPOST(2000),MODF
            INTEGER ACTNC(10),ACTNCALL(10),NNACT(2000),ACTNC2(10)
     + ,ACTLL2(10),ACTNCT(10),ACALLT(10)

            COMMON/FBRDAT/F,MODF,FBL,FSPACE,AF,DF
            COMMON/ACTIVE/NACT,ACTNC,NACTALL,ACTNCALL
            COMMON/ACTIVE2/NACTTEMP,ACTNCT,NALLT,ACALLT
            COMMON/RSLTPPK/PR,EPR,PPEAK,EPEAK
            COMMON/RSLTPOST/PPOST(2000),EPOST(2000),PFAIL,EFAIL
            COMMON/RSLTULT/PULT,EULT
            COMMON/FLAGP/IFLAGP
            COMMON/CRKTYP/ITYPE,INSTBL
            COMMON/CRKTYP2/ITYPTEMP,INSTEMP
            COMMON/BNCM/NC,M
            COMMON/DELTA/DEL
            COMMON/CRKLOC/XBEG(10),XEND(10),YBEG(10),YEND(10),AA(10)
     + ,ALPHA(10)
            COMMON/CRKLOC2/XBEGTEMP(10),XENDTEMP(10),YBEGTEMP(10),
     + YENDTEMP(10),AATEMP(10)
            COMMON/NF/NFGRPA(10),NFGRPB(10)
            COMMON/NF2/NGA(10),NGB(10)
            COMMON/XFBR/NFTOTAL(10),XNEW(10,2000)
            COMMON/XFBR2/NTL(10),XNEWTEMP(10,2000)
            COMMON/FIBFORC/FBRFRC(10)
            COMMON/FIBFORC2/FBRTEMP(10)
            COMMON/FLAGPOST/JFLAG,CODP,NCRIT
            COMMON/FSULT/SIGULT,FDMG
            COMMON/COUNT/ICOUNT
            COMMON/FILELBL/NOUT,NSUM,NCONF,NFBR,NCOUNT
            COMMON/FILE/IFILE



            IF(F.LE.0.00001)THEN
            PULT=PFAIL
c           PULT=PPEAK
            EULT=EFAIL
c           EULT=EPEAK
            ICOUNT=ICOUNT+1
            STRESS=0.0
            IF(IFILE.EQ.1)WRITE(NFBR,*)EULT,STRESS
            GO TO 9999
```

```
      ENDIF

c     DELE=abs(EFAIL-PFAIL/W/D/MOD)
      DELE=EFAIL
c     DELE=EPEAK
      TOGH3=0.

      CODP=DELE*H

      DUMMY=pfail
      IF(CODP.GE.FBL/2.) GO TO 2
      JFLAG=1


      CALL FIBER(fbrfrc(ncrit))
      print*,'ncrit=',ncrit
      STRAIN=CODP/H
      I=1
c     IF(FBRFRC(NCRIT).LE.PPEAK/10.) GO TO 2
      IF(IFILE.EQ.1)WRITE(nout,*)I,STRAIN,FBRFRC(NCRIT)
      IF(IFILE.EQ.1)WRITE(NNN,*)STRAIN,FBRFRC(NCRIT)


      ICOUNT=ICOUNT+1
      DO 1001 I11=1,NC
      IF(IFILE.EQ.1)WRITE(NFBR,*)STRAIN,FBRFRC(i11)
1001  CONTINUE

      DELCOD=((1.-FDMG)*FBL/2.)/ITERPOST

      print*,'delcod=',delcod
      STRLOW=STRAIN

      DO 1 J=1,ITERPOST
      I=I+1
      CODP=CODP+DELCOD
      print*,'j= ',j,'codp=',codp
      IF(CODP.GE.(1.-FDMG)*FBL/2.)GO TO 2
      CALL FIBER(fbrfrc(ncrit))
      print*,'i=',i,'ncrit=',ncrit,'fibforc=',fbrfrc(ncrit)
c     IF(FBRFRC(NCRIT).LE.PPEAK/10.)GO TO 2
      STRAIN=CODP/H
      if(strain.ge.epsmax) go to 2
      IF(IFILE.EQ.1)WRITE(nout,*)I,STRAIN,FBRFRC(NCRIT)
      IF(IFILE.EQ.1)WRITE(NNN,*)STRAIN,FBRFRC(NCRIT)

      TOGH3=TOGH3+(STRAIN-STRLOW)*FBRFRC(NCRIT)

      ICOUNT=ICOUNT+1
      DO 1005 I11=1,NC
      IF(IFILE.EQ.1)WRITE(NFBR,*)STRAIN,FBRFRC(NCRIT)
```

```
1005      CONTINUE

          STRLOW=STRAIN

1         CONTINUE
2         CONTINUE

          PULT=FBRFRC(NCRIT)
          EULT=STRAIN

9999      RETURN
          END



*****************************************************************
          SUBROUTINE POST(DPP,DLP,W,D,TKIC,NPOST,NNN)
          IMPLICIT DOUBLE PRECISION (A - H , O - Z)
          CHARACTER*2 ITYPE(10),INSTBL(10),ITYPE2(10),INSTBL2(10)
+ ,ITYPTEMP(10),INSTEMP(10)
          DOUBLE PRECISION L0(10),L1(10),SPOST(2000),MODF
          INTEGER ACTNC(10),ACTNCALL(10),NNACT(2000),ACTNC2(10)
+ ,ACTLL2(10),ACTNCT(10),ACALLT(10)

          COMMON/FBRDAT/F,MODF,FBL,FSPACE,AF,DF
          COMMON/ACTIVE/NACT,ACTNC,NACTALL,ACTNCALL
          COMMON/ACTIVE2/NACTTEMP,ACTNCT,NALLT,ACALLT
          COMMON/RSLTPPK/PR,EPR,PPEAK,EPEAK
          COMMON/RSLTPOST/PPOST(2000),EPOST(2000),PFAIL,EFAIL
          COMMON/FLAGP/IFLAGP
          COMMON/CRKTYP/ITYPE,INSTBL
          COMMON/CRKTYP2/ITYPTEMP,INSTEMP
          COMMON/BNCM/NC,M
          COMMON/DELTA/DEL
          COMMON/CRKLOC/XBEG(10),XEND(10),YBEG(10),YEND(10),AA(10)
+ ,ALPHA(10)
          COMMON/CRKLOC2/XBEGTEMP(10),XENDTEMP(10),YBEGTEMP(10),
+ YENDTEMP(10),AATEMP(10)
          COMMON/NF/NFGRPA(10),NFGRPB(10)
          COMMON/NF2/NGA(10),NGB(10)
          COMMON/XFBR/NFTOTAL(10),XNEW(10,2000)
          COMMON/XFBR2/NTL(10),XNEWTEMP(10,2000)
          COMMON/FIBFORC/FBRFRC(10)
          COMMON/FIBFORC2/FBRTEMP(10)
          COMMON/FLAGPOST/JFLAG,CODP,NCRIT
          COMMON/COUNT/ICOUNT
          COMMON/FILELBL/NOUT,NSUM,NCONF,NFBR,NCOUNT
          COMMON/FILE/IFILE


          IF(F.LE.0.00001)THEN
```

```
      PFAIL=PPEAk/20.
      EFAIL=EPEAK
      GO TO 9999
      ENDIF

      IFAIL=0
      I=1
      CALL SET
      PPOST(1)=PPEAK-DPP
      NNACT(1)=NACT
      NACTLL2=NACTALL
      DO 19 II=1,NACT
      ACTNC2(II)=ACTNC(II)
19    CONTINUE
      DO 109 II=1,NACTALL
      ACTLL2(II)=ACTNCALL(II)
109   CONTINUE

      DO 17 K=1,NC
      ITYPE2(K)=ITYPE(K)
      INSTBL2(K)=INSTBL(K)
17    CONTINUE

1     IFLAGP=1
      NACT=NNACT(1)
      NACTALL=NACTLL2
      DO 119 II=1,NACT
      ACTNC(II)=ACTNC2(II)
119   CONTINUE
      DO 129 JJ=1,NACTALL
      ACTNCALL(JJ)=ACTLL2(JJ)
129   CONTINUE

      DO 130 II=1,NC
      ITYPE(II)=ITYPE2(II)
      INSTBL(II)=INSTBL2(II)
130   CONTINUE

      CALL RESET
      CALL FIBER(PPOST(1))
c     if(ppost(1).lt.fbrfrc(ncrit))ppost(1)=fbrfrc(ncrit)
      CALL SIF(PPOST(1))
      CALL CRIT(TKIC)

      IF(NACT.EQ.0)THEN
      CALL RESET

2     DO 37 K=1,NC
      ITYPE(K)=ITYPE2(K)
      INSTBL(K)=INSTBL2(K)
37    CONTINUE
```

```
                        DO 20 J=1,NNACT(1)
                        JJ=ACTNC2(J)
                        CALL INCLENG(JJ,ILGFLAG,W)
                        call crktype(jj,w)

                        IF(ILGFLAG.EQ.1.or.ppost(1).le.ppeak/20.) THEN
                        NCRIT=JJ
                        GO TO 5
                        ENDIF

 20                     CONTINUE
                        IFLAGP=0
                        CALL FIBER(PPOST(1))
c           if(ppost(1).lt.fbrfrc(ncrit))ppost(1)=fbrfrc(ncrit)
                        CALL SIF(PPOST(1))
                        CALL CRIT(TKIC)
                                        IF(NACT.EQ.0) THEN
                                        DO 707 K=1,NNACT(1)
                                        JJ=ACTNC2(K)
707                                     CONTINUE

                                        GO TO 2
                                        ELSE
                                        NNACT(1)=NACT
                                        DO 99 II=1,NACT
                                        ACTNC2(II)=ACTNC(II)
99                                      CONTINUE
C                       IF(EPOST(1).LT.EPEAK) EPOST(1)=EPEAK
           IF(IFILE.EQ.1)WRITE(nout,*)'***** POST PEAK VALUES *****'
           IF(IFILE.EQ.1)WRITE(nout,*)'**** STRESSES ----- STRAINS *****'
                                        CALL EFRAC(PPOST(1),EPOST(1))
                                        SPOST(1)=PPOST(1)/W/D
                                        I=1
           IF(IFILE.EQ.1)WRITE(nout,*)I,SPOST(1),EPOST(1)

IF(IFILE.EQ.1)WRITE(NNN,*)EPOST(1),SPOST(1)

                                        ICOUNT=ICOUNT+1
                                        DO 1001 I11=1,NC

IF(IFILE.EQ.1)WRITE(NFBR,*)EPOST(1),FBRFRC(I11)
1001                                    CONTINUE


                                        DO 47 K=1,NC
                                        ITYPE2(K)=ITYPE(K)
                                        INSTBL2(K)=INSTBL(K)
47                                      CONTINUE
                                        NNACT(1)=NACT
                                        CALL SET
```

```
                                    GO TO 333
                                    ENDIF
              ELSE
              CALL RESET
              PPOST(1)=PPOST(1)-DPP

              IF(PPOST(1).LT.PPEAK/20.0) THEN
              PRINT*,'PPOST(1) DROPPED BELOW PEAK/20.0'
              GO TO 333
              ENDIF


              IF(PPOST(1).LT.PPEAK/20.0) THEN
              PPOST(1)=PPOST(1)+DPP
              PRINT*,'PPOST(1) DROPPED BELOW PEAK/20.0 =',PPOST(1)

              GO TO 5
              ENDIF

              GO TO 1
              ENDIF

333           CONTINUE
              I=1


 3            I=I+1

              PPOST(I)=PPOST(I-1)-DPP
              GO TO 34

33            PPOST(I)=PPOST(I)-DPP

34            IF(PPOST(I).LE.PPEAK/20.) THEN
               IFAIL=2
              PPOST(I)=PPOST(I)+DPP

               GO TO 5
              ENDIF
              IFLAGP=1
              call fiber(ppost(i))
c             if(ppost(i).lt.fbrfrc(ncrit))ppost(i)=fbrfrc(ncrit)
              CALL SIF(PPOST(I))
              CALL CRIT(TKIC)
              IF(NACT.EQ.0)THEN
              CALL RESET

4                           DO 57 K=1,NC
                            ITYPE(K)=ITYPE2(K)
                            INSTBL(K)=INSTBL2(K)
57                          CONTINUE
```

```
                    DO 21 J=1,NNACT(I-1)
                    JJ=ACTNC2(J)
                    CALL INCLENG(JJ,ILGFLAG,W)
                    call crktype(jj,w)
                    IF(ILGFLAG.EQ.1.or.ppost(i).lt.ppeak/20.0) THEN

                    NCRIT=JJ
                     IFAIL=3
                     GO TO 5
                    ENDIF
 21                 CONTINUE
                    IFLAGP=0
                    CALL FIBER(PPOST(I))
c          if(ppost(i).lt.fbrfrc(ncrit))ppost(i)=fbrfrc(ncrit)
                    CALL SIF(PPOST(I))
                    CALL CRIT(TKIC)
                    IF(NACT.EQ.0) THEN
                    GO TO 4
                    ELSE
                    CALL EFRAC(PPOST(I),EPOST(I))
                    NNACT(I)=NACT
                    DO 29 J=1,NACT
                    ACTNC2(J)=ACTNC(J)
29                  CONTINUE
                    SPOST(I)=PPOST(I)/W/D
C                   IF(EPOST(I).LT.EPEAK) EPOST(I)=EPEAK
        IF(IFILE.EQ.1)WRITE(nout,*)I,SPOST(I),EPOST(I)
                    IF(IFILE.EQ.1)WRITE(NNN,*)EPOST(I),SPOST(I)


                    ICOUNT=ICOUNT+1

                    IF(IFILE.EQ.1) THEN
                    DO 1002 I11=1,NC
                    WRITE(NFBR,*)EPOST(I),FBRFRC(I11)
1002                CONTINUE
                    ENDIF


                    DO 67 K=1,NC
                    ITYPE2(K)=ITYPE(K)
                    INSTBL2(K)=INSTBL(K)
67                  CONTINUE

                    CALL SET

                    GO TO 3
                    ENDIF
        ELSE
        NACT=NNACT(I-1)
```

```
            DO 107 K=1,NC
            ITYPE(K)=ITYPE2(K)
            INSTBL(K)=INSTBL2(K)
107         CONTINUE

            DO 108 K=1,NACT
            ACTNC(K)=ACTNC2(K)
108         CONTINUE
            CALL RESET
            GO TO 33
            ENDIF

5           CALL EFRAC(PPOST(I),EPOST(I))
            PFAIL=PPOST(I)
            SFAIL=PPOST(I)/W/D
            EFAIL=EPOST(I)
            spost(i)=ppost(i)/w/d
            NPOST=I
 if(ifile.eq.1) write(nnn,*)epost(i),spost(i)


            IF(IFILE.EQ.1) THEN
            WRITE(nout,*)'NUMBER OF ITERATIONS TO FAILURE IS: ',NPOST
            WRITE(nout,*)'FAILURE LOAD = PPOST(NPOST) = ',PPOST(I)
            WRITE(nout,*)'FAILURE STRESS = SPOST(NPOST) = ',SPOST(I)
            WRITE(nout,*)'FAILURE STRAIN = EPOST(NPOST) =',EPOST(I)
            IF(IFAIL.EQ.2) THEN
            WRITE(nout,*)'IFAIL=2;SPECIMEN FAILED BECAUSE LOAD<PPEAK/20'
            ELSEIF(IFAIL.EQ.3) THEN
            WRITE(nout,*)'IFAIL=3;SPECIMEN FAILED BECAUSE AA(J)>W/3'
            ENDIF
            ENDIF

9999        RETURN
            END

*************************************************************************

            SUBROUTINE SET

            IMPLICIT DOUBLE PRECISION (A - H , O - Z)
            INTEGER ACTNC(10),ACTNCT(10),ACTNCALL(10),ACALLT(10)
            CHARACTER*2 ITYPE(10),ITYPTEMP(10),INSTBL(10),INSTEMP(10)
            COMMON/CRKLOC/XBEG(10),XEND(10),YBEG(10),YEND(10),AA(10),
 + ALPHA(10)
            COMMON/CRKLOC2/XBEGTEMP(10),XENDTEMP(10),YBEGTEMP(10),
 + YENDTEMP(10),AATEMP(10)
            COMMON/CRKTYP/ITYPE,INSTBL
            COMMON/CRKTYP2/ITYPTEMP,INSTEMP
            COMMON/ACTIVE/NACT,ACTNC,NACTALL,ACTNCALL
            COMMON/ACTIVE2/NACTTEMP,ACTNCT,NALLT,ACALLT
```

```
      COMMON/NF/NFGRPA(10),NFGRPB(10)
      COMMON/NF2/NGA(10),NGB(10)
      COMMON/XFBR/NFTOTAL(10),XNEW(10,2000)
      COMMON/XFBR2/NTL(10),XNEWTEMP(10,2000)
      COMMON/FIBFORC/FBRFRC(10)
      COMMON/FIBFORC2/FBRTEMP(10)
      COMMON/BNCM/NC,M

      NACTTEMP=NACT
      NALLT=NACTALL

      DO 25 I=1,NACT
      ACTNCT(I)=ACTNC(I)
25    CONTINUE

      DO 26 J=1,NACTALL
      ACALLT(J)=ACTNCALL(J)
26    CONTINUE

      DO 101 K=1,NC
      XBEGTEMP(K)=XBEG(K)
      XENDTEMP(K)=XEND(K)
      YBEGTEMP(K)=YBEG(K)
      YENDTEMP(K)=YEND(K)
      AATEMP(K)=AA(K)
      ITYPTEMP(K)=ITYPE(K)
      INSTEMP(K)=INSTBL(K)
      NGA(K)=NFGRPA(K)
      NGB(K)=NFGRPB(K)
      NTL(K)=NFTOTAL(K)
      FBRTEMP(K)=FBRFRC(K)

      DO 99 KK=1,1000
      XNEWTEMP(K,KK)=XNEW(K,KK)
99    CONTINUE
101   CONTINUE



      RETURN
      END

*********************************************************************

      SUBROUTINE RESET

      IMPLICIT DOUBLE PRECISION (A - H , O - Z)
      INTEGER ACTNC(10),ACTNCT(10),ACTNCALL(10),ACALLT(10)
      CHARACTER*2 ITYPE(10),ITYPTEMP(10),INSTBL(10),INSTEMP(10)
      COMMON/CRKLOC/XBEG(10),XEND(10),YBEG(10),YEND(10),AA(10),
     + ALPHA(10)
```

```
      COMMON/CRKLOC2/XBEGTEMP(10),XENDTEMP(10),YBEGTEMP(10),
     + YENDTEMP(10),AATEMP(10)
      COMMON/CRKTYP/ITYPE,INSTBL
      COMMON/CRKTYP2/ITYPTEMP,INSTEMP
      COMMON/ACTIVE/NACT,ACTNC,NACTALL,ACTNCALL
      COMMON/ACTIVE2/NACTTEMP,ACTNCT,NALLT,ACALLT
      COMMON/NF/NFGRPA(10),NFGRPB(10)
      COMMON/NF2/NGA(10),NGB(10)
      COMMON/XFBR/NFTOTAL(10),XNEW(10,2000)
      COMMON/XFBR2/NTL(10),XNEWTEMP(10,2000)
      COMMON/FIBFORC/FBRFRC(10)
      COMMON/FIBFORC2/FBRTEMP(10)
      COMMON/BNCM/NC,M

      NACT=NACTEMP
      NACTALL=NALLT

      DO 25 I=1,NACT
      ACTNC(I)=ACTNCT(I)
25    CONTINUE

      DO 26 J=1,NACTALL
      ACTNCALL(J)=ACALLT(J)
26    CONTINUE

      DO 101 K=1,NC
      XBEG(K)=XBEGTEMP(K)
      XEND(K)=XENDTEMP(K)
      YBEG(K)=YBEGTEMP(K)
      YEND(K)=YENDTEMP(K)
      AA(K)=AATEMP(K)
      ITYPE(K)=ITYPTEMP(K)
      INSTBL(K)=INSTEMP(K)
      NFGRPA(K)=NGA(K)
      NFGRPB(K)=NGB(K)
      NFTOTAL(K)=NTL(K)
      FBRFRC(K)=FBRTEMP(K)

      DO 99 KK=1,1000
      XNEW(K,KK)=XNEWTEMP(K,KK)
99    CONTINUE
101   CONTINUE



      RETURN
      END
*************************************************************************
      SUBROUTINE SIF(P)
      IMPLICIT DOUBLE PRECISION (A - H , O - Z)
      COMPLEX Z0(10)
```

```
      DOUBLE PRECISION L(10),ALPHA(10),A(200,200),B(200),
     + RK1(10),LK1(10),X(200)
      COMMON/B1/M,N,Z0,L,ALPHA
      COMMON/B2/A,B,X
      COMMON/B3/RK1,LK1
      COMMON/B4/W,H,D


      CALL STRESSAP(P,W,H,D)
c     open(11,file='check.sif',status='new')
      nn=2*n*m/6
      ir=2*n*m-nn*6
      CALL SETUP
      NN=2*N*M
      CALL LINEQN
      CALL SIFCALC(W)
C     IF(IFILE.EQ.1)WRITE(11,103)((i,rk1(i),lk1(i)),i=1,n)
C 103 format('1',25x,'the sifs are:',/<n>(i5,5x,f20.10,5x,f20.10/))
c     CALL OUTPUT11
      RETURN
      END
**********************************************************************
**********************************************************************
      SUBROUTINE STRESSAP(P,W,H,D)
      IMPLICIT DOUBLE PRECISION (A - H , O - Z)
      DOUBLE PRECISION L(10),ALPHA(10)
      COMPLEX Z0(10)
 COMMON/B1/M,N,Z0,L,ALPHA
      COMMON/B2/A(200,200),B(200),X(200)
      COMMON/B10/IFLAG10
      COMMON/FIBFORC/FBRFRC(10)

C     COMMON/B11/NH,NV
C     READ(1,*)ISTRESS
C     READ(1,*)PRESS
C     IF(ISTRESS.EQ.1) GO TO 15
      J=0
      JJ=N*M
      DO 10 I=1,N
      DO 20 K=1,M
      J=J+1
      JJ=JJ+1
      IF(IFLAG10.EQ.0) B(J)=-P/W/D
      IF(IFLAG10.EQ.1) B(J)=abs(FBRFRC(I))-P/W/D
      IF(B(J).GT.0) B(J)=0
      PRESS=-P/W/D
      B(JJ)=0
20    CONTINUE


 10   CONTINUE
```

```
C 15        CONTINUE
            RETURN
            END
*****************************************************************
            SUBROUTINE SETUP
            IMPLICIT DOUBLE PRECISION (A - H , O - Z)
            DOUBLE PRECISION A(200,200),B(200),X(200),D,L(10),
 + L2(10),ALPHA2(10),ALPHA(10)
            COMPLEX Z0(10),ZZ(10),ZIJ,ZB0
            DOUBLE PRECISION THETA(10)
            CHARACTER*10 FLAG
            COMMON/CRKLOC/XBEG(10),XEND(10),YBEG(10),YEND(10),L
 + ,ALPHA
            COMMON/B1/M,N,Z0,L2,ALPHA2
            COMMON/B2/A,B,X
C           COMMON/CORN/NCORN,ZZ,THETA
C           COMMON/PLANE/IPLANE,POISSON
C           COMMON/B11/NH,NV
C           COMMON/S1/PI,PR,PR1,PR2,PR3,CON,COND
C           COMMON/S2/SXXS,SXXN,SYYS,SYYN,SXYS,SXYN
C           COMMON/BET/XM(150),YM(150),ZB0(150),AA(150),BET(150),SINBET(150),
C + COSBET(150)
C           COMMON/NB/NUMBE
            PI=3.141592654
            DO 30 I=1,2*N*M
                        A(I,I)=1.0
30          CONTINUE
            IRAW=0
            DO 35 K=1,N
            DO 40 I=1,M
            IRAW=IRAW+1
            IC=0
            DO 45 LL=1,N
            IF(LL.NE.K)THEN
             DO 50 J=1,M
             DLJ=PI*L(LL)/M*SIN((2*J-1)*PI/2.0/REAL(M))
             CALL KERNELS(LL,J,K,I,FNN,FNT,FTN,FTT)
             A(IRAW,(LL-1)*M+J)=DLJ*FNN
             A(IRAW,N*M+(LL-1)*M+J)=DLJ*FTN
             A(N*M+IRAW,(LL-1)*M+J)=DLJ*FNT
             A(N*M+IRAW,N*M+(LL-1)*M+J)=DLJ*FTT
50          CONTINUE
            ENDIF
45          CONTINUE
40          CONTINUE
35          CONTINUE
            RETURN
            END
*****************************************************************
            SUBROUTINE KERNELS(LL,J,K,I,FNN,FNT,FTN,FTT)
            IMPLICIT DOUBLE PRECISION (A - H , O - Z)
```

```
      DOUBLE PRECISION FNN,FNT,FTN,FTT
      DOUBLE PRECISION L(10),SL,SK,AL,A,AL1,AL2
DOUBLE PRECISION ALPHA(10),FF
      COMPLEX Z3,ZB,ZK
      REAL TREAL
      PARAMETER (PI=3.141592654D0)
      COMPLEX Z,Z1,Z2,XL,XLB,G,G1,GB,GB1
+,GG,GG1,FN,FT,Z0(10),ZB0(10)
      COMMON/B1/M,N,Z0,L,ALPHA
C     COMMON/BET/XM(150),YM(150),ZB0,AA(150),BET(150),SINBET(150),
C + COSBET(150)
      A=L(LL)
      SL=A*DCOS(DBLE((2*J-1)*PI/2.0/REAL(M)))
      SK=L(K)*DCOS(DBLE((2*I-1)*PI/2.0/REAL(M)))
      ALL=ALPHA(LL)
      ALK=ALPHA(K)
      AL=ALL-ALK
      ZK=Z0(K)
Z=(ZK+SK*CEXP((0,1.)*REAL(ALPHA(K)))-Z0(LL))
+ *CEXP((0,-1.)*REAL(ALPHA(LL)))
      X=REAL(Z)
      Y=AIMAG(Z)
      R1=SQRT(Y*Y+(X-A)*(X-A))
      R2=SQRT(Y*Y+(X+A)*(X+A))
      T=TH(X,Y,A)

      TREAL=REAL(T)
      Z3=CMPLX(0.,TREAL)
      XL=SQRT(R1*R2)*(COS(T)+(0,1)*SIN(T))

C     IF(X.GT.A)XL=SQRT(X*X-A*A)
C     IF(X.LT.-A)XL=-SQRT(X*X-A*A)
C     IF(ABS(X).LT.A)XL=(0,-1)*SQRT(A*A-X*X)

      T=TH(X,-Y,A)
      TREAL=REAL(T)
      Z3=CMPLX(0.,TREAL)
      XLB=SQRT(R1*R2)*CEXP(Z3)
      G=(1.0,0.0)/XL/(Z-SL)
      GB=(1.,0.0)/XLB/(CONJG(Z)-SL)
      G1=G/(0.,1.)
      GB1=GB/(0.,1.)
      ZB=CONJG(Z)
      GG=(A**2+SL*Z-2.0*Z**2)/XL**3/(Z-SL)**2
      GG1=GG/(0.,1.)
      AL2=2*AL
      AL1=0.0
      Z1=CMPLX(REAL(AL1),REAL(AL2))

      FN=-(G+CONJG(G)+CEXP(Z1)*(Z-CONJG(Z))*CONJG(GG))*
+ SQRT(A**2-SL**2)/2.0/PI
```

```
      FT=(CONJG(G)*(1.-2.*CEXP(Z1))-G+CEXP(Z1)*(Z-CONJG(Z))*
     + CONJG(GG))*SQRT(A**2-SL**2)/2./PI/(0.,1.)

      FNN=REAL(FN)
      FNT=-AIMAG(FN)
      FTN=REAL(FT)
      FTT=-AIMAG(FT)



      RETURN
      END
*****************************************************************
      DOUBLE PRECISION FUNCTION TH(X,Y,A)
      IMPLICIT DOUBLE PRECISION (A - H , O - Z)
      DOUBLE PRECISION X,Y,A
      PI=3.141592654
      IF(Y.EQ.0.)GO TO 10
      IF(X.GT.A) THEN
      TH=.5*(ATAN2(Y,X-A)+ATAN2(Y,X+A))
      ELSEIF(X.LT.-A) THEN
      TH=PI-.5*(ATAN2(Y,A-X)+ATAN2(Y,-X-A))
      ELSE
      IF(Y.GT.0.) TH=PI/2.+.5*(ATAN2(Y,X+A)-ATAN2(Y,A-X))
      IF(Y.LT.0.) TH=.5*(3.*PI+ATAN2(-Y,A-X)-ATAN2(-Y,A+X))
      ENDIF
      IF(X.EQ.A)THEN
      IF(Y.GT.0.) TH=.5*(PI/2.+ATAN2(Y,2.*A))
      IF(Y.LT.0.) TH=.5*(3.5*PI-ATAN2(-Y,2.*A))
      ENDIF
      IF(X.EQ.-A) THEN
      IF(Y.GT.0.) TH=.5*(1.5*PI-ATAN2(Y,2.*A))
      IF(Y.LT.0.) TH=.5*(2.5*PI+ATAN2(-Y,2.*A))
      ENDIF
      GO TO 11
10    IF(X.GT.A) TH=0.
      IF(X.LT.-A) TH=PI
11    CONTINUE
      RETURN
      END
*****************************************************************
 SUBROUTINE LINEQN
      IMPLICIT DOUBLE PRECISION (A - H , O - Z)
      DOUBLE PRECISION A(200,200),B(200),X(200),
     + AM(200,200),L(10)
      INTEGER IPIVOT(200)
      COMPLEX Z0(10)
      COMMON/B1/M,N,Z0,L,ALPHA(10)
      COMMON/B2/A,B,X
      COMMON/PIVOT/IPIVOT,AM
C     COMMON/NB/NUMBE
```

```
NN=N*M
      CALL FACTOR(NN)
      CALL SOLVE(NN)
RETURN
END
*****************************************************************
SUBROUTINE FACTOR(N)
      IMPLICIT DOUBLE PRECISION (A - H , O - Z)
DOUBLE PRECISION A(200,200),AM(200,200),B(200),X(200)
INTEGER IPIVOT(200)
      COMMON/B2/A,B,X
      COMMON/PIVOT/IPIVOT,AM



NM1=N-1
      DO 8 I=1,NM1
      PIVOT=0.0
      DO 3 J=I,N
      TEMP=ABS(A(J,I))
      IF(PIVOT.GE.TEMP) GO TO 3
      PIVOT=TEMP
      IPIVOT(I)=J
3     CONTINUE
      IF(PIVOT.EQ.0.0) GO TO 13
      IF(IPIVOT(I).EQ.I) GO TO 5
      DO 4 K=1,N
      TEMP=A(I,K)
      A(I,K)=A(IPIVOT(I),K)
      A(IPIVOT(I),K)=TEMP
4 CONTINUE
5     IP1=I+1
      DO 7 K=IP1,N
      AM(K,I)=-A(K,I)/A(I,I)
      A(K,I)=0.0
      DO 6 J=IP1,N

      A(K,J)=AM(K,I)*A(I,J)+A(K,J)


6     CONTINUE
7 CONTINUE
8 CONTINUE
13    RETURN
      END
*****************************************************************
      SUBROUTINE SOLVE(N)
      IMPLICIT DOUBLE PRECISION (A - H , O - Z)
DOUBLE PRECISION A(200,200),B(200),X(200),AM(200,200)
INTEGER IPIVOT(200)
      COMMON/B2/A,B,X
```

```
      COMMON/PIVOT/IPIVOT,AM

      DO 8 I=1,N-1
J=I
      TEMP=B(I)
      B(I)=B(IPIVOT(I))
      B(IPIVOT(I))=TEMP
      DO 7 K=J+1,N
      B(K)=AM(K,J)*B(J)+B(K)
7     CONTINUE
8     CONTINUE
      X(N)=B(N)/A(N,N)
      DO 10 K=1,N-1
      Q=0.0
      DO 9 J=1,K
QQ=Q

      Q=QQ+A(N-K,N+1-J)*X(N+1-J)


9     CONTINUE
      X(N-K)=(B(N-K)-Q)/A(N-K,N-K)
10    CONTINUE
      RETURN
      END
*****************************************************************
      SUBROUTINE SIFCALC(W)
      IMPLICIT DOUBLE PRECISION (A - H , O - Z)
      COMPLEX Z0(10)
      CHARACTER*2 ITYPE(10),INSTBL(10)
      DOUBLE PRECISION RK1(10),LK1(10),RK2(10),LK2(10),L(10)
+ ,AV1(10),TM,SM,ALPHA(10)
      PARAMETER (PI=3.141592654)
      COMMON/B1/M,N,Z0,L,ALPHA
      COMMON/CRKLOC/XBEG(10),XEND(10),YBEG(10),YEND(10),AA(10),
+ ALPHA2(10)
      COMMON/B2/A(200,200),B(200),X(200)
      COMMON/B3/RK1,LK1
      COMMON/CRKTYP/ITYPE,INSTBL

      DO 55 LL=1,N


      L(LL)=AA(LL)

                  RK1(LL)=0.0
                  RK2(LL)=0.
                  LK1(LL)=0.0
                  LK2(LL)=0.
                  DO 60 I=1,M
      TM=COS((2*I-1)*PI/2.0/REAL(M))
```

```
            SM=SIN((2*I-1)*PI/2./REAL(M))
            RK1(LL)=RK1(LL)+X((LL-1)*M+I)*L(LL)*(1+TM)
            LK1(LL)=LK1(LL)+X((LL-1)*M+I)*L(LL)*(1-TM)
            RK2(LL)=RK2(LL)+X(N*M+(LL-1)*M+I)*L(LL)*(1+TM)
            LK2(LL)=LK2(LL)+X(N*M+(LL-1)*M+I)*L(LL)*(1-TM)

60          CONTINUE

            A1=L(LL)

            BETA=1.0+0.256*A1/W-1.152*(A1/W)**2+12.2*(A1/W)**3

            IF(ITYPE(LL).NE.'IN') THEN

            BETA=1.12-0.23*A1/W+10.56*(A1/W)**2-21.74*(A1/W)**3
+ +30.42*(A1/W)**4

            ENDIF

            RK1(LL)=-BETA*SQRT(PI/L(LL))*RK1(LL)/REAL(M)
            LK1(LL)=-BETA*SQRT(PI/L(LL))*LK1(LL)/REAL(M)
            RK2(LL)=-BETA*SQRT(PI/L(LL))*RK2(LL)/REAL(M)
            LK2(LL)=-BETA*SQRT(PI/L(LL))*LK2(LL)/REAL(M)




55          CONTINUE
            RETURN
            END
*************************************************************************
```

Appendix B:

Postprocessor Source Code

APPENDEX B: Postprocessor Source Code

```
 PROGRAM POSTP
C
C Define the data arrays.
C
 REAL MOD0,MODF,XDRA(3000,100),YDRA(3000,100)
            INTEGER NUMF(10),UN(10)
            CHARACTER*20 FIL(10),DEVICE,FTYPE
            CHARACTER*60 TITLE
            CHARACTER*60 HEAD,HEAD1
            CHARACTER*50 BUFF
            CHARACTER*16 BUFFM(50)
            CHARACTER*16 AGDSHN(50),AGBNCH(50)
            CHARACTER*10 VAR1,VAR
            DIMENSION XRA(200),YRA(200),DST(220),IND(240)
C

            OPEN(51,FILE='frc2.dat',STATUS='OLD')

            OPEN(50,FILE='SUMALL',STATUS='OLD')

            OPEN(49,FILE='STRSVAR',STATUS='OLD')
            OPEN(48,FILE='STRNVAR',STATUS='OLD')

C Initialize GKS.
C
 CALL OPNGKS
C
C Specify subscripting of XDRA and YDRA.
C


            READ(51,*)TITLE
            READ(51,*)NMAT,NTEST,NRAND
            READ(51,*)FTYPE,F,MODF,FBL,DF,IFBFLAG,SIGULT,FDMG
            PI=3.141592654
            READ(51,*)ISEED,NL
            READ(51,*)P1,NS1,DPMAX,DPMIN,NMAX,NMIN,MAXFLAG
            READ(51,*)DPP,NLP
            READ(51,*)NBOND,NVOID,M
            READ(51,*)MOD0,TKI0,TAU,W,H,D,AGGRAD,AGGVOL
            READ(51,*)TOLS,TOL1
            READ(51,*)ITERPOST
            READ(51,*)NVAR,VAR,VARMIN,DELVAR
            READ(51,*)IFILE,ISTAT
            READ(51,*)ALTAU
            READ(51,*)CONFLEV
            READ(51,*)EFCT
```

```
C
      PRINT*,'ENTER maximum strain levels 1 & 2, '

      print*,' and maximum stress level for the curve plots'
      print*,' you need to enter three values..'
C
      read*,xmax,xmax2,ymax

      IPLOT=0

      PRINT*,'ENTER IPLOTFLAG VALUE'
      PRINT*,'ENTER 0 FOR THE COMPLETE SET OF FRAMES'
      PRINT*,'ENTER 1 FOR THE SUMMARY SET OF VAR VRS. OUTPUT'

      READ*,IPLOT

c plot NRAND stress-strain curve for each material

      DO 1020 IVAR=1,NVAR

      II=IVAR-1



      WRITE(BUFF,994)IVAR
994   FORMAT('CONF',I1)
      NCONF=30+IVAR
      OPEN(NCONF,FILE=BUFF,STATUS='OLD')

      WRITE(BUFF,995)IVAR
995   FORMAT('FBR',I1)
      NFBR=60+IVAR
      OPEN(NFBR,FILE=BUFF,STATUS='OLD')

      WRITE(BUFF,996)IVAR
996   FORMAT('COUNT',I1)
      NCOUNT=70+IVAR
      OPEN(NCOUNT,FILE=BUFF,STATUS='OLD')



      IF(IPLOT.EQ.1) GO TO 1021

      DO 19 J=1,NRAND

      UN(J)=80+IVAR*NRAND+J
      WRITE(BUFF,997)IVAR,J
997   FORMAT('PLOT',I1,I1)

      OPEN(UNIT=UN(J),FILE=BUFF,STATUS='OLD')
```

```
      READ(UN(J),*,END=18)(XDRA(I,J),YDRA(I,J),I=1,3000)
18    NUMF(J)=I-1

19    CONTINUE
C
      MAX=0
      DO 17 I=1,NRAND
      IF(MAX.LT.NUMF(I)) MAX=NUMF(I)
17    CONTINUE


      DO 16 J=1,NRAND
      IF(NUMF(J).LT.MAX)THEN
      DO 15 I=NUMF(J),MAX

      XDRA(I,J)=XDRA(NUMF(J),J)
      YDRA(I,J)=YDRA(NUMF(J),J)

15    CONTINUE
      ENDIF
16    CONTINUE

      CALL DISPLA(2,2,1)
CALL AGSETI ('ROW.',2)
      CALL AGSETI('WINDOWING.',1)

      CALL AGSETF('GRID/LEFT.',.05)
      CALL AGSETF('GRID/RIGHT.',.50)
      CALL AGSETF('GRID/BOTTOM.',.50)
      CALL AGSETF('GRID/TOP.',.975)

      CALL SET(0.,1.,0.,1.,0.,1.,0.,1.,1)

      XRA(1)=.505
      YRA(1)=.50
      XRA(2)=.505
      YRA(2)=.975
      XRA(3)=.975
      YRA(3)=.975
      XRA(4)=.975
      YRA(4)=.50
      XRA(5)=XRA(1)
      YRA(5)=YRA(1)
      CALL CURVE(XRA,YRA,5)

      call pwrit(.75,.985,'DATA INPUT',10,1,0,0)
      CALL PWRIT(.75,.95,TITLE,30,1,0,0)
```

```
      CALL PWRIT(.75,.925,'VF -- MODF -- FBL -- DF - SGULT -FDMG',
     + 42,1,0,0)
      WRITE(BUFF,1002)F
1001  FORMAT(F10.2)
1002  FORMAT(F10.6)
      CALL PWRIT(.54,.90,BUFF,6,1,0,0)
      WRITE(BUFF,1001)MODF
      CALL PWRIT(.62,.90,BUFF,7,1,0,0)
      WRITE(BUFF,1002)FBL
      CALL PWRIT(.70,.90,BUFF,7,1,0,0)
      WRITE(BUFF,1002)DF
      CALL PWRIT(.78,.90,BUFF,8,1,0,0)
      WRITE(BUFF,1001)SIGULT
      CALL PWRIT(.85,.90,BUFF,8,1,0,0)
      WRITE(BUFF,1002)FDMG
      CALL PWRIT(.92,.90,BUFF,8,1,0,0)
      CALL PWRIT(.65,.875,'NBOND --- NVOID --- M',22,1,0,0)
      WRITE(BUFF,1003)NBOND
1003  FORMAT(I3)
      CALL PWRIT(.55,.85,BUFF,3,1,0,0)
      WRITE(BUFF,1003)NVOID
      CALL PWRIT(.65,.85,BUFF,3,1,0,0)
      WRITE(BUFF,1003)M
      CALL PWRIT(.75,.85,BUFF,3,1,0,0)
      CALL PWRIT(.65,.825,'MOD0 --- TKI0 --- TAU',22,1,0,0)
      WRITE(BUFF,1001)MOD0
      CALL PWRIT(.55,.8,BUFF,8,1,0,0)
      WRITE(BUFF,1002)TKI0
      CALL PWRIT(.65,.8,BUFF,8,1,0,0)
      WRITE(BUFF,1002)TAU
      CALL PWRIT(.75,.8,BUFF,8,1,0,0)
      CALL PWRIT(.55,.775,'TOL',3,1,0,0)
      WRITE(BUFF,1002)TOLS
      CALL PWRIT(.55,.75,BUFF,10,1,0,0)
      WRITE(BUFF,1991)
1991  FORMAT(' NVAR VAR VARMIN DELVAR')
      CALL PWRIT(.65,.725,BUFF,40,1,0,0)
      WRITE(BUFF,1992)NVAR,VAR,VARMIN,DELVAR
1992  FORMAT(10x,I2,2X,A4,2X,F6.4,2X,F6.4)
      CALL PWRIT(.65,.70,BUFF,40,1,0,0)
      CALL AGSETF('X/MIN.',0.)
      CALL AGSETF('X/MAX.',XMAX)
      CALL AGSETF('Y/MIN.',0.)
      CALL AGSETF('Y/MAX.',YMAX)

      CALL AGSETI('LEFT/MAJOR/TYPE.',1)
      CALL AGSETF('LEFT/MAJOR/BASE.',.1)
      CALL AGSETI('LEFT/MINOR/SPACING.',1)

      CALL AGSETI('BOTTOM/MAJOR/TYPE.',1)
      CALL AGSETF('BOTTOM/MAJOR/BASE.',0.0001)
```

```
            CALL AGSETI('BOTTOM/MINOR/SPACING.',5)

            CALL AGSETC('LABEL/NAME.','L')
            CALL AGSETI('LINE/NUMBER.',100)
            CALL AGSETC('LINE/TEXT.','STRESSES (IN KSI)$')

            CALL AGSETC('LABEL/NAME.','B')
            CALL AGSETI('LINE/NUMBER.',-100)
            CALL AGSETC('LINE/TEXT.','STRAINS$')

C
C Change text of bottom label.
C
 CALL AGSETC ('LABEL/NAME.','B')
 CALL AGSETI ('LINE/NUMBER.',-100)
 CALL AGSETC ('LINE/TEXT.','STRAINS $')
C
C
C Draw the graph, using EZMXY.
C
            vartemp=varmin+(ivar-1)*delvar
            if(var.eq.'f'.or.var.eq.'F') then
            var='vf'
            var1='vf(%)'
            else
            var1=var
            endif

            write(head1,8000)var1,vartemp
C
8000        format(' Stress-Strain Curves; [',a5,'=',f8.4,']')

C           CALL SET(0.,1.,.5,1.,0.,XMAX,0.,YMAX,1)
 CALL EZMXY (XDRA,YDRA,3000,NRAND,MAX,head1)

C
C
*****************************************
c*****************************************
c
            NC=NBOND+NVOID
            IROW=NRAND

            ICOL=4
            IF(IROW.GT.3) IROW=3

            BOTT=.1
            TOP=.2
```

```
      DO 22 IK=1,IROW
      ALEFT=.05
      RIGHT=.15

      IF(IK.NE.1)THEN
      BOTT=BOTT+.1+.025
      TOP=BOTT+.1
      ENDIF

      do 21 ij=1,ICOL

      IF(IJ.NE.1) THEN
      ALEFT=ALEFT+.1+.025
      RIGHT=ALEFT+.1
      ENDIF

      CALL SET(ALEFT,RIGHT,BOTT,TOP,0.,1.,-0.25,1.25,1)
      DO 100 LL=1,NC
      READ(NCONF,*)XRA(1),YRA(1),XRA(2),YRA(2)
      IF(XRA(1).LT.0.) XRA(1)=0.
      IF(XRA(2).LT.0.) XRA(2)=0.
      IF(XRA(2).GT.1.) XRA(2)=1.

      CALL CURVE(XRA,YRA,2)
100   CONTINUE

      IF(IJ.GE.3) THEN
      READ(NCONF,*)XRA(1),YRA(1),XRA(2),YRA(2)
      IF(XRA(1).NE.0.)XRA(1)=0.
      IF(XRA(2).NE.1)XRA(2)=1.
      CALL CURVE(XRA,YRA,2)
      IF(IJ.EQ.4) THEN
      XRA(1)=0.
      YRA(1)=YRA(1)-FBL/2
      XRA(2)=1.
      YRA(2)=YRA(2)-FBL/2
      CALL CURVE(XRA,YRA,2)
      ENDIF
      ENDIF


      XRA(1)=0.
      YRA(1)=-0.25
      XRA(2)=0.
      YRA(2)=1.25
      XRA(3)=1.
      YRA(3)=1.25
      XRA(4)=1.
      YRA(4)=-0.25
      XRA(5)=XRA(1)
      YRA(5)=YRA(1)
```

```
            CALL CURVE(XRA,YRA,5)

21          continue
22          CONTINUE
            call set(0.,1.,0.,1.,0.,1.,0.,1.,1)
            call pwrit(0.1,0.05,'original',8,1,0,0)
            call pwrit(.225,0.05,'peak',4,1,0,0)
            call pwrit(.350,0.05,'post',4,1,0,0)
            call pwrit(.475,0.05,'fail',4,1,0,0)

            CALL FRAME

C**********************

c what follows draws the crack patterns in a separate page
c for each material, therefore I'am skipping it.

            go to 8001

            REWIND NCONF
            IROW=NRAND

            ICOL=4
            IF(IROW.GT.3) IROW=3

            BOTT=.05
            TOP=.31



            DO 202 IK=1,IROW
            ALEFT=.025
            RIGHT=.25

            IF(IK.NE.1)THEN
            BOTT=BOTT+.26+.025
            TOP=BOTT+.26
            ENDIF

            do 201 ij=1,ICOL

            IF(IJ.NE.1) THEN
            ALEFT=ALEFT+.225+.025
            RIGHT=ALEFT+.225
            ENDIF

            CALL SET(ALEFT,RIGHT,BOTT,TOP,0.,1.,-0.25,1.25,1)
            DO 1000 LL=1,NC
            READ(NCONF,*)XRA(1),YRA(1),XRA(2),YRA(2)
            IF(XRA(1).LT.0.) XRA(1)=0.
```

```
            IF(XRA(2).LT.0.) XRA(2)=0.
            IF(XRA(2).GT.1.) XRA(2)=1.

            CALL CURVE(XRA,YRA,2)
1000        CONTINUE


            IF(IJ.GE.3) THEN
            READ(NCONF,*)XRA(1),YRA(1),XRA(2),YRA(2)
            IF(XRA(1).NE.0.)XRA(1)=0.
            IF(XRA(2).NE.1)XRA(2)=1.
            CALL CURVE(XRA,YRA,2)
            IF(IJ.EQ.4) THEN
            XRA(1)=0.
            YRA(1)=YRA(1)-FBL/10.
            XRA(2)=1.
            YRA(2)=YRA(2)-FBL/10.
            CALL CURVE(XRA,YRA,2)
            ENDIF
            ENDIF


            XRA(1)=0.
            YRA(1)=-0.25
            XRA(2)=0.
            YRA(2)=1.25
            XRA(3)=1.
            YRA(3)=1.25
            XRA(4)=1.
            YRA(4)=-0.25
            XRA(5)=XRA(1)
            YRA(5)=YRA(1)

            CALL CURVE(XRA,YRA,5)

201         continue
202         CONTINUE
            call set(0.,1.,0.,1.,0.,1.,0.,1.,1)
            call pwrit(0.15,0.025,'original',8,1,0,0)
            call pwrit(.40,0.025,'peak',4,1,0,0)
            call pwrit(.65,0.025,'post',4,1,0,0)
            call pwrit(.88,0.025,'fail',4,1,0,0)
            call pwrit(.5,.95,'CRACK PROPAGATION PATTERNS',28,2,0,0)
            call frame


c what follows draws the fiber forces for each specimen, It is skipped

            NRAND1=NRAND
            IF(NRAND1.GT.4) NRAND1=4
```

```
      DO 191 J=1,NRAND1

      READ(NCOUNT,*)ICOUNT

      DO 192 J1=1,ICOUNT

      DO 193 J2=1,NC

      READ(NFBR,*)XDRA(J1,J2),YDRA(J1,J2)

193   CONTINUE
192   CONTINUE


      MAX=ICOUNT

      CALL DISPLA(2,2,1)
CALL AGSETI ('ROW.',2)
      CALL AGSETI('WINDOWING.',1)

      IF(J.LE.2)THEN
      BOTT=.05
      TOP=.45
      ALEFT=.05+(J-1)*(.55)
      RIGHT=J*.5
      ELSE
      JJ1=J-2
      BOTT=.55
      TOP=.95
      ALEFT=.05+(JJ1-1)*.55
      RIGHT=JJ1*.5
      ENDIF

      CALL AGSETF('GRID/LEFT.',ALEFT)
      CALL AGSETF('GRID/RIGHT.',RIGHT)
      CALL AGSETF('GRID/BOTTOM.',BOTT)
      CALL AGSETF('GRID/TOP.',TOP)
      YMAX2=2.*YMAX
      CALL AGSETF('X/MIN.',0.)
      CALL AGSETF('X/MAX.',XMAX2)
      CALL AGSETF('Y/MIN.',0.)
      CALL AGSETF('Y/MAX.',YMAX2)

      CALL AGSETI('LEFT/MAJOR/TYPE.',1)
      CALL AGSETF('LEFT/MAJOR/BASE.',.5)
      CALL AGSETI('LEFT/MINOR/SPACING.',1)

      CALL AGSETI('BOTTOM/MAJOR/TYPE.',1)
      CALL AGSETF('BOTTOM/MAJOR/BASE.',0.005)
      CALL AGSETI('BOTTOM/MINOR/SPACING.',1)
```

```
            CALL AGSETC('LABEL/NAME.','L')
            CALL AGSETI('LINE/NUMBER.',100)
            CALL AGSETC('LINE/TEXT.','AVG. FIBERS STRESS (KSI) ON CRACKS$')

            CALL AGSETC('LABEL/NAME.','B')
            CALL AGSETI('LINE/NUMBER.',-100)
            CALL AGSETC('LINE/TEXT.','STRAINS$')


            WRITE(BUFF,1009)J
1009        FORMAT(' SPECIMEN No: ',I1)
C
C Draw the graph, using EZMXY.
C

C           CALL SET(0.,1.,.5,1.,0.,XMAX,0.,YMAX,1)
 CALL EZMXY (XDRA,YDRA,3000,NC,MAX,BUFF)

C
191         CONTINUE

            CALL FRAME
C
8001        continue

1021        CONTINUE
1020        CONTINUE


**********************************
**********************************

            MAX=0
            JJ=0
            DO 78 IVAR=1,NVAR
            DO 79 J=1,NRAND
            JJ=JJ+1

            WRITE(BUFFM(JJ),991)VAR,IVAR
991         FORMAT('$$$$$',A3,I1,'$$$$$')
            AGDSHN(JJ)=BUFFM(JJ)

            UN(J)=80+IVAR*NRAND+J
            WRITE(BUFF,797)IVAR,J
797         FORMAT('PLOT',I1,I1)
            IF(IPLOT.EQ.0) THEN
            REWIND UN(J)
            ELSE
            OPEN(UNIT=UN(J),FILE=BUFF,STATUS='OLD')
            ENDIF
```

```
      READ(UN(J),*,END=998)(XDRA(I,JJ),YDRA(I,JJ),I=1,3000)
998   NUMF(JJ)=I-1


C


      IF(MAX.LT.NUMF(jj)) MAX=NUMF(jj)
79    continue
78    continue

      DO 177 I=1,JJ
      IF(NUMF(I).LT.MAX)THEN
      DO 277 III=NUMF(I)-1,MAX
      XDRA(III,i)=XDRA((NUMF(I)-1),i)
      YDRA(III,i)=YDRA((NUMF(I)-1),i)
277   CONTINUE
      ENDIF
177   CONTINUE



      CALL DISPLA(2,2,1)
 CALL AGSETI ('ROW.',2)
      CALL AGSETI('WINDOWING.',1)

      CALL AGSETF('GRID/LEFT.',.1)
      CALL AGSETF('GRID/RIGHT.',.850)
      CALL AGSETF('GRID/BOTTOM.',.10)
      CALL AGSETF('GRID/TOP.',.90)

      CALL SET(0.,1.,0.,1.,0.,1.,0.,1.,1)
      CALL AGSETF('X/MIN.',0.)
      CALL AGSETF('X/MAX.',XMAX)
      CALL AGSETF('Y/MIN.',0.)
      CALL AGSETF('Y/MAX.',YMAX)

      CALL AGSETI('LEFT/MAJOR/TYPE.',1)
      CALL AGSETF('LEFT/MAJOR/BASE.',.5)
      CALL AGSETI('LEFT/MINOR/SPACING.',1)

      CALL AGSETI('BOTTOM/MAJOR/TYPE.',1)
      CALL AGSETF('BOTTOM/MAJOR/BASE.',0.001)
      CALL AGSETI('BOTTOM/MINOR/SPACING.',1)

      CALL AGSETC('LABEL/NAME.','L')
      CALL AGSETI('LINE/NUMBER.',100)
      CALL AGSETC('LINE/TEXT.','STRESSES (IN KSI)$')

      CALL AGSETC('LABEL/NAME.','B')
      CALL AGSETI('LINE/NUMBER.',-100)
```

```
            CALL AGSETC('LINE/TEXT.','STRAINS$')

C
C Change text of bottom label.
C
 CALL AGSETC ('LABEL/NAME.','B')
 CALL AGSETI ('LINE/NUMBER.',-100)
 CALL AGSETC ('LINE/TEXT.','STRAINS $')
C
C
C Draw the graph, using EZMXY.
C
            CALL ANOTAT('STRAINS','STRESSES (KSI)',1,0,50,AGDSHN)
C           CALL SET(0.,1.,.5,1.,0.,XMAX,0.,YMAX,1)
            head1='Stress-Strain Curves; All materials'
            call ezmxy(xdra,ydra,3000,jj,max,head1)

            CALL FRAME


c************************************
************************************



            OPEN(UNIT=50,FILE='SUMALL',STATUS='OLD')
C           CALL AGSETI('DASH/SELECTOR.',1)

            CALL SET(0.1,.9,0.1,.9,0.,XMAX,0.,YMAX,1)

            JJ=NVAR

            DO 1022 IVAR=1, NVAR


            XDRA(1,IVAR)=0
            YDRA(1,IVAR)=0

            DO 1023 NN=2,6

            READ(50,*)X1,X2,Y1,Y2,X,Y

            JJ=JJ+1

            XDRA(1,JJ)=X1
            YDRA(1,JJ)=Y1
            XDRA(2,JJ)=X1
            YDRA(2,JJ)=Y2
            XDRA(3,JJ)=X2
            YDRA(3,JJ)=Y2
            XDRA(4,JJ)=X2
```

```
            YDRA(4,JJ)=Y1
            XDRA(5,JJ)=XDRA(1,JJ)
            YDRA(5,JJ)=YDRA(1,JJ)
            XDRA(6,JJ)=XDRA(1,JJ)
            YDRA(6,JJ)=YDRA(1,JJ)

            XDRA(NN,IVAR)=X
            YDRA(NN,IVAR)=Y
1023        CONTINUE
1022        CONTINUE



            CALL DISPLA(2,2,1)
 CALL AGSETI ('ROW.',2)
            CALL AGSETI('WINDOWING.',1)

C           CALL AGSETI('DASH/SELECTOR.',26)

            CALL AGSETF('GRID/LEFT.',.1)
            CALL AGSETF('GRID/RIGHT.',.9)
            CALL AGSETF('GRID/BOTTOM.',.1)
            CALL AGSETF('GRID/TOP.',.9)


            CALL AGSETF('X/MIN.',0.)
            CALL AGSETF('X/MAX.',XMAX)
            CALL AGSETF('Y/MIN.',0.)
            CALL AGSETF('Y/MAX.',YMAX)

            CALL AGSETI('LEFT/MAJOR/TYPE.',1)
            CALL AGSETF('LEFT/MAJOR/BASE.',.5)
            CALL AGSETI('LEFT/MINOR/SPACING.',1)

            CALL AGSETI('BOTTOM/MAJOR/TYPE.',1)
            CALL AGSETF('BOTTOM/MAJOR/BASE.',0.001)
            CALL AGSETI('BOTTOM/MINOR/SPACING.',5)

            CALL AGSETC('LABEL/NAME.','L')
            CALL AGSETI('LINE/NUMBER.',100)
            CALL AGSETC('LINE/TEXT.','STRESSES (IN KSI)$')

            CALL AGSETC('LABEL/NAME.','B')
            CALL AGSETI('LINE/NUMBER.',-100)
            CALL AGSETC('LINE/TEXT.','STRAINS$')

C
C Change text of bottom label.
C
 CALL AGSETC ('LABEL/NAME.','B')
```

```
 CALL AGSETI ('LINE/NUMBER.',-100)
 CALL AGSETC ('LINE/TEXT.','STRAINS $')
C
C
C Draw the graph, using EZMXY.
C

C          CALL SET(0.,1.,.5,1.,0.,XMAX,0.,YMAX,1)

           DO 1026 IVAR=1,JJ

           IF(IVAR.LE.NVAR)THEN
           WRITE(BUFFM(IVAR),1028)VAR,IVAR
1028       FORMAT('$',A3,I1,'$$$$$$')
           AGDSHN(IVAR)=BUFFM(IVAR)
           ELSE
           AGDSHN(IVAR)='$$$$$$$$$$$'
           ENDIF
1026       CONTINUE

           CALL ANOTAT('STRAINS','STRESSES (KSI) ',1,0,50,AGDSHN)


           MAX=6
           WRITE(HEAD,1029)VAR
1029       FORMAT('STRESS-STRAIN CURVES VS. ',A3)

 CALL EZMXY (XDRA,YDRA,3000,JJ,6,HEAD)

           CALL FRAME

           CALL AGSETF('X/MAX.',XMAX2)
           CALL AGSETF('X/MIN.',-.002)
           CALL ANOTAT('STRAINS','STRESSES (KSI)',1,0,50,AGDSHN)
           CALL EZMXY (XDRA,YDRA,3000,NVAR,6,HEAD)
           CALL FRAME

**************************************************
**************************************************

           OPEN(UNIT=49,FILE='STRSVAR',STATUS='OLD')

           XMAX1=XMAX
           XMAX=VARMIN+DELVAR*(NVAR-1)+DELVAR/2.

           JJ=5

           BUFFM(1)='$$$A*$$$$'
           BUFFM(2)='$$$A1$$$$'
           BUFFM(3)='$$$PEAK$$$'
           BUFFM(4)='$$$FAIL$$$'
```

```
      BUFFM(5)='$$$ULTM$$$'
      DO 1122 IVAR=1, NVAR


      DO 1123 NN=1,5

      READ(49,*)X,Y1,Y,Y2,SD

      JJ=JJ+1

      XDRA(1,JJ)=X
      YDRA(1,JJ)=Y1
      XDRA(2,JJ)=X
      YDRA(2,JJ)=Y2
      XDRA(3,JJ)=X
      YDRA(3,JJ)=Y2
      XDRA(4,JJ)=X
      YDRA(4,JJ)=Y2
      XDRA(5,JJ)=XDRA(1,JJ)
      YDRA(5,JJ)=YDRA(1,JJ)
      XDRA(6,JJ)=XDRA(1,JJ)
      YDRA(6,JJ)=YDRA(1,JJ)

      AGDSHN(NN)=BUFFM(NN)
      XDRA(IVAR,NN)=X
      YDRA(IVAR,NN)=Y
1123  CONTINUE
1122  CONTINUE



      CALL DISPLA(2,2,1)
 CALL AGSETI ('ROW.',2)
      CALL AGSETI('WINDOWING.',1)

C     CALL AGSETI('DASH/SELECTOR.',26)

      CALL AGSETF('GRID/LEFT.',.1)
      CALL AGSETF('GRID/RIGHT.',.9)
      CALL AGSETF('GRID/BOTTOM.',.1)
      CALL AGSETF('GRID/TOP.',.9)


      CALL AGSETF('X/MIN.',0.)
      CALL AGSETF('X/MAX.',XMAX)
      CALL AGSETF('Y/MIN.',0.)
      CALL AGSETF('Y/MAX.',YMAX)

      CALL AGSETI('LEFT/MAJOR/TYPE.',1)
      CALL AGSETF('LEFT/MAJOR/BASE.',.5)
```

```
            CALL AGSETI('LEFT/MINOR/SPACING.',1)

            BASE=DELVAR/4.
            CALL AGSETI('BOTTOM/MAJOR/TYPE.',1)
            CALL AGSETF('BOTTOM/MAJOR/BASE.',BASE)
            CALL AGSETI('BOTTOM/MINOR/SPACING.',1)

            CALL AGSETC('LABEL/NAME.','L')
            CALL AGSETI('LINE/NUMBER.',100)
            CALL AGSETC('LINE/TEXT.','STRESSES (IN KSI)$')

            CALL AGSETC('LABEL/NAME.','B')
            CALL AGSETI('LINE/NUMBER.',-100)
            CALL AGSETC('LINE/TEXT.',VAR)

C
C
C Draw the graph, using EZMXY.
C

C           CALL SET(0.,1.,.5,1.,0.,XMAX,0.,YMAX,1)

            DO 1126 IVAR=1,JJ


            IF(IVAR.LE.5)THEN
            AGDSHN(IVAR)=BUFFM(IVAR)
            ELSE
            AGDSHN(IVAR)='$$$$$$$$$$$'
            ENDIF
1126        CONTINUE



            XMIN=VARMIN-.05*DELVAR
            XMAX4=VARMIN+(NVAR-1)*DELVAR+.05*DELVAR
            CALL ANOTAT(VAR,'STRESSES (KSI)',1,0,50,AGDSHN)
            CALL AGSETF('X/MIN.',XMIN)
            CALL AGSETF('X/MAX.',XMAX4)

            WRITE(HEAD,1128)VAR
1128        FORMAT('STRESSES AT CONTROL POINTS VS. ',A4)

 CALL EZMXY (XDRA,YDRA,3000,JJ,NVAR,HEAD)

            CALL FRAME


            XMAX=XMAX1
**************************************************
**************************************************
```

```
      OPEN(UNIT=48,FILE='STRNVAR',STATUS='OLD')

      XMAX1=XMAX
      XMAX=VARMIN+DELVAR*(NVAR-1)+DELVAR/2.
      YMAX=XMAX1

      JJ=5

      BUFFM(1)='$$$A*$$$$'
      BUFFM(2)='$$$A1$$$$'
      BUFFM(3)='$$$PEAK$$$'
      BUFFM(4)='$$$FAIL$$$'
      BUFFM(5)='$$$ULT$$$$'

      DO 1222 IVAR=1, NVAR


      DO 1223 NN=1,5

      READ(48,*)X,Y1,Y,Y2,SD

      JJ=JJ+1

      XDRA(1,JJ)=X
      YDRA(1,JJ)=Y1
      XDRA(2,JJ)=X
      YDRA(2,JJ)=Y2
      XDRA(3,JJ)=X
      YDRA(3,JJ)=Y2
      XDRA(4,JJ)=X
      YDRA(4,JJ)=Y2
      XDRA(5,JJ)=XDRA(1,JJ)
      YDRA(5,JJ)=YDRA(1,JJ)
      XDRA(6,JJ)=XDRA(1,JJ)
      YDRA(6,JJ)=YDRA(1,JJ)

      AGDSHN(NN)=BUFFM(NN)
      AGDSHN(JJ)='$$$$$$$$$$'
      XDRA(IVAR,NN)=X
      YDRA(IVAR,NN)=Y
1223  CONTINUE
1222  CONTINUE



      CALL DISPLA(2,2,1)
CALL AGSETI ('ROW.',2)
      CALL AGSETI('WINDOWING.',1)
```

```
C       CALL AGSETI('DASH/SELECTOR.',26)

        CALL AGSETF('GRID/LEFT.',.1)
        CALL AGSETF('GRID/RIGHT.',.9)
        CALL AGSETF('GRID/BOTTOM.',.1)
        CALL AGSETF('GRID/TOP.',.9)


        CALL AGSETF('X/MIN.',0.)
        CALL AGSETF('X/MAX.',XMAX)
        CALL AGSETF('Y/MIN.',0.)
        CALL AGSETF('Y/MAX.',YMAX)

        CALL AGSETI('LEFT/MAJOR/TYPE.',1)
        CALL AGSETF('LEFT/MAJOR/BASE.',.001)
        CALL AGSETI('LEFT/MINOR/SPACING.',1)

        BASE=DELVAR/4.
        CALL AGSETI('BOTTOM/MAJOR/TYPE.',1)
        CALL AGSETF('BOTTOM/MAJOR/BASE.',BASE)
        CALL AGSETI('BOTTOM/MINOR/SPACING.',1)

        CALL AGSETC('LABEL/NAME.','L')
        CALL AGSETI('LINE/NUMBER.',100)
        CALL AGSETC('LINE/TEXT.','STRAINS$')

        CALL AGSETC('LABEL/NAME.','B')
        CALL AGSETI('LINE/NUMBER.',-100)
        CALL AGSETC('LINE/TEXT.',VAR)

C
C
C Draw the graph, using EZMXY.
C

C       CALL SET(0.,1.,.5,1.,0.,XMAX,0.,YMAX,1)

        DO 1226 IVAR=1,JJ


        IF(IVAR.LE.5)THEN
        AGDSHN(IVAR)=BUFFM(IVAR)
        ELSE
        AGDSHN(IVAR)='$$$$$$$$$$'
        ENDIF
1226    CONTINUE



        CALL ANOTAT(VAR,'STRAINS',1,0,50,AGDSHN)
```

```
            WRITE(HEAD,1228)VAR
1228        FORMAT('STRAINS AT CONTROL POINTS VS. ',A4)

            CALL AGSETF('GRID/LEFT.',.08)
            CALL AGSETF('GRID/RIGHT.',.50)
            CALL AGSETF('GRID/BOTTOM.',.1)
            CALL AGSETF('GRID/TOP.',.9)
            XMIN3=VARMIN-(.05)*DELVAR
            XMAX3=VARMIN+(NVAR-1)*DELVAR+.05*DELVAR
            CALL AGSETF('X/MIN.',XMIN3)
            CALL AGSETF('X/MAX.',XMAX3)

 CALL EZMXY (XDRA,YDRA,3000,JJ,NVAR,HEAD)


            CALL AGSETF('Y/MAX.',XMAX2)
            CALL AGSETF('Y/MIN.',-.002)
            YMAX=XMAX2


            CALL SET(.5,1.,0.,1.,0.,XMAX,0.,YMAX,1)
            CALL AGSETF('GRID/LEFT.',.58)
            CALL AGSETF('GRID/RIGHT.',1.)
            CALL AGSETF('GRID/BOTTOM.',.1)
            CALL AGSETF('GRID/TOP.',.9)
            CALL AGSETF('LEFT/MAJOR/BASE.',.005)
            CALL EZMXY(XDRA,YDRA,3000,JJ,NVAR,HEAD)
            CALL FRAME

            XMAX=XMAX1
C
C Close GKS.
C
 CALL CLSGKS
C
 STOP
C
 END
```

Appendix C:

Preprocessor Source Code

```
      PROGRAM PREP1
CHARACTER*70 S(0:50),C(0:50),TITLE
CHARACTER*20 ftype,VAR
REAL MOD0,MODF,MOD
S(0)=' '
S(1)='************************************************************'
S(2)='The program you are running (PREP1) is a prepprocessor '
S(3)='for the software FRC1. The main thrust is to generate '
S(4)='a new FRC1 input data file (FRC2.DAT) '
S(5)=' PREP1'
S(6)='describes each variable in familiar terms & asks the user'
S(7)='to imput its value, also PREP1 suggests typical of values'
S(8)='for certain variables whenever possible.An important thing'
S(9)='to keep in mind before starting is the fact that we are'
S(10)='trying to generate data that relates to a tension test of'
S(11)='fiber reinforced cement paste or mortar specimens.The user'
S(12)='must use consistant units during t he input of all the'
S(13)='variables. We highly recommand to the user to read the'
S(14)='optional brief description (about 30lines) of the software'
S(15)='FRC1.'

      WRITE(*,200)(S(I),I=0,15)
200 FORMAT(' ',16(5X,A60,/))
      WRITE(*,201)S(1)
201 FORMAT(' ',5X,A60,////,'Type: go in lower cases to continue')
      PAUSE

      S(2)='This program predicts, analytically, the maximum strength,'
      S(3)='the stress-strain curve, and the crack propagation prior &'
      S(4)='during load application of a fiber reinforced cementecious'
      S(5)='mortar. The type of loading allowed in this program is'
      S(6)='tension.The program randomly generates the cracks positions'
      S(7)='and sizes also the aggregate positions. Linear elastic'
      S(8)='fracture mechanics applied to a finite body with multiple,'
      S(9)='cracks is used. The prediction is based on'
      S(10)='the following known information: the mix proportions,'
      S(11)='the fiber properties, the fine aggregate content and'
      S(12)='average size, the matrix properties'
      S(13)='(especially the fracture toghness), and the'
      S(14)='fiber-matrix bond characteristics mainly the average'
      S(15)='bond strength and a reduction factor to account for'
      S(16)='frictional shear during post-peak.'

1     IREAD=100
      PRINT*,' '
      PRINT*,' DO YOU WANT TO READ THE DESCRIPTION AND'
      PRINT*,' INTRODUCTION OF THE SOFTWARE FRC1 ?'
      PRINT*,' '
```

```
      PRINT*,' ENTER 1 ----> YES'
      PRINT*,' ENTER 2 ----> NO BUT CONTINUE'
      PRINT*,' ENTER 3 ----> EXIT THE PROGRAM'
      READ*,IREAD
      IF(IREAD.EQ.1) THEN
      GO TO 11
      ELSEIF(IREAD.EQ.2) THEN
      GO TO 12
      ELSEIF(IREAD.EQ.3) THEN
      GO TO 5
      ELSE
      GO TO 1
      ENDIF

11    CONTINUE

      WRITE(*,202)(S(I),I=0,16)
202 FORMAT(' ',17(5X,A60,/))
      WRITE(*,203)S(1)
203 FORMAT(' ',5X,A60,///,'Type: go in lower cases to continue')

      PAUSE

      S(16)=S(1)
      S(17)='also t program does'
      S(18)='statistical paramathric analysis of the effects of'
      S(19)='variation of a chosen variable (e.g. fiber content).'
      S(20)='This analysis covers the following:(1)multiple'
      S(21)='comparison of means (T-Test) for peak stresses, peak'
      S(22)='strain and toghness.(2)Analysis of variance (ANOVA)'
      S(23)='for peak stresses, peak strains and peak toughnesses.'
      S(24)='The unique strong characteristics of the model are'
      S(25)='1. THE CAPABILITY OF USING MULTIPLE CRACKS'
      S(26)='2. A BUILT IN STATISTICAL PARAMATRIC ANALYSIS FOR'
      S(27)=' ANY CHOSEN VARIABLE'
      S(28)=' '
      S(29)='Typical stress strain curve which is the basis'
      S(30)='of the program is shown below'

      WRITE(*,204)(S(I),I=16,30)
204 FORMAT(' ',15(5X,A60,/))
      WRITE(*,205)S(1)
205 FORMAT(' ',5X,A60,///,'Type: go in lower cases to continue')
      PAUSE

      C(0)=S(0)
      C(1)=' Peak A2'
      C(2)=' ^'
      C(3)=' |'
      C(4)=' @@@@@'
      C(5)=' ^ @@@@ @@'
```

```
            C(6)=' S | @@@@ @@ ----> Post Peak'
            C(7)=' T | A1 <---- @@ @@@'
            C(8)=' R | @@ @@@@'
            C(9)=' E | @@ @@@@'
 C(10)=' S | @ ------> A*'
 C(11)=' S | @'
 C(12)=' | @'
 C(13)=' | @'
 C(14)=' | @'
 C(15)=' |@ '
 C(16)=' -|---------------------------------------->'
 C(17)=' STRAIN'
 C(18)=' '
 C(19)=' TYPICAL STRESS-STRAIN CURVE'

            WRITE(*,206)(C(I),I=0,18)
206 FORMAT(' ',19(5X,A60,/))
C           WRITE(*,201)S(1)
C201 FORMAT(' ',5X,A60,////,'Type: go in lower cases to continue')
            PAUSE

12          CONTINUE
            IFILE=100
            PRINT*,' '
c           PRINT*,' ARE YOU GENERATING A NEW DATA FILE OR MODIFYING'
c           PRINT*,' AN EXISTING (OLD) FILE ?'
            PRINT*,' '
            PRINT*,' ENTER 1 ---> GENERATE A NEW DATA FILE (FRC2.DAT)'
c           PRINT*,' ENTER 2 ---> MODIFY AN EXISTING DATA FILE'
            PRINT*,' ENTER 3 ---> EXIT THE PROGRAM'
            PRINT*,' '

            READ*,IFILE

            IF(IFILE.EQ.1) THEN
            CALL NEW
            ELSEIF(IFILE.EQ.2) THEN
            CALL OLD
            ELSEIF(IFILE.EQ.3) THEN
            GO TO 5
            ELSE
            GO TO 12
            ENDIF

5           STOP
            END
*****************************************************************
            SUBROUTINE NEW
            character*70 title
            character*20 var,ftype
            REAL MODF,MOD0
```

```
      PRINT*,' '
      PRINT*,' ENTER THE title OF THIS RUN; DESCRIPTION OF'
      PRINT*,' WHATEVER YOU ARE TESTING, UP TO 60 CHARACTERS ?'
      PRINT*,' WARNING!! title must be enclosed between single quotes'
      READ(*,101) TITLE
101   FORMAT(A60)


      PRINT*,' '
      PRINT*,' ENTER THE TYPE OR DESCRIPTION OF THE FIBER USED'
      PRINT*,' EXAMPLE: CARBON FIBER, STEEL FIBER, CELLELOSE,...?'
      PRINT*,' USE UP TO 20 CHARACTERS'
      PRINT*,' WARNING!! description must be enclosed in single quotes'
      READ(*,102) FTYPE
102   FORMAT(A20)

      PRINT*,' '
      PRINT*,' ENTER FIBER CONTENT (VF%) IN % ?'
      PRINT*,' '
      READ*,F
      F=F/100.0


      PRINT*,' '
      PRINT*,' ENTER FIBER MODULUS OF ELSTICITY ?'
      PRINT*,' '
      READ*,MODF


      PRINT*,' '
      PRINT*,' ENTER FIBER LENGTH ?'
      PRINT*,' '
      READ*,FBL


      PRINT*,' '
      PRINT*,' ENTER FIBER DIAMETER ?'
      PRINT*,' '
      READ*,DF

      IFBFLAG=1


      PRINT*,' '
      PRINT*,' ENTER FIBER ULTIMATE STRENGTH (STRESS) ?'
      PRINT*,' '
      READ*,SIGULT

      PRINT*,' '
```

```
      PRINT*,' It is known that when a fiber is bridging a crack'
      PRINT*,' or being pulled out of a matrix, there is a small'
      PRINT*,' portion of the fiber embedded length that is bond'
      PRINT*,' free. This portion of the fiber embedded length is'
      PRINT*,' the closest to the face of the crack or surface of'
      PRINT*,' the matrix from which the fiber is being pulled. '
      PRINT*,' This portion is only a small fraction of the total'
      PRINT*,' embedded length, and has no shear stress acting on'
      PRINT*,' it. Also, this portion depends on the type of '
      PRINT*,' fiber and matrix. It is believed that this portion'
      PRINT*,' is less than 0.1 of the embedded length. We label '
      PRINT*,' this parameter as the bond damaged portion of the '
      PRINT*,' embedded length.'
      PRINT*,' '
      PRINT*,' ENTER THE BOND DAMAGED PORTION OF THE FIBER'
      PRINT*,' EMBEDDED LENGTH. IF YOU ARE NOT SURE THEN ENTER 0'
      PRINT*,' '
      READ*,FDMG

      PRINT*,' '
      PRINT*,' ENTER THE MODULUS OF ELASTICITY OF THE MATRIX ?'
      PRINT*,' Notice: This value is not the modulus of the'
      PRINT*,' composite, rather it is the modulus of the '
      PRINT*,' paste without fibers. It is dependent on the'
      PRINT*,' water/cement ratio and the fine aggregate '
      PRINT*,' type, size, and content. This value can be '
      PRINT*,'          easily find from the litterature.'
      PRINT*,' '
      READ*,MOD0

      PRINT*,' '
      PRINT*,' Enter the cement paste fracture toughness'
PRINT*,' (TKI0). This linear fracture mechanics material'
PRINT*,' property is very critical to the accuracy of the'
PRINT*,' results. Therefore, it should be selected very'
      PRINT*,' carefully. This input variable is dependent on the'
      PRINT*,' water/cement ratio, the additives to the cement'
      PRINT*,' paste, curing conditions, age of the specimen'
      PRINT*,' (however, it stabilizes after an age of about'
      PRINT*,' 14 days). '
      PRINT*,' '
      PRINT*,' ENTER PASTE FRACTURE TOGHNESS ?'
      READ*,TKI0

      PRINT*,' '
      PRINT*,' The fiber-matrix average [along the embedded'
      PRINT*,' length] bond strength TAU. This input variable'
      PRINT*,' is as important as the previously described'
      PRINT*,' variable [Fracture toughness TKI0]. TAU is'
      PRINT*,' usually determined experimentally using a fiber'
      PRINT*,' pull-out test. This variable is dependant on the'
```

```
PRINT*,' fiber type and matrix charactistics '

PRINT*,' PLEASE ENTER THE VALUE OF TAU'

READ*,TAU

PRINT*,' '
PRINT*,' The prevous variable TAU does not accuratly'
PRINT*,' and fully describe the fiber matrix load transfer'
PRINT*,' and interaction. In fact, the phenomena is best'
PRINT*,' described using a pull-out load-fiber slip curve.'
PRINT*,' Which reflects that not only the shear changes'
PRINT*,' along the fiber embedded length but it also'
PRINT*,' deteriorates [changes] at any fixed point along'
PRINT*,' the fiber as the fiber starts slipping. That is'
PRINT*,' the shear at any point along the fiber changes'
PRINT*,' from being elastic to friction at, and theis change'
PRINT*,' is not sudden or abrupt but rather gradual. The'
PRINT*,' ration [ALTAU] of the frictional shear to the'
PRINT*,' elastic shear is dependant on the fiber type and'
PRINT*,' matrix characteristics. However, for most fiber'
PRINT*,' used with cement the frictional shear is less then'
PRINT*,' the maxium elastic shear which makes the ration'
PRINT*,' less than 1 [with some exceptions]. To account for'
PRINT*,' the prevously described phenomena, FRC1 uses the'
PRINT*,' ratio of the frictional shear to the maximum'
PRINT*,' elastic shear as an input variables. [less than 1]'
PRINT*,' Use 1 if not sure about this ratio.'
PAUSE
PRINT*,' Enter the ratio of the friction to the elastic'
PRINT*,' shear (ALTAU).'
PRINT*,' '

READ*,ALTAU

PRINT*,' '
PRINT*,' enter the width [w] of your tension specimen'
PRINT*,' '
READ*,W

PRINT*,' enter the length [H] of your tension specimen,'
PRINT*,' [or if you know the strain gage length used in the'
PRINT*,' test, then enter the strain gage length]'
PRINT*,' '
READ*,H

PRINT*,' '
PRINT*,' Enter the depth (D) of your tension specimen'
PRINT*,' '
READ*,D
```

```
      PRINT*,' '
      PRINT*,' Enter the average fine aggregate size used in the'
      PRINT*,' matrix.'
      PRINT*,' '
      READ*,AGGRAD
AGGRAD=AGGRAD/2.0

      PRINT*,' '
      PRINT*,' enter the volume fraction of five aggregate [in %]'
      PRINT*,' '
      READ*,AGGVOL
      AGGVOL=AGGVOL/100.0

      PRINT*,' '
      PRINT*,' There are two types of crack in cement-based'
      PRINT*,' materials: cracks that originate from inbetween'
      PRINT*,' inclusions [fibers & aggregates] and matrix; and'
      PRINT*,' cracks that originate from void and pores. We label'
      PRINT*,' the first type as bond cracks and the latter as void'
      PRINT*,' cracks. The number of bond and void cracks can be'
      PRINT*,' input arbitrarily however they should be> 1 and for'
      PRINT*,' practical reasons if???? interactivly the sum of'
      PRINT*,' bond and void cracks should be less or equal to 4,'
      PRINT*,' unless you are running the software FRC1 on a'
      PRINT*,' supercomputer. The upper limit on the sum of cracks'
      PRINT*,' to 4 is due to the fact that it takes a long'
      PRINT*,' processing time to process the output interactively'
      PRINT*,' which makes it impractical. However if you are'
      PRINT*,' running the program in batch mode and can afford to'
      PRINT*,' wait a few days to a week for the completion of the'
      PRINT*,' run that upperlimit can be increased to up to 10 to'
      PRINT*,' 20 total # of cracks.'
      PRINT*,' Notice:[1] If there is no aggregate in the matrix'
      PRINT*,' the number of bond cracks should be kept to the'
      PRINT*,' minimum of 1. [2] With 2 cracks the program'
      PRINT*,' runs reasonably fast interactivly.'
      PRINT*,' Remember: if running the program interactively the'
PRINT*,' total # of cracks should be kept below 4.'
      PRINT*,' '
      PRINT*,' enter the number of bond cracks [NBOND]'

      READ*, NBOND

      PRINT*,' enter the number of void cracks [NVOID] '

      READ*, NVOID

      PRINT*,' '
      PRINT*,' Enter the number of intergration points [M] along'
      PRINT*,' each crack used in computation of stress intensity'
      PRINT*,' factor we recommend the use of a value of 15 to 20.'
```

```
            PRINT*,' M=20 gives more accurate results, however the program'
            PRINT*,' runs faster with M=15 with less but adequate accuracy.'
            PRINT*,' We do not reccomend the use of M less then 10 for'
            print*,' accurate results'
            PRINT*,' '
            PRINT*,' '
            PRINT*,' For faster runs but not accurate results M<10'
            PRINT*,' [M=9,8,7,6,or 5] may be used [especially when running'
            PRINT*,' the program for the first time].'
            PRINT*,' '
            PRINT*,' At no condition M<5 can be used.'
            PRINT*,' '
            PRINT*,' Enter the number of intergration points along each'
PRINT*,' crack [preferably between 10 to 20]. ?'

            READ*,M
             TOLS=.01
TOL1=.01

            PRINT*,' '
PRINT*,' Enter the name of the input variable you want to vary'
            PRINT*,' and use at different treatment levels of paramatric'
            PRINT*,' statistical study. This study is about the effect of'
            PRINT*,' variation of this chosen variable on the stress-'
            PRINT*,' strains and peak toughness. The results can be'
            PRINT*,' presented in the form of graphs and statistical'
            PRINT*,' tables. The statistical table are ANOVA tables and'
            PRINT*,' multiple please inter one of the following:'
            PRINT*,' '
            PRINT*,' F ---> fiber content [VF]'
            PRINT*,' MODF ---> fiber models of elasticity'
            PRINT*,' FBL ---> fiber length'
            PRINT*,' DF ---> fiber diameter'
            PRINT*,'SIGULT ---> fiber ultimate strength'
            PRINT*,' FDMG ---> shear free portion of embedded fiber length'

PRINT*,' X ---> exit program'
            print*,'WARNING!! the above must be between single quotes'
            READ(*,103)VAR

103         FORMAT(A10)

            If (VAR.EQ.'X') go to 6

            PRINT*,' '
            PRINT*,' Enter the number of treatments [NVAR] to be'
            PRINT*,' considered for the chosen input variable.'
            PRINT*,' Remember that each treatment value is a different'
            PRINT*,' material and each material has a certain number of'
            PRINT*,' specimens [NRAND] to be tested, therefore the higher'
            PRINT*,' the number of treatments [NVAR] the longer it takes'
```

```
PRINT*,' for the program to run. We do not recommand using a'
PRINT*,' value greater than 3 for practical reasons in the'
PRINT*,' interactive mode. A value of 2 will run reasonably'
PRINT*,' fast depending on the other parameters previously'
PRINT*,' discussed. Use 1 if you have only one material or'
PRINT*,' when you want a quick run of the program. Values'
PRINT*,' greater than 3 can be used when the program is run'
PRINT*,' in the batch mode and the user is to wait a long'
PRINT*,' period of time for the run to complete.'
PRINT*,' '
PRINT*,' ENTER THE NUMBER OF TREATMENTS (NVAR)'
PRINT*,' '
READ*,NVAR

PRINT*,' '
PRINT*,' Enter the minimum value of of the chosen input'
PRINT*,' variable to be treated in the statistical'
PRINT*,' paramatric analysis. This is the first variable'
PRINT*,' value that will be run. If you specified only one'
PRINT*,' treatment (NVAR=1), then this minimum value is '
PRINT*,' the only value that will be used.'
PRINT*,' note: If the variable chosen to be studied is the'
PRINT*,' fiber content (VAR=F), then enter this '
PRINT*,' value in %, e.g. 1, or 2,...'
PRINT*,' '
PRINT*,' ENTER THE THE MINIMUM VALUE OF THE VARIABLE TO BE'
PRINT*,' STUDIED ?'
PRINT*,' '
READ*,VARMIN
IF(VAR.EQ.'F') VARMIN=VARMIN/100.0

PRINT*,' '
PRINT*,' Enter the incremental value of variable to studied'
PRINT*,' If you want the results for the following three '
PRINT*,' fiber contents 1%, 1.5%, and 2%, then your '
PRINT*,' incremental value is .5'
PRINT*,' '
PRINT*,' ENTER THE INCREMENTAL VALUE ? '
PRINT*,' '
READ*,DELVAR
IF(VAR.EQ.'F') DELVAR=DELVAR/100.0

PRINT*,' '

print*,' enter the number of specimens per material to be'
print*,' generated ? (NRAND) preferrably use 1, 2, or 3'
print*,' notice: the higher the # of specimens the longer'
print*,' it takes for the program to run.'
read*,nrand

nmat=1
```

```
      ntest=1
      print*,'enter an integer seed for random numb generation'
      print*,'any integer will work'
      read*,iseed
      nl=1
      print*,'enter # of points to be generated in the'
      print*,'post peak region (50 to 500)'
      read*,iterpost
      efct=1
      print*,'enter confidence level for statistical analysis'
      print*,' (70 to 95) (in %)'
      read*,conflev
      print*,'enter value of ISTAT flag (use 1 usually)'
      print*,' use 0 if you DO NOT want a statistical report'
      read*,istat
      print*,'enter value of IFILE flag for generation of data'
      print*,'files that are to be used with the post processor'
      print*,'POSTP.OUT for graphics outputs.'
      print*,'enter 1 -----> yes generate data files'
      print*,'enter 0 -----> no DO NOT generate data files'
      read*,ifile
      nmin=1
      nmax=1
      maxflag=2
      print*,'enter an approximate guess of the peak load to'
      print*,'start with. any value will work. however, the'
      print*,'closer your guess to the actual value the faster'
      print*,' will the program work.'
      read*,p1
      print*,'enter the maximum strain value after which the '

      print*,'simulation will stop'
      read*,epsmax
      print*,'enter maximum load increment (e.g. .002)if using ksi'
      read*,dpmax
      print*,'enter minnimum load increment (e.g. .001)if using ksi'
      read*,dpmin
      nl=1
      nlp=1
      dpp=dpmax
      open(unit=51,file='frc2.prep',status='new')

      write(51,9001)title
9001  format(a50)
      write(51,*)nmat,ntest,nrand
      write(51,9002)ftype,f,modf,fbl,df,ifbflag,sigult,fdmg
9002  format(a20,4(1x,f15.5),1x,i3,1x,2(1x,f15.5))
      write(51,*)iseed,nl
      write(51,*)p1,ns1,dpmax,dpmin,nmax,nmin,maxflag
      write(51,*)dpp,nlp
      write(51,*)nbond,nvoid,m
```

```
      write(51,*)mod0,tki0,tau,w,h,d,aggrad,aggvol
      write(51,*)tols,tol1
      write(51,*)iterpost
      write(51,9003)nvar,var,varmin,delvar
9003  format(i3,1x,a10,2(1x,f15.8))
      write(51,*)ifile,istat
      write(51,*)altau
      write(51,*)conflev
      write(51,*)efct
      write(51,*)epsmax


      print*,' '
      print*,'@@@@@@@@@@@@@@@@'
      print*,'@@@@@@@@@@@@@@@@'
      print*,'@@@@@@@@@@@@@@@@'
      print*,' '
      print*,' $$$$$$$$ W A R N I N G !!! $$$$$$$$$$$$'
      print*,' '
      print*,' YOUR TEMPORARILY DATA FILE IS FRC2.PREP '
      print*,' You need to copy FRC2.PREP into a file called'
      print*,' frc2.dat , so it can be used by the software'

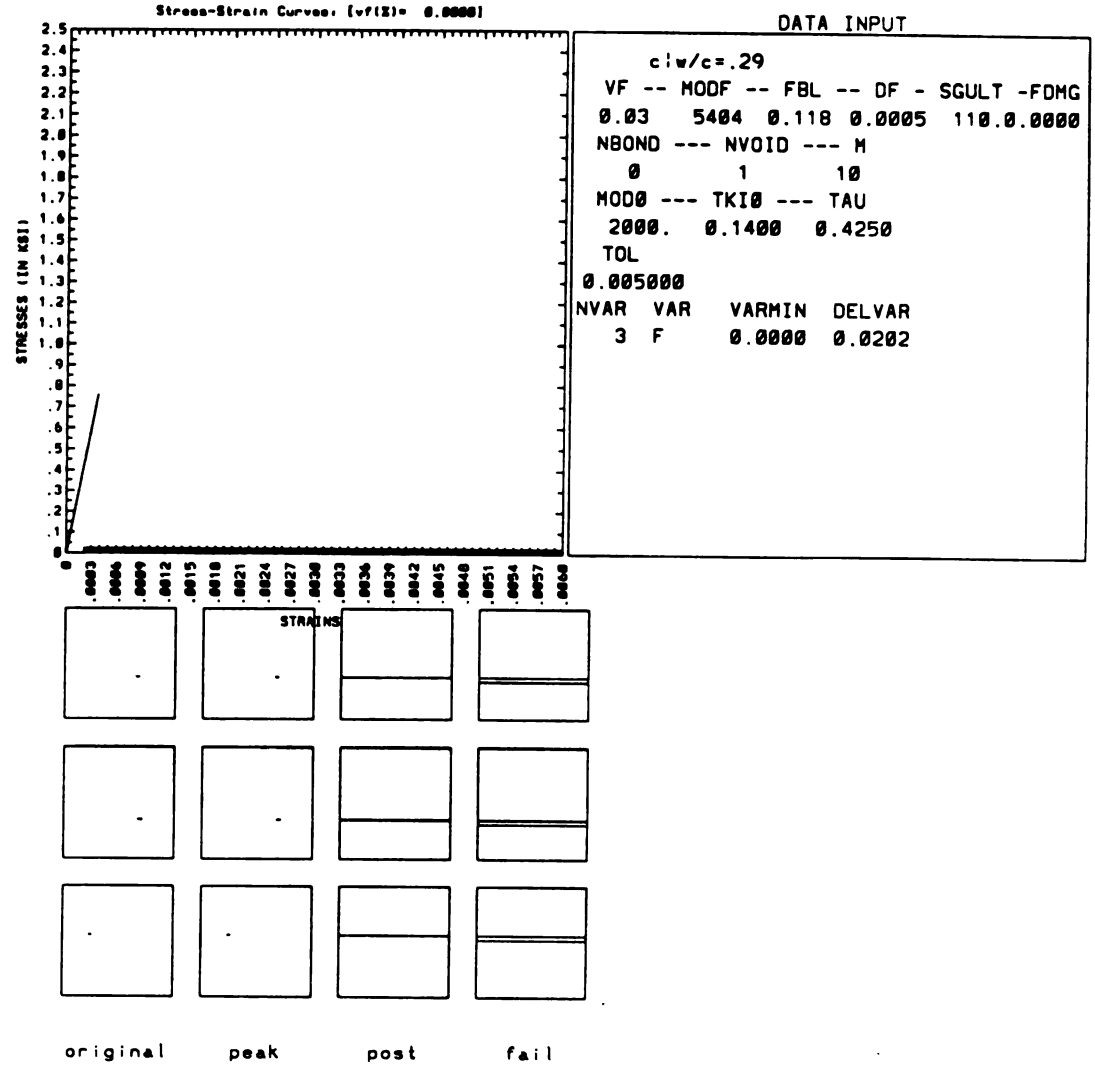
      print*,' '
      print*,'@@@@@@@@@@@@@@@@'
      print*,'@@@@@@@@@@@@@@@@'
      print*,'@@@@@@@@@@@@@@@@'
6     RETURN
      END
*****************************************************************
      SUBROUTINE OLD
      REAL MODF,MOD0

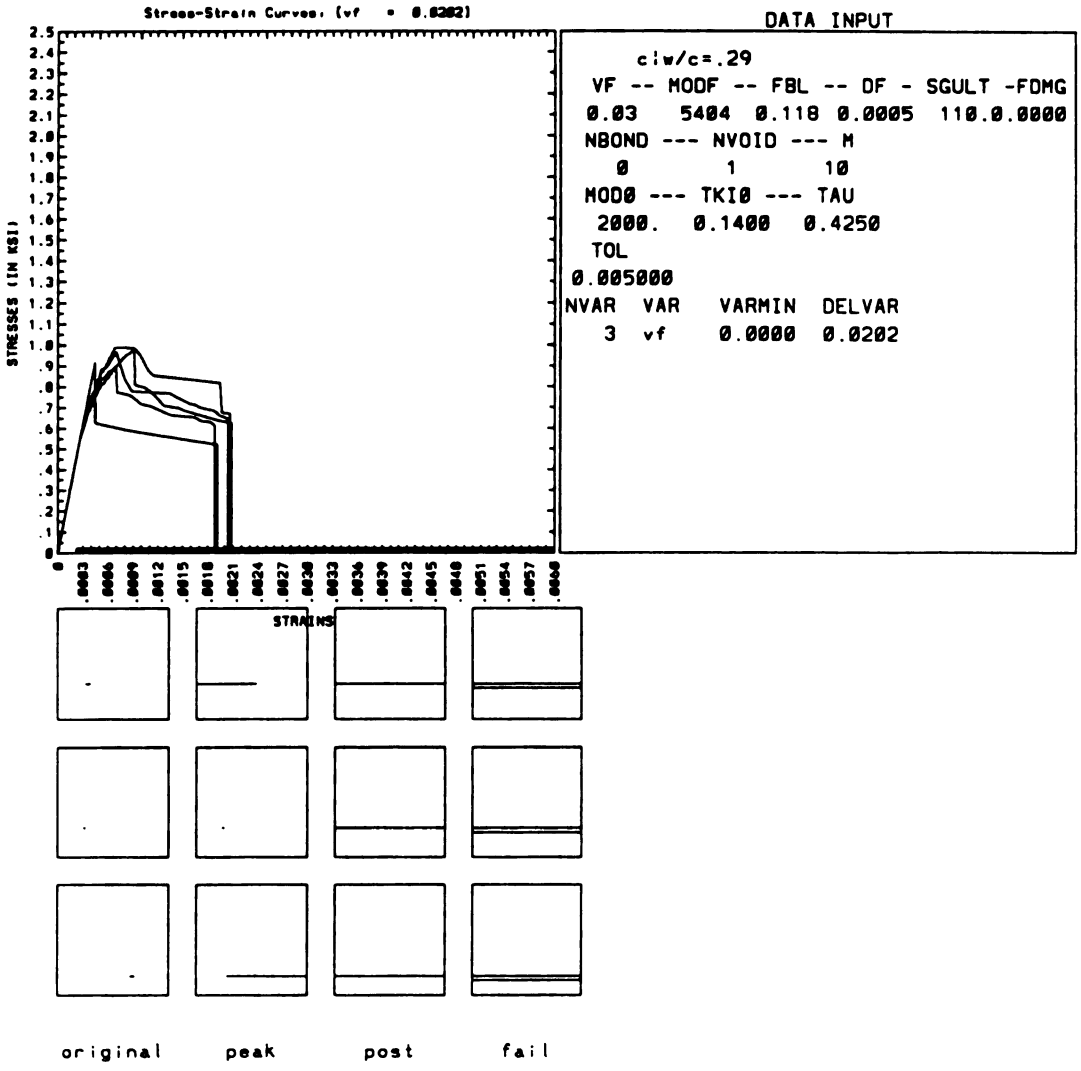
      RETURN
      END
*****************************************************************
```

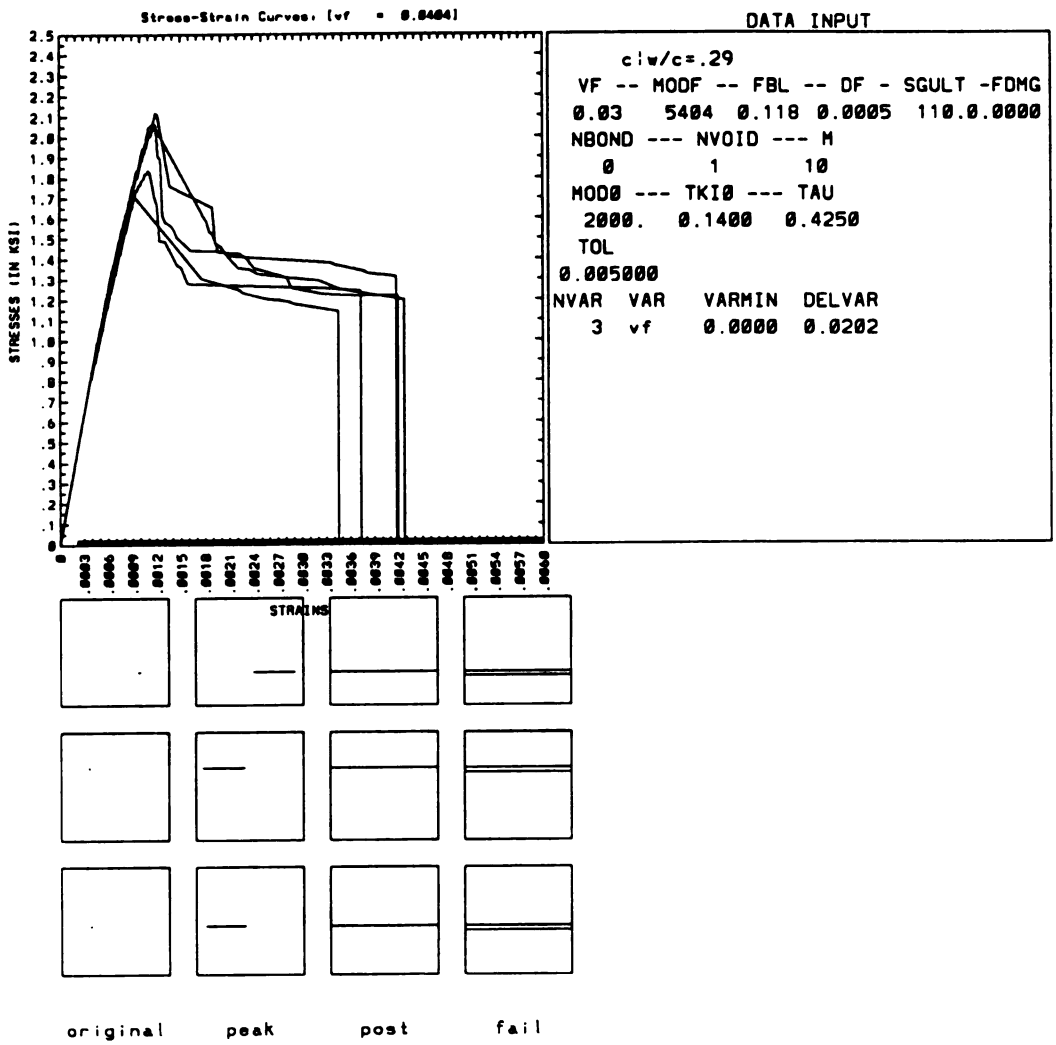
Appendix D:

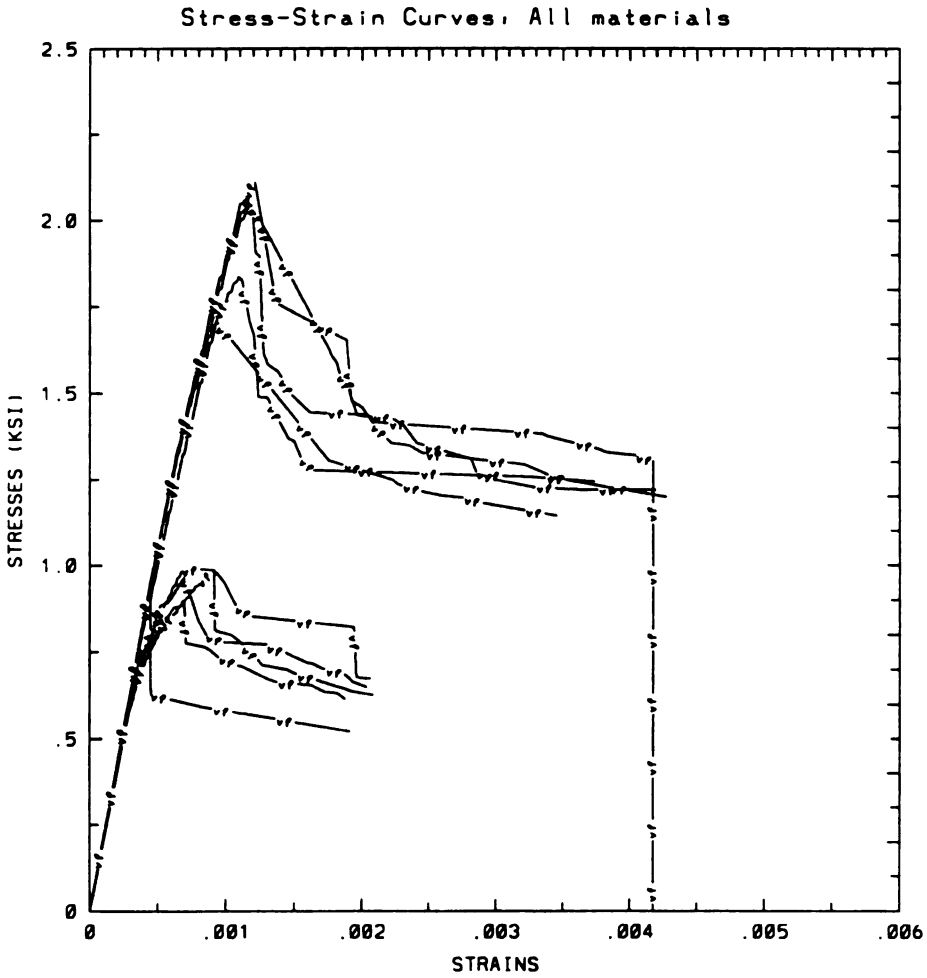
Typical Program Output; Graphics Frames

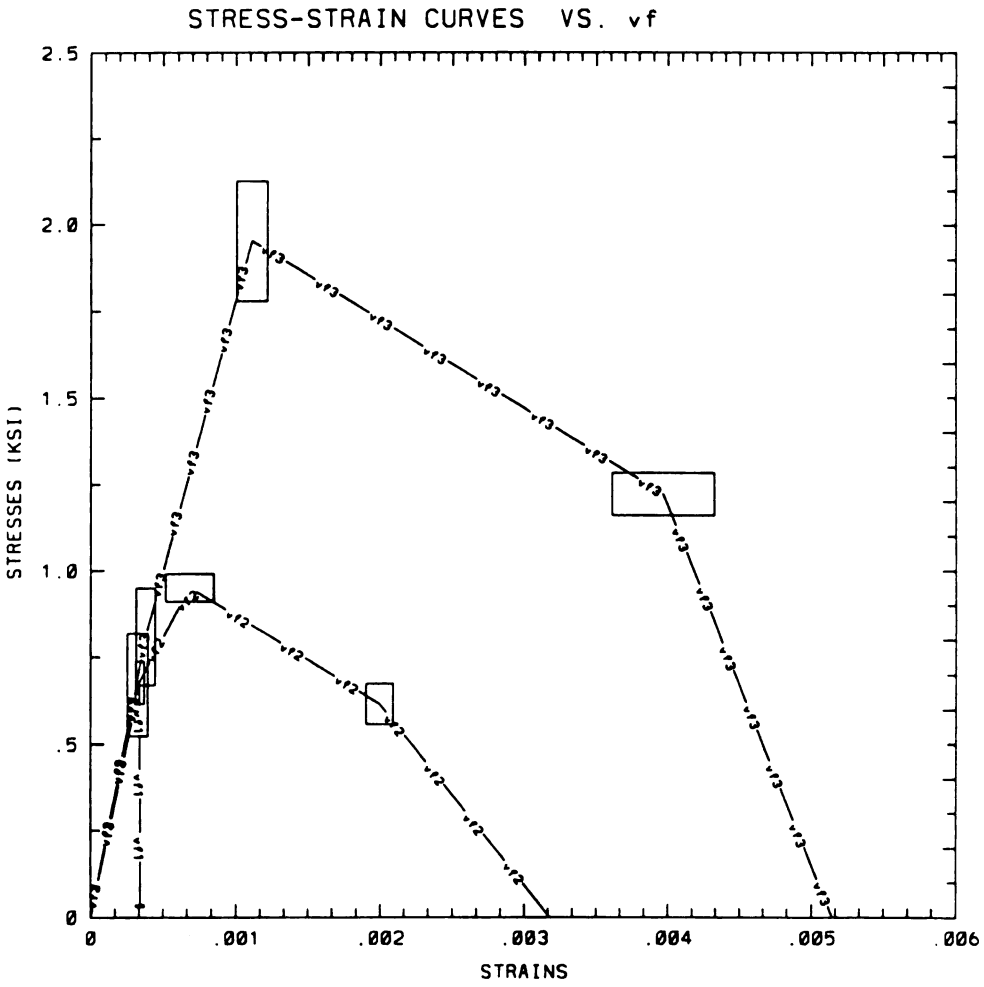
APPENDEX D: Typical Program Output; Graphics frames

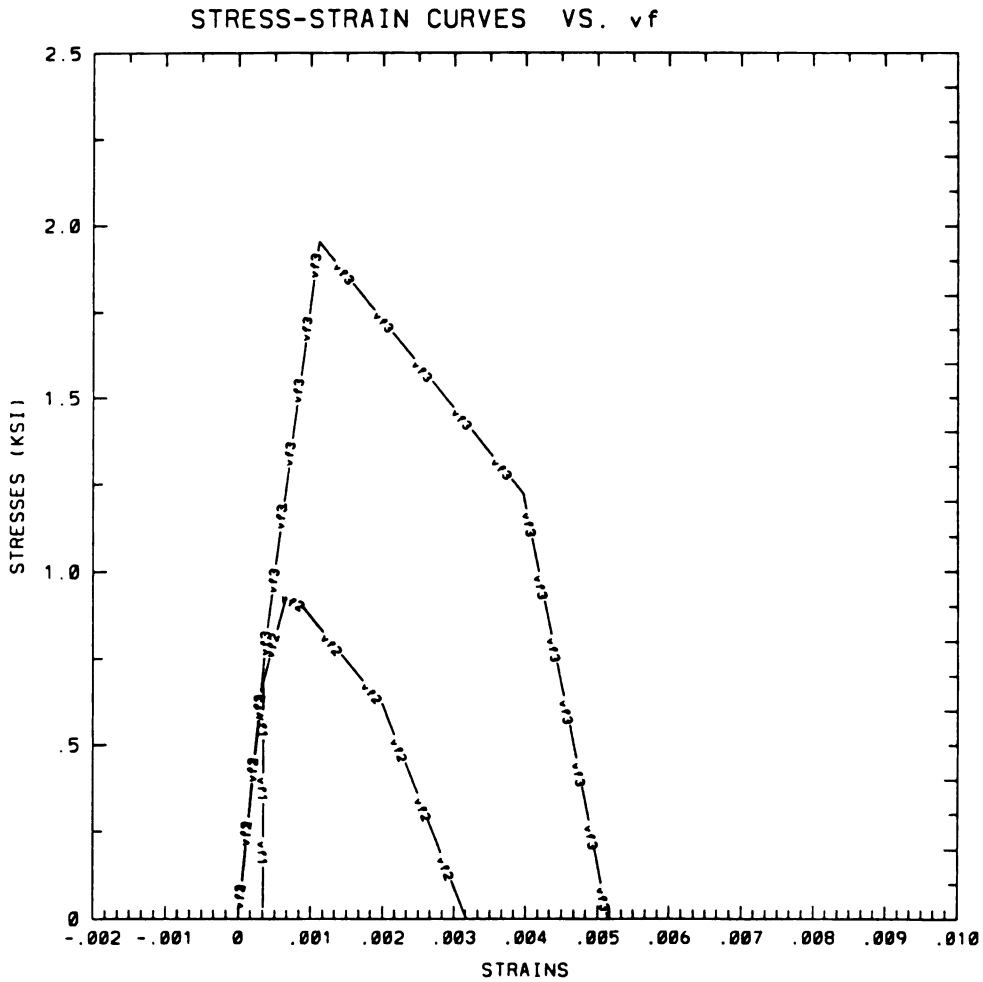


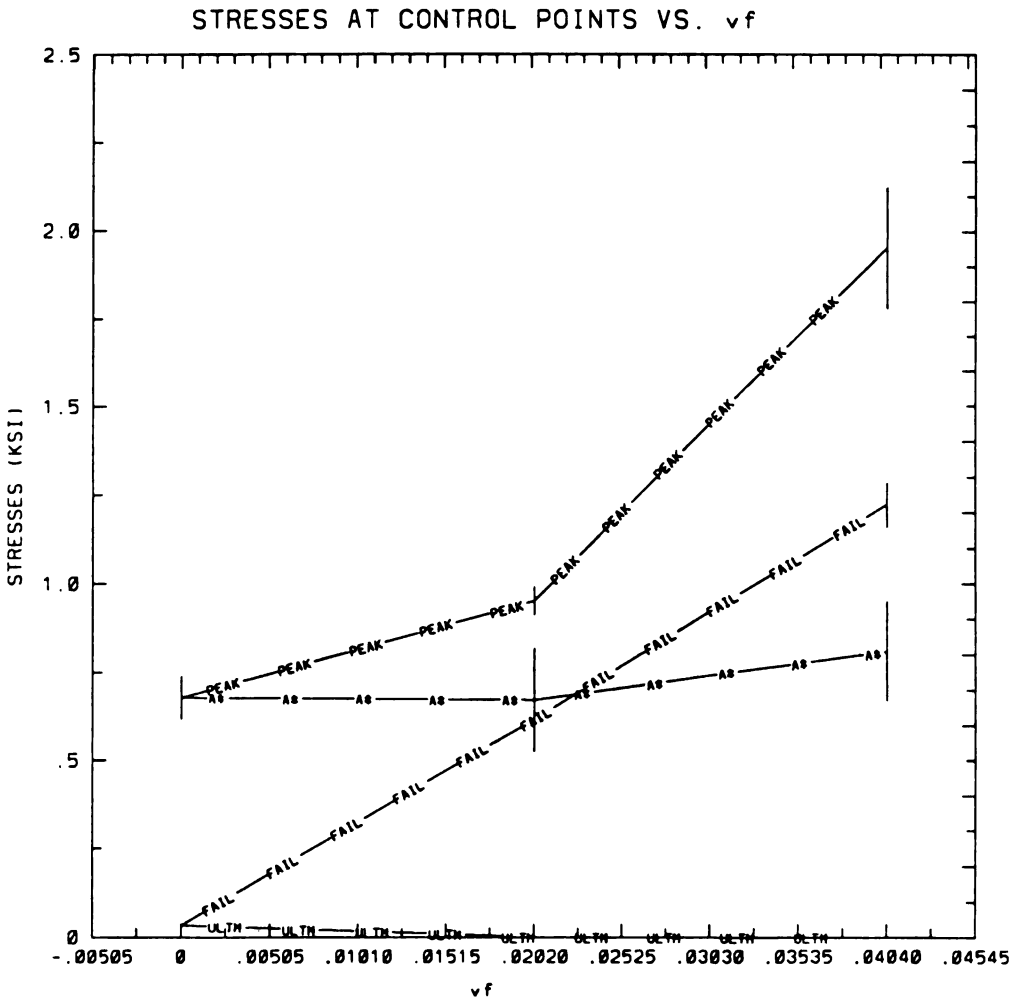

Stress-Strain Curves: (vf = 0.0202)
STRESSES (IN KSI)
STRAINS
DATA INPUT
c!w/c=.29
VF -- MODF -- FBL -- DF - SGULT -FDMG
0.03 5404 0.118 0.0005 110.0.0000
NBOND --- NVOID --- M
0 1 10
MOD0 --- TKI0 --- TAU
2000. 0.1400 0.4250
TOL
0.005000
NVAR VAR VARMIN DELVAR
3 vf 0.0000 0.0202
original
peak
post
fail

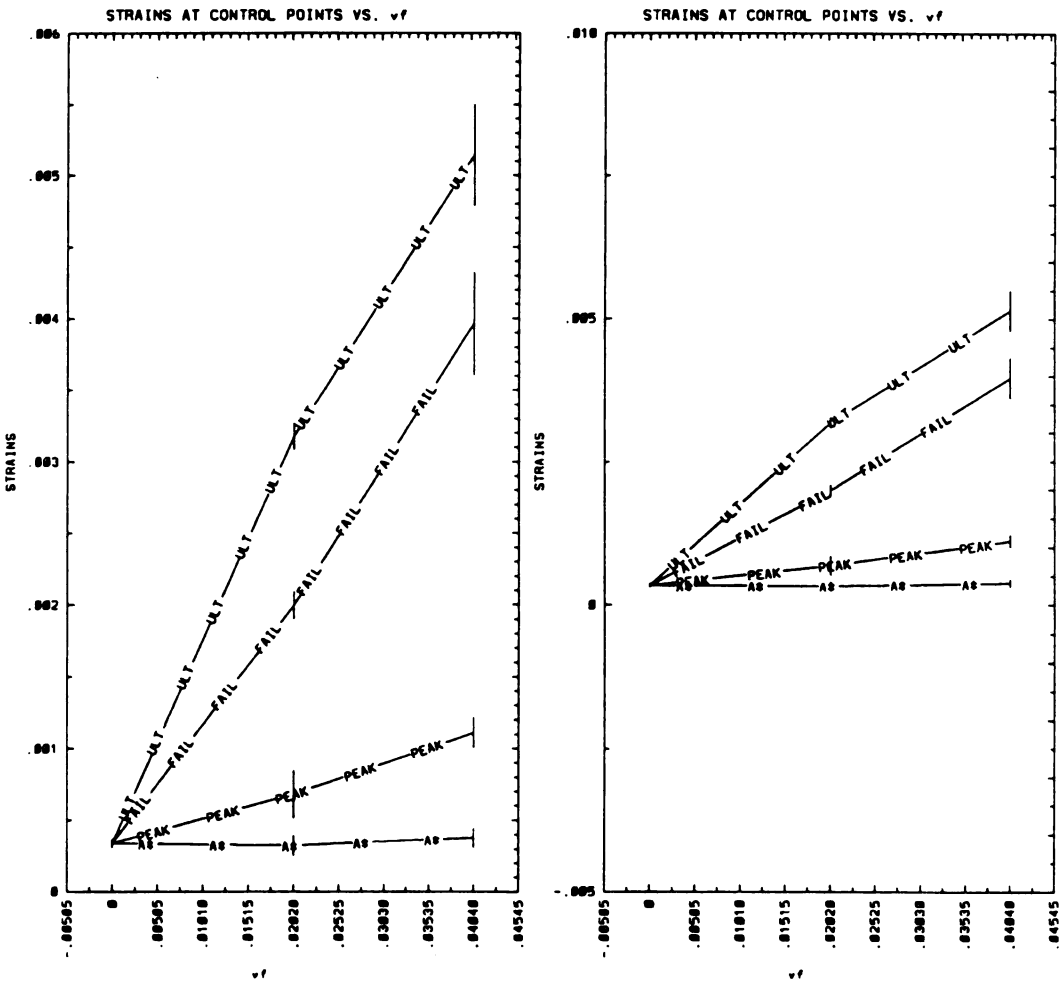

Stress-Strain Curves: [vf = 0.0404]
STRESSES (IN KSI)
STRAINS
DATA INPUT
c!w/c=.29
VF -- MODF -- FBL -- DF - SGULT -FDMG
0.03 5404 0.118 0.0005 110.0.0000
NBOND --- NVOID --- M
0 1 10
MOD0 --- TKI0 --- TAU
2000. 0.1400 0.4250
TOL
0.005000
NVAR VAR VARMIN DELVAR
3 vf 0.0000 0.0202
original
peak
post
fail


Stress-Strain Curves: All materials
STRESSES (KSI)
2.5
2.0
1.5
1.0
.5
0
0
.001
.002
.003
.004
.005
.006
STRAINS


STRESS-STRAIN CURVES VS. vf
STRESSES (KSI)
STRAINS
2.5
2.0
1.5
1.0
.5
0
.001
.002
.003
.004
.005
.006
vf3
vf2


STRESS-STRAIN CURVES VS. vf
STRESSES (KSI)
2.5
2.0
1.5
1.0
.5
0
-.002 -.001 0 .001 .002 .003 .004 .005 .006 .007 .008 .009 .010
STRAINS


STRESSES AT CONTROL POINTS VS. vf
STRESSES (KSI)
2.5
2.0
1.5
1.0
.5
0
-.00505
0
.00505
.01010
.01515
.02020
.02525
.03030
.03535
.04040
.04545
vf
PEAK
AS
FAIL
ULTM


STRAINS AT CONTROL POINTS VS. vf
STRAINS
vf
ULT
FAIL
PEAK
AS
STRAINS AT CONTROL POINTS VS. vf
STRAINS
vf
ULT
FAIL
PEAK
AS

Appendix E:

Typical Program Output;

'REPORT2.STAT' file

```
1

*****************************************************************************************************************
*                                                                                                               *
*                                          G E N E R A L   D A T A                                              *
*                                                                                                               *
*****************************************************************************************************************
*                                                                                                               *
*                                                                                                               *
*                                                                                                               *

0*       TITLE: c|w/c=.42|vf=1.72%&3.98%|nc=2      MTR.-ID.(NMAT):  1     TEST-ID.(ITEST):  1     NUMB.-OF-SPEC.(NRAND): 3
*                                                                                                               *
*                                                                                                               *
*                                                                                                               *
 *    FIBER CHARACTERISTICS INFORMATION
*                                                                                                               *
*    ---------------------------------                                                                          *
*                                                                                                               *
*       FIBER TYPE    CONTENT (VF%)    MODULUS    LENGTH    DIAMETER    ULT. STRENGHT    DAMG. PORTION    SAPACING FLAG     *
*                                                                                                               *
*       CARBON FIB       0.03180000    5404.9000  0.3937  0.00057090       110.942000     0.0000000000         1           *
*                                                                                                               *

0*    MATRIX CHARACTERISTICS INFORMATION
*                                                                                                               *
*    ---------------------------------                                                                          *
*                                                                                                               *
*       MTRX.-MOD.     MTRX.-FRAC.-TOGH.     TOT.-FRAC.-TOGH     FIB.-MTRX-BOND     REDC.TAU     NUMBER OF CRACKS     #INTEG-PNTS
*       MOD0           TKI0                  TKIC                TAU                ALTAU        NBOND NVOID NC       M
*                                                                                                               *
*        2000.0000       0.15000               0.15000            0.200000           0.8000       2     2    4          10
*                                                                                                               *

0*                   SPECIMEN DIMENTIONS                          AGGREGATE CONTENT
                     -------------------                          -----------------

          WIDTH(IN.)      DEPTH(IN.)      HEIGHT(IN.)          VOLUME FRACTION     RADIUS (SIZE)
            ( W )           ( D )           ( H )                (AGGVOL)            (AGGRAD)
          1.181100        0.472441        1.000000               0.0010000000        0.0000000000
0*    PROGRAM CONTROL DATA
*    --------------------

*       ISEED      NL      P1       NS1      DPMAX      DPMIN      NMAX      NMIN      MAXFLAG      DPP      NLP      TOLERANCE
*
*           1      11    0.50000     5     0.00200    0.00100      1         1          2         0.00100    5      0.00500000
*                                                                                                               *
```

```
0*    DATA CONTROLLING THE TREATMENT VARIABLE AND OUTPUT CONTROL FLAGS
*    ================================================================
*
*       # TREATS   TREAT. VAR.   LOWEST TREAT. VALUE   TREAT. INCREMNT   #POST PEK PNTS   OUTPT FILES FLAG   STAT. REPORT FLAG
*       (NVAR)      (VAR)          (VARMIN)              (DELVAR)          (ITERPOST)       IFILE=0 NO, 1YES  ISTAT=0 NO,1 YES
*
*         2         F                  0.01720000           0.01460000     50                      1                 1
*                                                                                                                              *

1

          VARIABLE DEFINING TREATMENTS: F              NUMBER OF TREATMENTS:  2     NUMBER OF SAMPLES PER TREATMENT:  3

0                          |-----------------------D E P E N D E N T  V A R I A B L E S----------------------|
0 LEV TRET-VALUE STRESS  A* STRAIN  A* STRESS  A1 STRAIN  A1 PEAK  STRS PEAK  STRN ULT-STRESS ULT-STRAIN TOUGHNESS1 TOUGHNESS
2
  --- ---------- ---------- ---------- ---------- ---------- ---------- ---------- ---------- ---------- ---------- ---------
-


    1  0.0172000  0.6759807  0.0003289  0.6759807  0.0003295  0.6777728  0.0016453  0.0578849  0.1187684  0.0011803  0.026079
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    1  0.0172000  0.6125391  0.0002981  0.6125391  0.0002985  0.6143312  0.0009184  0.0519020  0.1067217  0.0005479  0.017765
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----
|INDXES|SAMPL|MEAN(X)| STD(X)|SAMPL|MEAN(Y)| STD(Y)|MEAN OF|STD.ERR| T-TEST|T-TEST |NL:X-Y>=0|NL:X-Y<=0|NL:X-Y= 0|95%CONF. IN
TRVL
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| X Y  |SIZ:X|       |       |SIZ:Y|       |       | (X-Y) | (X-Y) | D.O.F |VAL(T=)|AL:X-Y <0|AL:X-Y >0|AL:X-Y<>0|  ON DIFFER
ENCE
|      |     |       |       |     |       |       |       |       |       |       |         |         |         |
|      |     |       |       |     |       |       |       |       |       |       |         |         |         |
| 1 2  |   3 | 0.6477| 0.0319|   3 | 0.6911| 0.0233|-0.0433| 0.0228|     4 | -1.901|  0.0647 |  0.9353 |  0.1294 |-0.1241_ 0.
0374


  D     | For a given significancelevel (40% to 1%) do we reject (R) or accept (A) the
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  C A   |_____________________________________________________________________________
  I B   |NULL HYPOTHESES: MEAN(X-Y)>=0||NULL HYPOTHESES: MEAN(X-Y)<=0||NULL HYPOTHESES: MEAN(X-Y) =0||
  S L   |ALTR HYPOTHESES: MEAN(X-Y) <0||ALTR HYPOTHESES: MEAN(X-Y) >0||ALTR HYPOTHESES: MEAN(X-Y)<>0||
  I E   |
  O     |  SIGNIFICANCE LEVEL (%)     ||  SIGNIFICANCE LEVEL (%)     ||  SIGNIFICANCE LEVEL (%)     ||
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|INDXES|40|35|30|25|20|15|10| 5| 2| 1||40|35|30|25|20|15|10| 5| 2| 1||40|35|30|25|20|15|10| 5| 2| 1||
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***** ONE-WAY ANOVA ****** FILE: PEAK.DAT
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----
|INDXES|SAMPL|MEAN(X)| STD(X)|SAMPL|MEAN(Y)| STD(Y)|MEAN OF|STD.ERR| T-TEST|T-TEST |NL:X-Y>=0|NL:X-Y<=0|NL:X-Y= 0|95%CONF. IN
TRVL
| X Y  |SIZ:X|       |       |SIZ:Y|       |       | (X-Y) | (X-Y) | D.O.F |VAL(T=)|AL:X-Y <0|AL:X-Y >0|AL:X-Y<>0|  ON DIFFER
ENCE
|      |     |       |       |     |       |       |       |       |       |       |         |         |         |
|      |     |       |       |     |       |       |       |       |       |       |         |         |         |
| 1 2  |   3 | 0.0009| 0.0003|   3 | 0.0007| 0.0001| 0.0003| 0.0002|     4 |  1.379|  0.8802 |  0.1198 |  0.2397 |-0.0004_ 0.
0010


  D     | For a given significancelevel (40% to 1%) do we reject (R) or accept (A) the
  E T   |null hypotheses shown below, and what kind of relation is valid between the 2 treatmment indeces
  C A   |_____________________________________________________________________________________________
  I B   |NULL HYPOTHESES: MEAN(X-Y)>=0||NULL HYPOTHESES: MEAN(X-Y)<=0||NULL HYPOTHESES: MEAN(X-Y) =0||
  S L   |ALTR HYPOTHESES: MEAN(X-Y) <0||ALTR HYPOTHESES: MEAN(X-Y) >0||ALTR HYPOTHESES: MEAN(X-Y)<>0||
  I E   |
  O     |  SIGNIFICANCE LEVEL (%)     ||  SIGNIFICANCE LEVEL (%)     ||  SIGNIFICANCE LEVEL (%)     ||
_____________________________________________________________________________________________________
|INDXES|40|35|30|25|20|15|10| 5| 2| 1||40|35|30|25|20|15|10| 5| 2| 1||40|35|30|25|20|15|10| 5| 2| 1||
_____________________________________________________________________________________________________
| 1 2  | A| A| A| A| A| A| A| A| A| A|| R| R| R| R| R| R| A| A| A| A|| R| R| R| R| A| A| A| A| A| A||
|rltion|NS|NS|NS|NS|NS|NS|NS|NS|NS|NS||NS|NS|NS|NS|NS|NS|<=|<=|<=|<=||<>|<>|<>|<>| =| =| =| =| =| =||
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OF ERROR---- SQUARS ------------------- FRDM.
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***** COMPARISON OF MEANS:for file: TOGH2.DAT
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                                                                                                    |HYPOTHESES(NL)&ACCEPT ALTERNATE (AL) |
|------|-----|-------|-------|-----|-------|-------|-------|-------|-------|-------|---------|---------|---------|-----------
----
|INDXES|SAMPL|MEAN(X)| STD(X)|SAMPL|MEAN(Y)| STD(Y)|MEAN OF|STD.ERR| T-TEST|T-TEST |NL:X-Y>=0|NL:X-Y<=0|NL:X-Y= 0|95%CONF. IN
TRVL
| X Y  |SIZ:X|       |       |SIZ:Y|       |       | (X-Y) | (X-Y) | D.O.F |VAL(T=)|AL:X-Y <0|AL:X-Y >0|AL:X-Y<>0|  ON DIFFER
ENCE
|      |     |       |       |     |       |       |       |       |       |       |         |         |         |
|      |     |       |       |     |       |       |       |       |       |       |         |         |         |
| 1 2  |   3 | 0.0226| 0.0043|   3 | 0.0333| 0.0012|-0.0108| 0.0026|     4 | -4.182|  0.0075 |  0.9925 |  0.0150 |-0.0199_-0.
0016


  D     | For a given significancelevel (40% to 1%) do we reject (R) or accept (A) the
  E T   |null hypotheses shown below, and what kind of relation is valid between the 2 treatmment indeces
  C A   |_____________________________________________________________________________________________
  I B   |NULL HYPOTHESES: MEAN(X-Y)>=0||NULL HYPOTHESES: MEAN(X-Y)<=0||NULL HYPOTHESES: MEAN(X-Y) =0||
  S L   |ALTR HYPOTHESES: MEAN(X-Y) <0||ALTR HYPOTHESES: MEAN(X-Y) >0||ALTR HYPOTHESES: MEAN(X-Y)<>0||
  I E   |
  O     |  SIGNIFICANCE LEVEL (%)     ||  SIGNIFICANCE LEVEL (%)     ||  SIGNIFICANCE LEVEL (%)     ||
_____________________________________________________________________________________________________________________
|INDXES|40|35|30|25|20|15|10| 5| 2| 1||40|35|30|25|20|15|10| 5| 2| 1||40|35|30|25|20|15|10| 5| 2| 1||
_____________________________________________________________________________________________________________________
| 1 2  | R| R| R| R| R| R| R| R| R| R|| A| A| A| A| A| A| A| A| A| A|| R| R| R| R| R| R| R| R| R| A||
|rltion| <| <| <| <| <| <| <| <| <| <||<=|<=|<=|<=|<=|<=|<=|<=|<=|<=||<>|<>|<>|<>|<>|<>|<>|<>|<>| =||
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***** ONE-WAY ANOVA ****** FILE: TOGH2.DAT
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320

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OF ERROR---- SQUARS ------------------- FRDM.
 ------SQURS                                    REJECT NULL
--------     ------                        -------
    ----              ------                 -----------

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    1.5027079976412D-02
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-----------------------------------------------------
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***** COMPARISON OF MEANS:for file: STPEAK.DAT
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|------|-----|-------|-------|-----|-------|-------|-------|-------|-------|---+---|---------|---------|---------|-----------
----
|INDXES|SAMPL|MEAN(X)| STD(X)|SAMPL|MEAN(Y)| STD(Y)|MEAN OF|STD.ERR| T-TEST|T-TEST |NL:X-Y>=0|NL:X-Y<=0|NL:X-Y= 0|95%CONF. IN
TRVL
| X Y  |SIZ:X|       |       |SIZ:Y|       |       | (X-Y) | (X-Y) | D.O.F |VAL(T=)|AL:X-Y <0|AL:X-Y >0|AL:X-Y<>0|  ON DIFFER
ENCE
|      |     |       |       |     |       |       |       |       |       |       |         |         |         |
|      |     |       |       |     |       |       |       |       |       |       |         |         |         |
| 1 2  |   3 | 0.0014| 0.0004|   3 | 0.0010| 0.0000| 0.0004| 0.0002|     4 |  1.639|  0.9121 |  0.0879 |  0.1758 |-0.0005_ 0.
0012


  D      | For a given significancelevel (40% to 1%) do we reject (R) or accept (A) the
  E T    |null hypotheses shown below, and what kind of relation is valid between the 2 treatmment indeces
  C A    |_____________________________________________________________________________________________
  I B    |NULL HYPOTHESES: MEAN(X-Y)>=0||NULL HYPOTHESES: MEAN(X-Y)<=0||NULL HYPOTHESES: MEAN(X-Y) =0||
  S L    |ALTR HYPOTHESES: MEAN(X-Y) <0||ALTR HYPOTHESES: MEAN(X-Y) >0||ALTR HYPOTHESES: MEAN(X-Y)<>0||
  I E    |
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  O     |  SIGNIFICANCE LEVEL (%)     ||  SIGNIFICANCE LEVEL (%)     ||  SIGNIFICANCE LEVEL (%)     ||
_____________________________________________________________________________________________________
|INDXES|40|35|30|25|20|15|10| 5| 2| 1||40|35|30|25|20|15|10| 5| 2| 1||40|35|30|25|20|15|10| 5| 2| 1||
_____________________________________________________________________________________________________
| 1 2  | A| A| A| A| A| A| A| A| A| A|| R| R| R| R| R| R| R| A| A| A|| R| R| R| R| R| A| A| A| A| A||
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***** ONE-WAY ANOVA ****** FILE: STPEAK.DAT
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SOURCE  ---- SUM OF ------------------- DEG. OF
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OF ERROR---- SQUARS ------------------- FRDM.
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 (error)
-----------------------------------------------------
TOTAL           5.7411056778840D-07  5

  TOTAL NUMBER OF DATA ENTRIES =   6
```

CARBON FIBER REINFORCED CEMENT COMPOSITES: LATEX MODIFICATION EFFECTS

By

Fadhel Aouadi

PART II OF

A DISSERTATION

Submitted To:

Michigan State University

In Partial Fulfillment Of The Requirements

For The Degree Of

DOCTOR OF PHILOSOPHY

Department Of Civil And Environmental

Engineering

1992

CR-82-524

ABSTRACT

CARBON FIBER REINFORCED CEMENT COMPOSITES: LATEX MODIFICATION EFFECTS

By

Fadhel Aouadi

A new repair material was developed through latex modification of carbon fiber reinforced cement. The matrix mix composition, latex type and content, and application methodologies were optimized. A comprehensive experimental data base was generated on the mechanical properties, shrinkage characteristics, water absorption, freeze-thaw durability, acid resistance, and durability characteristics in hot-humid environments of latex modified carbon fiber reinforced cement.

Effects of the following application methodologies on the performance-characteristics of the developed repair material were investigated: casting, spraying, and traveling.

Practical guidelines are also provided which, together with the experimental data generated in this investigation, can be used to select the developed latex modified carbon fiber reinforced cement or alternative repair materials for satisfying specific repair job requirements.

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CHAPTER 1 INTRODUCTION

Fiber reinforcement and latex modification are two major developments in the concrete technology which have found growing popularity in the past two decades. These two new developments have advanced independently from each other; while there seems to exist important potentials for their joint use in concrete. Latex modification can improve certain aspects of concrete behavior which are not much influenced by the presence of fibers. Latex polymers can pronounce some key effects of the fiber reinforcement in concrete.

The research summarized in this report is concerned with the joint action of latex polymers and carbon fibers in cement-based materials for repair applications. The selection of carbon fibers was made based on their desirable durability characteristics and effectiveness as reinforcement fibers for cement. Selection of a specific latex polymer for use in carbon fiber reinforced cement was one of the tasks accomplished in this study.

Brief backgrounds on carbon fiber reinforced cement and the latex modification technique are presented in Chapter 2, which also elaborates on the potentials for the joint action of latex polymers and carbon fibers in cement-based materials.

The first phase of experimental work in this study, which is reported in Chapter 3, was concerned with a preliminary selection of the cementitious matrix mix proportions and selecting the suitable latex types for carbon fiber reinforced cement. This phase was followed by the optimization of the matrix composition for carbon fiber reinforced cements incorporating different latex contents. This work, which is summarized in Chapter 4, was aimed at selecting the optimum latex content and developing a comprehensive set of experimental data for latex-modified carbon fiber reinforced cement. The effects of latex modification on durability characteristics of carbon fiber reinforced cement under the action of repeated freeze-thaw cycles, acid attack, and exposure to hot-humid environments are described in Chapter 5 and 6.

The repair application methodologies of latex modified carbon fiber reinforced cement are investigated in Chapter 7. Some practical guidelines for the selection of latex

modified carbon fiber reinforced cement and alternative materials for satisfying specific upper job requirements are presented in Chapter 8.

A summary of the activities and outcomes of the research project is given in Chapter 9.

CHAPTER 2

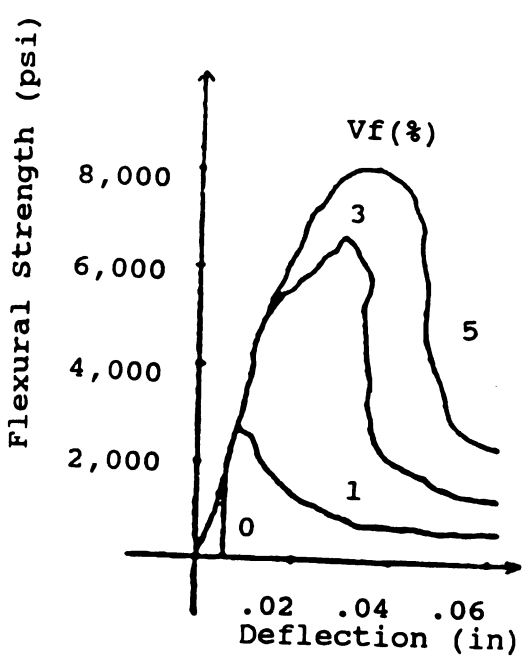
BACKGROUND

2.1 GENERAL

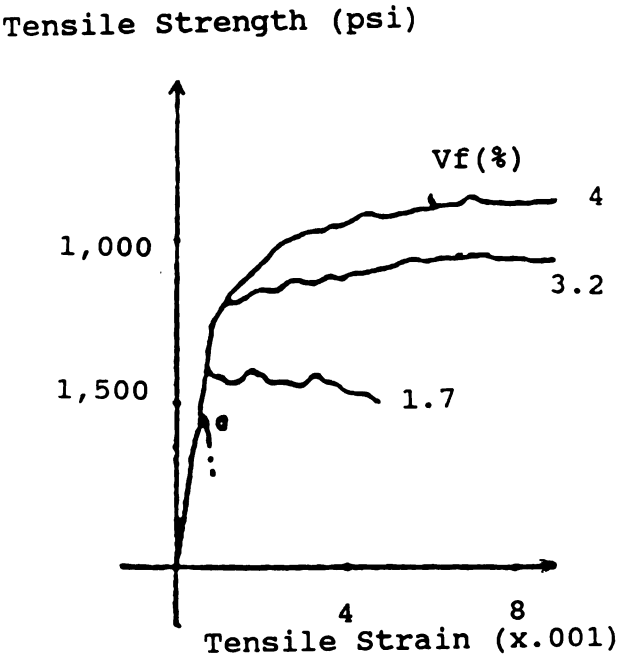
This chapter describes some key aspects of the performance characteristics of carbon fiber reinforced and latex modified cement-based materials. The potentials for joint action of latex polymers and carbon fibers in cement are also discussed, with due consideration given to the repair applications of the material.

2.2 CARBON FIBER REINFORCED CEMENT

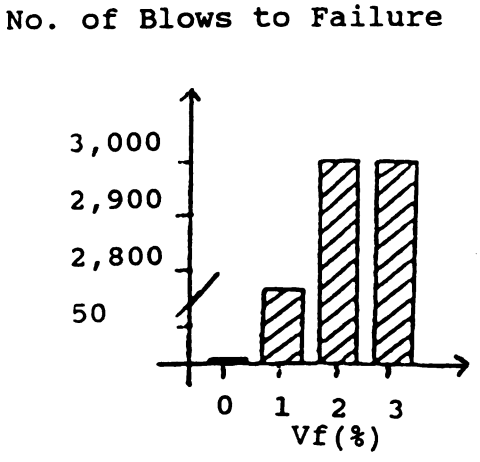
Cementitious materials are generally weak in tension and fail in a brittle manner under different stress systems. These problems result mainly from the ease of initiation and propagation of microcracks, and the lack of post-cracking tensile resistance in cement-based materials. Carbon fiber reinforcement is an effective technique for hindering the propagation of microcracks in cementitious matrices. Carbon fiber reinforced cement (CFRC) composites are thus tough materials with desirable tensile strength and impact resistance. The crack-stabilization action of carbon fibers in cement matrices results in major improvements in the flexural and tensile load and deformation capacities (Figs. 2.1-a, b), impact resistance (Fig. 2.1-c), and drying shrinkage characteristics (Fig. 2.1-d) of cement-based materials. The typical improvements presented in Fig. 2.1 correspond to a condition with 3% volume fraction of carbon fibers with 3 mm(0.12 in) length and a diameter of 10 microns (0.0004 in) (Ref. 1).



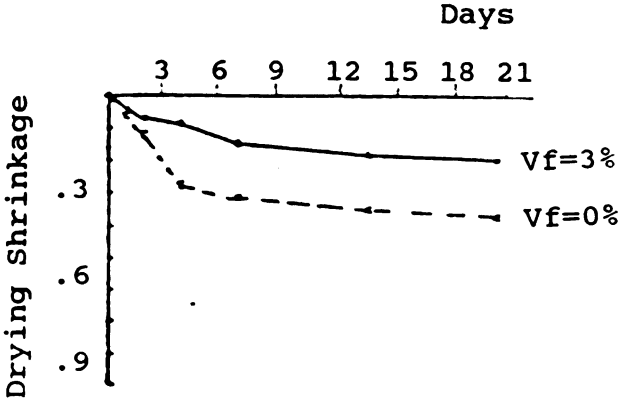
(a) Flexural Behavior



(b) Tensile Behavior



(c) Impact Resistance



(d) Drying Shrinkage2

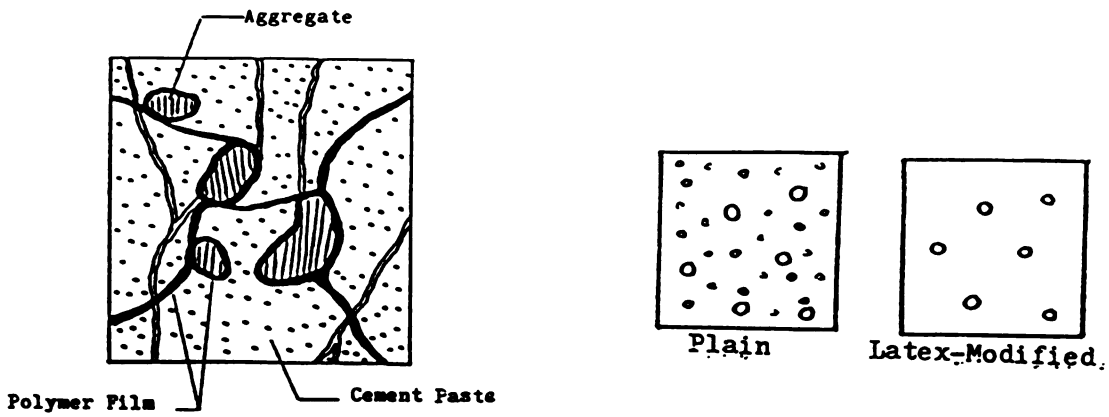
FIGURE 2.1 Typical Improvements In The Performance of Cementitious Materials Resulting From Carbon Fiber Reinforcement.

The desirable reinforcement properties of carbon fibers in cement, together with their excellent durability characteristics and chemical resistance, make carbon fiber reinforced cement a strong candidate for substituting conventional concrete and other materials in applications involving severe exposure and loading conditions.

2.3 LATEX-MODIFIED CONCRETE

A latex consists of very small (0.05-1.0 microns = 0.000002-0.00004 in) spherical particles of polymers held in suspension by the use of surface- active agents (Refs. 4,5). Latex polymers can markedly improve concrete properties without requiring any significant change in its processing technology. Cement in latex modified concrete hydrates and cures in the same manner as in conventional concrete. As the cement hydration process continues, the polymers will coalesce and bond to form a continuous polymer film (Fig. 2.2-a). As a result, latex modified concrete has a less porous structure and less permeability when compared with plain concrete (Fig. 2.2 - b). The

film-formation process in latex modified concrete is the result of water loss from the latex emulsion, either to evaporation or to the cement hydration, after which the polymer particles are forced together either by the growth of the cement hydrate or by capillary action created by the water loss. In order to obtain the benefits of latex modified concrete, it is important that sufficient polymer particles be present in the mix to develop a continuous polymer film throughout the concrete mix. It is this continuous film which imparts the superior physical and chemical properties of latex modified concrete.



(a) Schemata for Latex-Modified

(b) Pore Features of Plain Concrete and Latex-ModifiedConcrete

FIGURE 2.2 Structure of Latex-Modified Concrete.

Another factor enhancing the efficiency of latex in concrete applications is its desirable bonding to cement hydrate and aggregates. The bond between polymer and cement appears to form in the early stages of cement hydration, with the polymer bonding through the calcium ions present in cement (Ref. 5). Once this bond is developed, it is strong and irreversible. Latex particles coat the cement gel, aggregates and fibers with a monolayer which eventually coalesces as the

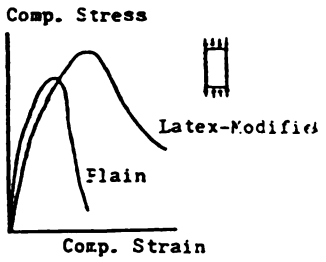
various particles come into contact. This leads to a composite action between different constituents of fiber reinforced concrete, and adds to the desirable effects of fiber reinforcement. Another advantage of latex modification is the improvement of fresh mix flow characteristics. The polymer particles are coated with surfactants that also act as highly effective dispersants for cement particles. Hence, the polymer admixture not only acts as a water reducer, but also improves the thixotropic nature of fresh concrete. Under loading, when microcracks tend to propagate and interconnect inside concrete, the polymer binder bridges the microcracks. The "fibers" of latex can be seen in Fig. 2.3 to bridge the microcracks, whereas in conventional concrete the void is unfilled.



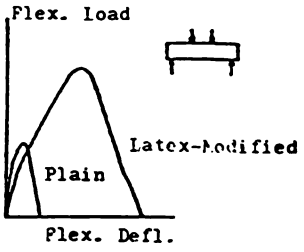
(a) Plain Concrete (b) Latex-Modified Concrete

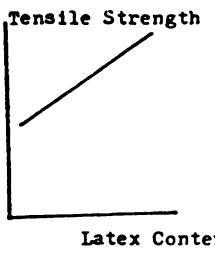
FIGURE 2.3 Arrest of Microcracks in Latex-Modified Concrete (Magnification 12,000x) (Ref. 6).

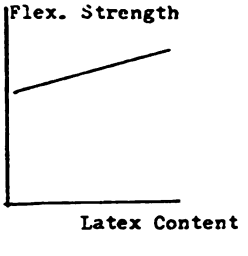
The presence of latex in concrete, through the mechanisms discussed above, results in concretes with enhanced ductility (Fig. 2.4-a), tensile and flexural strength (Fig. 2.4-b), bond to steel fibers and old concrete (Fig. 2.4-c), impermeability (Fig. 2.4-d), chemical resistance (Fig. 2.4-e), and freeze-thaw durability (Fig. 2.4-f).



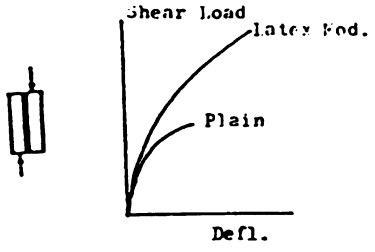
(a) Ductility



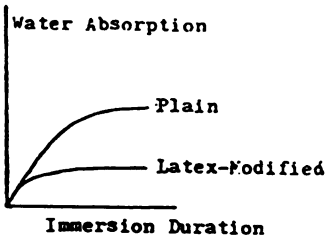




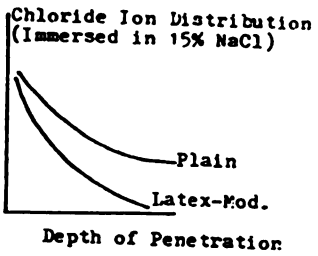
(b) Tensile and Flexural Strengths



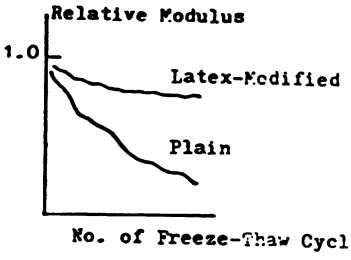
(c) Adhesion



(d) Impermeability



(e) Chemical Resistance



(f) Freeze-Thaw Durability

FIGURE 2.4 Improvements In Concrete Properties Resulting From Latex Modification (Refs. 2-6).

2.4 CONCEPT OF LATEX-MODIFIED FIBROUS CEMENT

The enhancements in concrete structure resulting from latex modification (reduced porosity, and bonding of polymers to mix inclusions), desirably match those resulting from carbon fiber reinforcement (microcrack stabilization and bridging of macrocracks). Latex polymers are expected to enhance the fiber-matrix bond characteristics and thus pronounce the reinforcement properties of carbon fibers in cement.

The concept of latex modified carbon fiber reinforced cement, once materialized, can lead to the development of cementitious materials with desirable impermeability and durability characteristics and improved bonding to substrate (latex polymer effects), and enhanced flexural strength and toughness properties and impact resistance (carbon fiber effects which tend to be pronounced by latex modification). With cement constituting the bulk of this new material, it is also expected to be cost-efficient and relatively inexpensive. The potential advantages of latex modified carbon fiber reinforced cement lend themselves ideally to repair applications where particularly strong demands exist on the material performance characteristics.

2.5 SUMMARY

A brief background was presented on the mechanisms of action of carbon fibers and latex polymers in cement-based materials. Typical improvements in the performance characteristics of cement resulting from either latex modification or carbon fiber reinforcement were discussed. The potentials for joint action of latex polymers and carbon fibers in cementitious materials are introduced.

CHAPTER 3

PRELIMINARY SELECTION OF MIX COMPOSITION AND LATEX TYPE

3.1 GENERAL

There are some aspects of the carbon fiber reinforced cement (CFRC) mix constituents which may influence the action of latex when added to CFRC mixtures. These mixes typically include relatively high silica fume contents. The fine particles of silica fume and also the relatively large surface area of carbon fibers may act to absorb some constituents (e.g. surfactants) of the latex polymer composition, potentially leading to adverse effects on the workability of fresh mix and the development of a coherent cement-polymer co-matrix. These potential distinctions between the actions of latex polymers in the conventional concrete and CFRC made it necessary to select the mix proportions of latex modified CFRC carefully, based on a comprehensive experimental study that is summarized in this chapter. Selection of the latex polymer type which best fits CFRC composites was another task accomplished in this phase of the experimental research. This chapter provides a review of the materials, manufacturing techniques, and test procedures used for the selection of the mix proportions and latex types in latex modified CFRC composites. The test results and the optimum proportions and latex types are also discussed.

3.2 MATERIALS, MANUFACTURING PROCEDURES AND TEST TECHNIQUES

3.2.1 Materials

The materials used in this phase of study were cement, silica fume, silica sand, superplasticizer, antifoaming agent, carbon fiber, latex polymer, and regular tap water. A brief description of these materials is presented below.

a- Cement: Regular Type I Portland cement was used in all the mixtures. Table 3.1 presents some basic chemical and physical properties of the cement.

Table 3.1 Properties of the Portland Cement Type I Used in This Study.

Compound	CaO	SiO2	Al2O3	Fe2O3	MgO	SO3	K2O
Content (%)	63.24	21.14	5.76	2.93	2.06	2.46	0.79

Specific Gravity	Specific Surface (m2/kg)
3.15	160

b- Silica Fume: Silica fume in CFRC mixtures helps with the dispersion of carbon fibers and also contributes to the hardened material performance. It is a fine, highly reactive pozzolanic material. The silica fume used in this study was a product of Elkem Chemicals, and its physical and chemical properties are presented in Table 3.2.

Table 3.2 Properties of EMS 960 Silica Fume (Ref. 7).

Component	SiO2	C	Fe2O3	MgO	Al2O3	K2O	Na2O
Content (%)	96.5	1.4	0.15	0.20	0.15	0.04	0.20

Specific Gravity	Specific Surface	Bulk Density
2.3	200,000 cm2/g	225kg/m3 (14lb/ft3)

Ave. Particle Size	Particles < 0.45 microns (18*10-5 in)
0.15 microns (6x10-5 in)	99.5 %

c- Silica Sand: Grade 40 Silica Sand, provided by Unimin Corporation, was used in this investigation. The maximum particle size was 0.5 mm (0.02 in), and the gradation of this sand is presented in Table 3.3.

Table 3.3 Gradation of Grade 40 Silica Sand.

U.S. Sieve	40	50	70	100	140
% Passing	72	23.3	4.8	1.2	0.1

d- Superplasticizer: The presence of large Silica Fume contents in CFRC mixtures have adverse effects on the fresh mix workability. Hence, relatively large dosages of superplasticizer are necessary to improve the workability of fresh CFRC mixtures. The superplasticizer used in this study was Daracem 100, a product of W.R. Grace & Company (Ref. 8).

e- Antifoaming Agent: Anti-Foam B Emulsion Class 2 from Dow Corning was used, and is identified as Polydimethyl Siloxane. This material is a surface active agent which reduces the surface tension of the mix so that bubbles generated in the mixing process burst, thus the fraction of air voids in cement will be reduced. This polymer is very non-reactive and non-polar.

f- Carbon Fiber: Pitch-based carbon fibers provided by the Ashland Carbon Fiber Division (Ref. 9), with desirable strength and durability characteristics and relatively low cost, were used in this investigation. Some key properties of these fibers are presented in Table 3.4. The fibers used in this study have a length of 1.5 mm (1/16 in.), and in some cases 3 mm (1/8 in.).

Table 3.4 Properties of Pitch-Based Carbon Fibers.

Diameter	Specific gravity	Tensile strength	Modulus of elasticity	Elongation
10 microns (4x10-4 in)	1.6	690 MPa (100 ksi)	55,000 MPa (8,000 ksi)	1.4 %

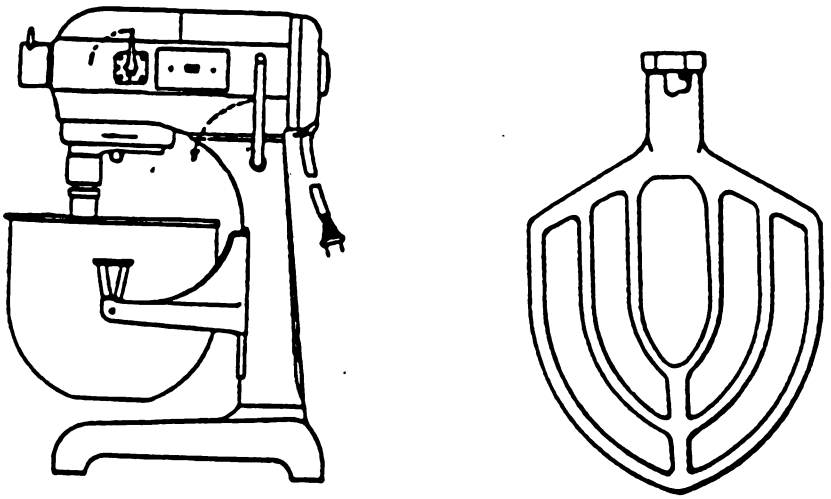
g- Latex: Wide ranges of commercially available latex types were used in this phase of the research. These included different Styrene Butadiene, Acrylic, Vinyl Acetate, Natural Rubber, etc. Table 3.5 introduces some basic properties of the latex polymers used in this research.

Table 3.5 Properties of the Latex Polymers Used in This Study.

Product name	Polymer type	% solids by weight	PH	Viscosity cps	Weight (lb)/ Gallon or[specific gravity]	Particle size(Ang)
BASF	Styrene Butadiene	47	9.5	26	8.4 [ ]	—
Dow Chemicals Modifier A	Styrene Butadiene	47.5	10.6	37	[1.040]	1950
Union Carbide						
UCAR 413	Acrylic	47	9.5	50	[1 to 1.2]	—
UCAR 414	Acrylic	47	9.5	50	[1 to 1.2]	—
UCAR 417	Acrylic	51	5	50	[1 to 1.2]	—
National Starch and Chemical Corp. Nacrylic 78-6232	Styrene/ Acrylic	55	8.5	400	[1.01]	1500
NL Chemical, Inc. AROLON 845-W-45	Styrene/ Acrylic	44-46	8-8.5	100-300	[1.05]	—
Rohm and Haas Comp POLYCO 571	Vinyl Acetate Homopolymer	55	4.7	2200	[1.01]	1700
REMR Acryl-Set	Styrene/ Acrylic	24.5			8.4	
Gunthrie Latex, Inc. UNITEX/Dynatex						
Unitex High Ammonia	Natural Rubber	61.8	10.3	74	—	—
Dynatex PCP Low Ammonia	Natural Rubber	61.64	9.7	78	—	—
Dynatex GTZ Low Ammonia	Natural Rubber	62.04	9.95	76	—	
Fox Industries, Inc. FX-338	Acrylic	46	9.5-10		8.8 [1.056]	
Fox Industries, Inc. FX-337		47	10.5	100	[1.01-1.03]	

3.2.2 Manufacturing Procedure

Latex modified carbon fiber-cement mixtures were manufactured in a 12-liter mortar mixer (see Figure 3.1).



(a) The Mixer (b) The Mixing Blade

FIGURE 3.1 Conventional Mortar Mixer.

The mixing procedure selected for the manufacture of latex modified CFRC composites was as follows:

1 - charge the mixer with all the silica fume and 3/4 of the liquid (water + chemical admixtures), and mix at low speed for about 2 minutes until a uniform mixture is achieved;

2 - add the fibers gradually as the mixer is running over a period of about 2 minutes;

3 - add the silica sand followed by the remainder of water;

4 - add the latex slowly to ensure the homogeneity of the mixture, and then mix for another 1 minute;

5 - add the cement, and then mix for 2 minutes;

6 - stop the mixer for about 30 seconds;

7 - change the mixing speed to medium, and mix for about 2.5 minutes.

The specimens were cast in the molds, and were vibrated externally on a vibrating table. They were kept inside the molds under a plastic sheet for 24 hours, and were then demolded and exposed to a regular laboratory environment until the test age of 14 days. This was the standard curing condition referred to as dry during. Other curing conditions were also tried in later phases of the project.

3.2.3 Mix Proportions

The main objective of this phase of the study was to select mix proportions which best suit late modified carbon fiber reinforced cement for achieving desirable fresh mix and hardened material properties. Considering the lack of previous studies in this area, the procedure followed in the selection of the mix proportion was based on a trial and adjustment procedure. This process proved to be a timely one, because some important aspects of latex performance in carbon fiber cement were found to be different from those in conventional concrete. Hence, some important changes had to be made in the initial trial mix compositions.

Table 3.6 summarizes the proportions of the trial mixes considered in this phase of the research for optimizing the proportions of the cementitious matrix. The latex type used in the mixes of Table 3.6 was FX-337 produced by Fox Industries, Inc. (see Table 3.5). The latex-binder ratio was kept constant at 0.1 by weight in order to concentrate on the effects of the cementitious matrix mix proportions on the composite material properties. Based on the test results obtained from the mixes of Table 3.6, the cementitious matrix mix proportions were selected. This phase of experimental study was then completed through the assessment of the effects of different latex types in carbon fiber reinforced cement composites.

Table 3.6 Mix Proportions in Experimental Study Performed to Select the Cementitious Matrix.

mix no.	W/b	Sf/b	Fa/b	L/b	Sp/b	Sr/b	Vf (%)	Lf (mm.)	S.S. (%)
1	0.348	0.13	0	0.1	0.032	0.0031	1.89	3	25
2	0.348	0.13	0	0	0.032	0.0031	1.89	3	25
3	0.37	0.13	0	0.1	0.032	0.005	3	3	25
4	0.39	0.2	0.1	0.1	0.032	0.005	3	3	25
5	0.45	0.2	0.1	0.1	0.032	0.005	3	3	25
6	0.45	0.2	0	0.1	0.032	0.005	3	3	25
7	0.45	0.2	0	0.1	0.032	0	3	3	25
8	0.45	0.2	0	0.1	0.032	0.005	3	1.5	25
9	0.4	0.2	0	0.1	0.032	0.005	3	1.5	25
10	0.37	0.2	0	0.1	0.032	0.005	3	1.5	25
11	0.37	0.2	0	0	0.032	0.005	3	1.5	25
12	0.37	0.2	0	0.1	0.032	0.005	3	1.5	25
13	0.37	0.2	0	0.1	0.032	0.005	3	1.5	25
14	0.37	0.2	0	0.1	0.032	0.005	3	1.5	25
15	0.348	0.2	0	0.05	0.032	0.005	3	1.5	25
16	0.306	0.2	0	0	0.032	0.005	3	1.5	25

where: W = water; b = binder; Sf = silica fume; Fa = fly ash; L = latex; Sp = superplasticizer; Sr = set retarder; Vf = volume of fibers (%); Lf = length of fibers (mm); S.S.= silica sand; Af = antifoam

The cementitious matrices introduced in Table 3.6 include a relatively large number of chemical and mineral admixtures, each of them used for a specific main reason discussed in the following. Silica fume facilitates the dispersion of carbon fibers, while its damage to workability has been overcome through the use of a superplasticizer. Set retarder is also used to reduce the loss of workability with time which is adversely influenced by the use of silica fume. Fly ash was also considered for improving the workability of fresh mix. The antifoaming agent was needed to control the air content which tends to increase when latex polymers are used in cementitious mixes.

Based on the results obtained from the mixtures presented in Table 3.6, in order to select the optimum latex types for application to carbon fiber reinforced cement, all the latices presented in Table 3.5 were investigated in a carbon fiber cement composite with mix proportions given in Table 3.7. The latex-binder ratio was kept constant in this phase of study at a value of 0.1.

Table 3.7 Mix Proportions in the Experimental Study For Selecting the Latex Type.

W/b	Sf/b	Fa/b	L/b	Sp/b	Sr/b	Vf	Lf	S.S	Af/b
0.37	0.20	0	10%	0.032	0.005	3%	1.5mm	25%	0.015

Towards the completion of this phase of study, it was noticed that the set retarder is having detrimental effects on the performance of our optimized composites. In order to investigate this effect, a mix without set retarder was tried to make a better selection of the composition for using in the later phases of this study. The proportions of this special mix without set retarder are present in Table 3.8. This mix incorporated silica sand no. 100, which is finer than the silica sand no. 40 used in the mixes of Tables 3.6 and 3.7. It is worth mentioning that this mix performed quite satisfactorily (to be discussed later) and the future phases of this research project were conducted with set retarder removed from the mix composition.

Table 3.8 Proportions of the Mix Without Set Retarder.

W/b	Sf/b	Fa/b	L/b	Sp/b	Sr/b	Vf	Lf	S.S	Af/b
0.37	0.20	0	10%	0.032	0	3%	1.5mm	25%	0.015

3.2.4 Test Techniques

The latex-modified carbon fiber reinforced cement composites prepared in this phase of study were characterized in the fresh state through the performance of the flow table test (ASTM C-87) on the fresh mixtures at 1, 5, and 10 minutes after the completion of mixing (to assess the workability of the fresh mix and its loss with time). The void content of the fresh mix was also obtained by the volumetric method (ASTM C- 173). The flexural and compressive strengths of the material were measured after 7 days of air curing following the procedures outlined in ASTM C-1018 and ASTM C-873, respectively. Three flexural specimens 38.1 x 38.1 x 152.4 mm (1.5 x 1.5 x 6 in), were tested for each mix by center-point loading on a span of 114.3 mm (4.5 in.). The compression specimens were 76.2 mm (3 in) in diameter and 152.4 mm (6 in) high. Two compression specimens were tested for each mix.

3.3 EXPERIMENTAL RESULTS

The test date generated in this phase of study will be presented here in three stages:

1 - selection of cementitious matrix mix proportions;

2 - selection of the latex type; and

3 - performance of the mix without set retarder.

3.3.1 Selection of the Cementitious Matrix Mix Proportions

Test results obtained for the mixes of Table 3.6 are presented in Table 3.9.

Table 3.9 Test Results For Mixes of Table 3.6

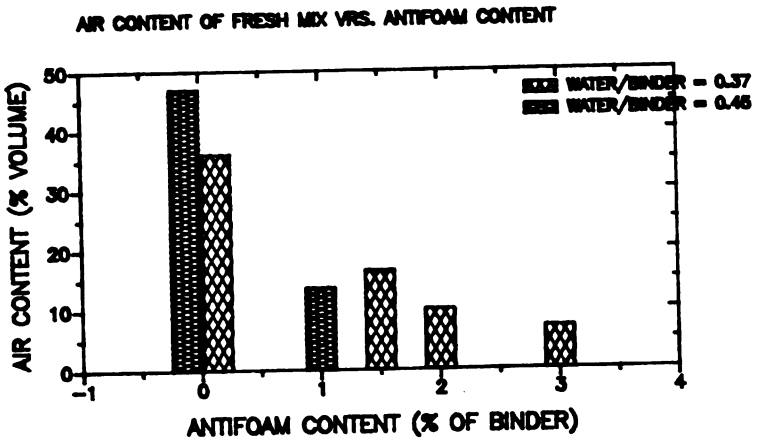
Mix Number	Flow (%)			Air Content (%)	Flexural Strength (psi) (7-day)	Compressive Strength (psi) (7-day)
	1 min.	5 min.	10 min.			
1	54	16	8			
2	77	51	41	26		
3	11	1	0	50	414	
4	11	4	0	51	268	
5	51	46	21	46	408	453
6	63	45	31	47	353	326
7	30	21	14	56	286	283
8	126	110	103	14	376	
9	98	87	64	20	327	708
10	62	58	34	16	683	807
11	> 100	>100	>100	10	420	779
12	23	4	7	9	351	595
13	45	31	27	7	396	566
14	16	3	0	36	340	
15	56	41	27	11	318	
16	68	48	43	19	381	

As mentioned earlier, the mix proportions in this phase were selected based on trial and adjustment. A general analysis of the results had to be performed in order to select the optimum cementitious matrix mix proportions. Some trends observed in the test results are discussed below followed by the presentation of conclusions regarding the best mix proportions for the material.

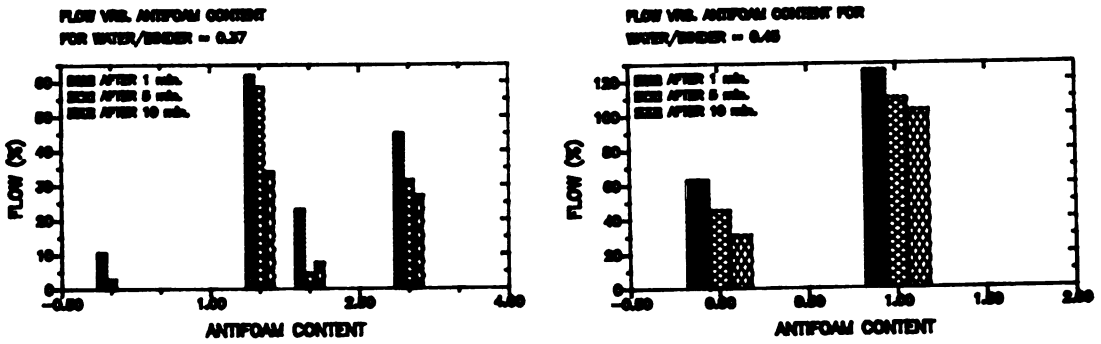
a- Effects of the Antifoaming Agent: The introduction of latex polymer to cementitious materials results in an increase in air content. It is thus necessary to use antifoaming agent in latex-modified cement-based materials. This agent can be either premixed with the latex or added to the mix during the manufacture. It should be noted that the antifoam content that best fits the fiber reinforced cement composition is not necessarily the one that works in plain concrete. An important objective in this preliminary phase of investigation was to obtain the optimum antifoam content for application to carbon fiber reinforced cement. Fig. 3.2 shows, based on the test results obtained for the mixes introduced in Table 3.6 (results given in Table 3.9), the effects of antifoam content on different properties of the fresh and hardened latex modified CFRC with a latex-cement ratio of 0.1 and 3% volume fraction of carbon fibers of length 1.5 mm (1/15 in).

As shown in Fig. 3.2-a, the air content (which is excessively high in mixes without antifoaming) drops rather significantly with the use of antifoam-binder ratio of 1 to 2%. Further increase in antifoam content seems to have smaller effects on the air content of carbon fiber reinforced cement in Fig. 3.2-a.

Fig. 3.2-b presents the antifoam effects on the workability (flow) of latex modified CFRC mixtures. This figure indicates that the workability of fresh mix tends to improve with increasing antifoaming agent up to an antifoam-binder ratio below 2%. Further increase in antifoam content seems to adversely influence the fresh mix workability. The flexural and compressive strength test results presented in Fig. 3.2-c also indicate that optimum results can be obtained at 1 to 2% antifoam-binder ratio. One may thus conclude that the optimum antifoam-binder ratio for the latex modified CFRC mixture of this study is about 1.5%.

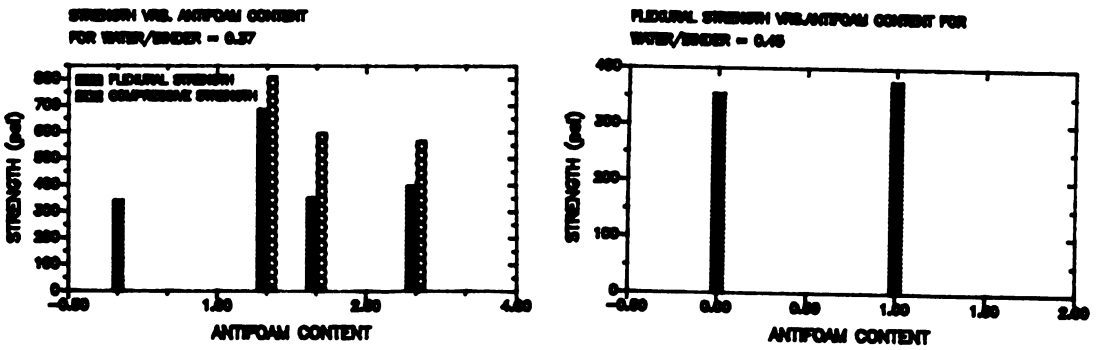


(a) Air Content



water/binder=0.37 water/binder=0.45

(b) Flow



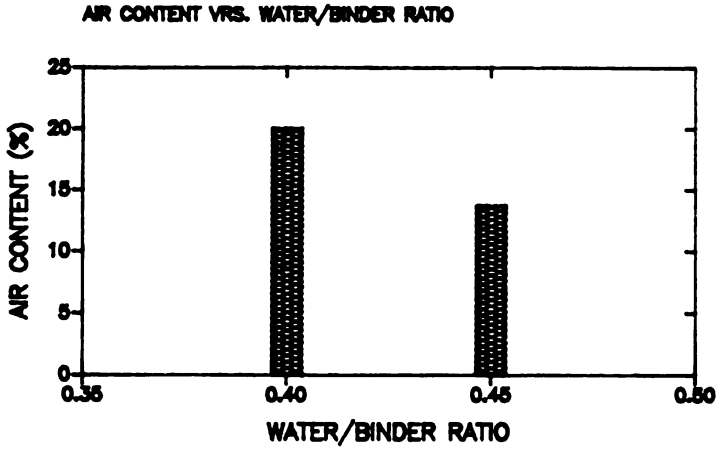
water/binder=0.37 water/binder=0.45

(c) Strength

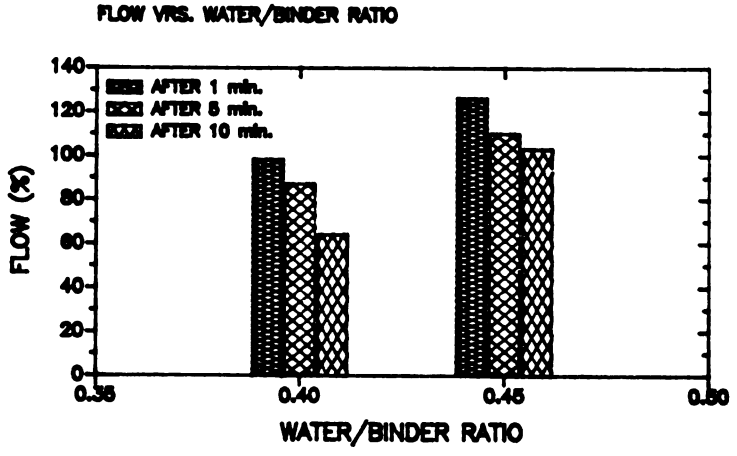
FIGURE 3.2 The Effects of Antifoam Content on the Material Properties of Latex-Modified Carbon-Fiber Reinforced Cement.

b- Effects of Water-Binder Ratio: The effects of water-binder ratio on material properties of latex-modified CFRC composites incorporating 10% latex-binder ratio and 1% antifoam-binder ratio is represented in Fig. 3.3 (fiber length 1.5 mm (1/16 in)). Fig. 3.3 has been developed based on test results of mixes of Table 3.6 (results given in Table 3.9). Figs. 3.3-a and - b are indicative of some drop in air content and increase in flow with increasing water-binder ratio. The decrease of air content may be used to justify the slight increase in flexural strength observed in Fig. 3.3-c resulting from the increase in water content. These results indicate that variations in water-binder ratio around values close to 0.40 have relatively small effects on the hardened material performance, mainly due to the fact that the damage to the strength of hydration products resulting from increased water-binder ratio would be compensated for by the improved compactibility and thus porosity of the composite material at higher water-binder ratios.

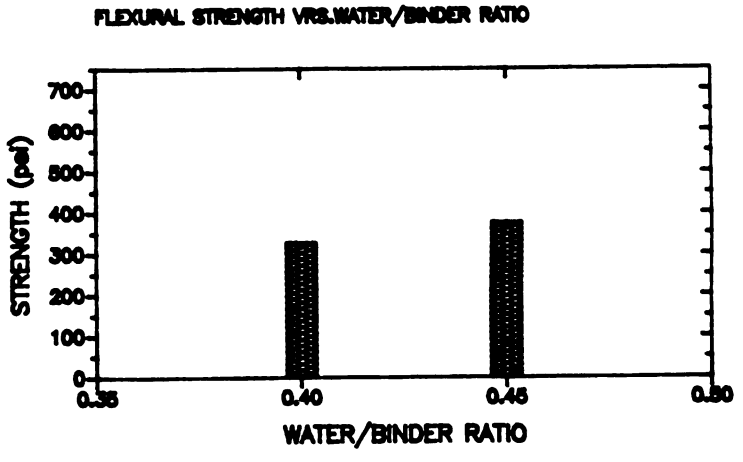
c- Effects of Fly Ash-Binder Ratio: The effects of fly ash content on the performance characteristics of latex-modified CFRC composites with a latex-binder ratio of 0.1, but without antifoaming agent, are shown in Fig. 3.4. This figure is developed using the test results presented in Table 3.9 for mixes of Table 3.6. The results show relatively small effects of fly ash on air content (Fig. 2.4-b). There is a slight improvement in strength as a result of fly ash application, as shown in Fig. 3.4-c. It should be noted that the inclusion of an antifoaming agent could modify the fly ash effects observed in Fig. 3.4. At this stage, however, it was decided to avoid making the mix further complex, and thus fly ash was eliminated from the mix composition.



(a) Air Content

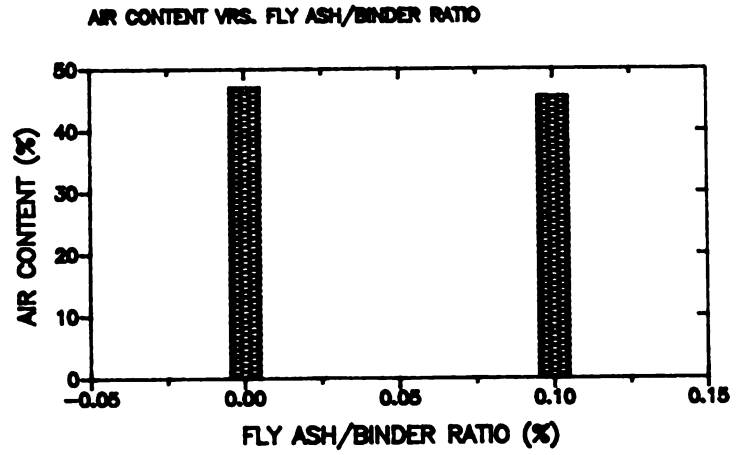


(b) Flow

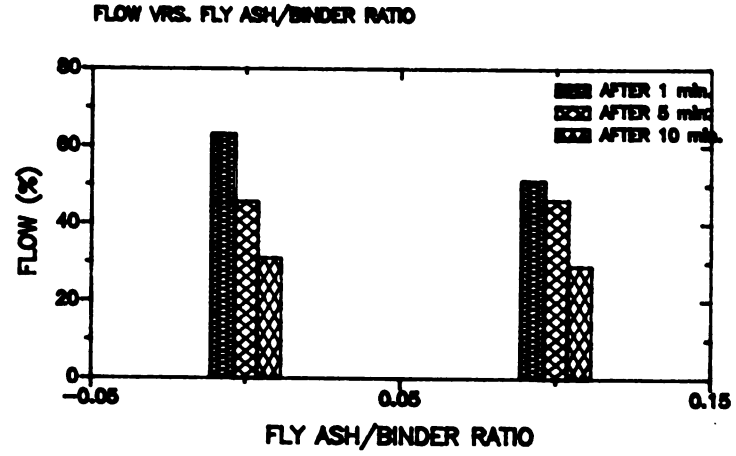


(c) Flexural Strength

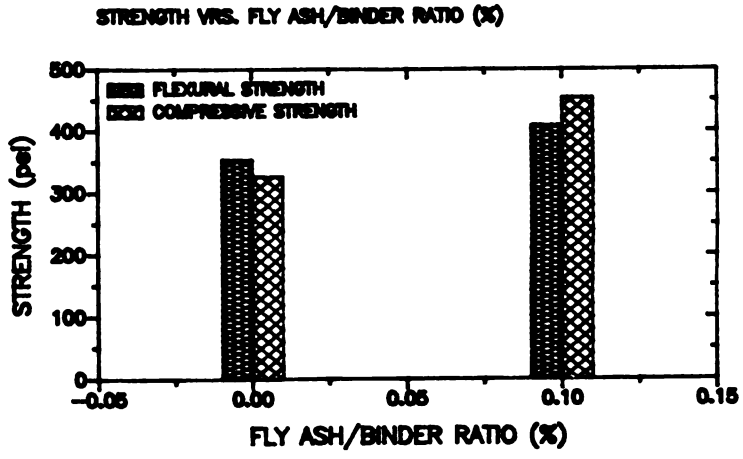
FIGURE 3.3 Effects of Water-Binder Ratio on the Material Properties of Latex-Modified Carbon Fiber Reinforced Cement.



(a) Air Content



(b) Flow



(c) Strength

FIGURE 3.4 Effects of Fly ash on the material Properties of Latex-Modified Carbon Fiber Reinforced Cement.

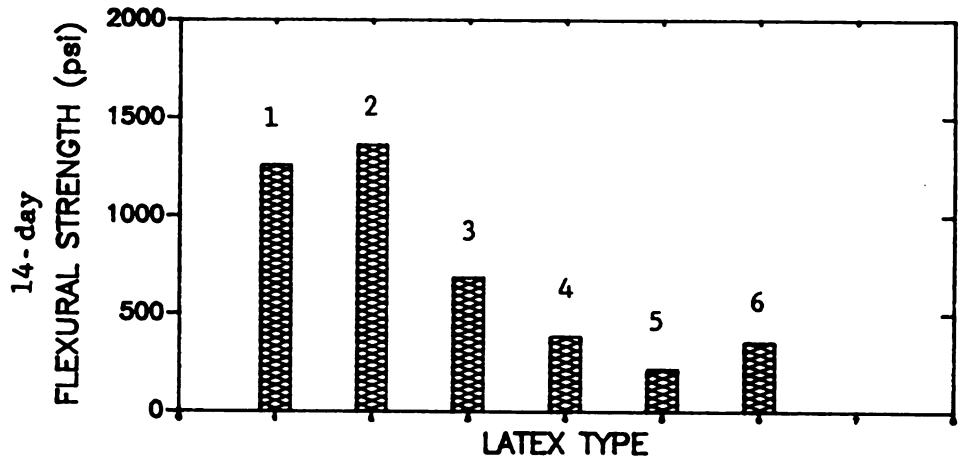
Based on the test results presented above, the following mix proportions were selected for latex-modified CFRC composites with a latex- binder ratio (by weight) of 0.1: water-binder ratio = 0.37; silica fume-binder ratio = 0.2; fly ash-binder ratio = 0; superplasticizer-binder ratio = 0.032; set retarder-binder ratio = 0.005; antifoam-binder ratio = 0.015; silica sand grade 40 filling 25% of the volume; fiber volume fraction = 3%; and fiber length = 1.5 mm (1/16 in). It should be noted that this mix proportion was the basis for the experimental study presented in a later chapter of this report (only the water-binder ratio was changed when the latex-binder ratio was varied); but some results generated towards the end of this phase of the research (which are presented later in this chapter) indicated that the removal of set retarder can substantially enhance the effects of polymer latex in CFRC composites. This finding will be considered in later phases of the research project.

3.3.2 Selection of the Latex Type

In order to select two latex types for use in the remainder of this investigation, a series of mixtures with the same mix proportions and latex contents (10% by weight of cement) were prepared following the mixing techniques and dry-curing procedure described earlier and the strength characteristics of these latex modified carbon fiber reinforced cements were assessed. The common mix proportions were as follows:

water/binder = 0.37
superplasticizer/binder = 0.032
sand (volume fraction) = 25% antifoam/binder = 0.015
set retarder/binder = 0.005
silica fume/binder = 0.2
carbon fiber (volume fraction) = 3%
carbon fiber length = 1.5 mm (1/16 in.)

Based on the strength test results presented in Fig. 3.5, it was decided to use two styrene butadiene latexes (Modifier A of Dow Chemical and the latex of BASF). Fig. 3.5 also indicates that there are a number of latex types which also perform favorably in carbon fiber reinforced cement.



where: 1 = SBR, BASF; 2 = SBR, Dow Chemical; 3 = Acrylic UCAR 413, Union Carbide; 4 = VAE, Rohm and Haas; 5 = NR Unitex High Ammonia, Gunthrie; 6 = NR Dynatex PCP Low Ammonia, Gunthrie;

FIGURE 3.5 Strength Test Results Obtained for Carbon Fiber Cements Modified with Different Latex Types.

3.3.3 Performance of the Mix Without Set Retarder

Considering some similarities between set retarders and polymer latexes, as far as the coating of cement particles is concerned, a special mix without set retarder was included in the experimental study. The mix had the following proportions:

water/binder = 0.37; superplasticizer/binder = 0.032; sand (Grade 100, volume fraction) = 25%; antifoaming/binder = 0.015; silica fume/binder = 0.2; carbon fiber (volume fraction) = 3%; carbon fiber length = 1.5 mm. (1/16 in.); latex (BASF styrene butadiene)/binder = 10%.

The flexural strength characteristics of this mix without set retarder (and small aggregates) are compared with those of the conventional mix with set retarder and larger aggregates (both mixes having the same latex type and content). Fig. 3.6 is indicative of

major improvements in the flexural strength of latex modified carbon fiber cement resulting from the removal of set retarder accompanied with the use of finer aggregates. This important conclusion was, however, reached towards the end of this phase of experimental research. Its implications will be reflected in the future phases of the research. Figure 3.6 Effects of the Removal of Set Retarder Together With the Use of Finer Aggregates on Strength Characteristics of Carbon Fiber Reinforced Cement.

3.4 SUMMARY AND CONCLUSIONS

The results of our experimental study for the optimization of latex modified CFRC mixtures are presented. Decisions were made on the matrix mix constituents and proportions, the latex type, and the manufacturing procedures. The experimental study was performed in two phases. First, the matrix mix proportions were decided by a trial and adjustment procedure based on strength test results, and then, at constant mix proportions, the effects of different latex types on the performance characteristics of CFRC composites were assessed, and two latex polymers were selected for use in future phases of the study.

The following conclusions were derived from the experimental data generated in this part of study:

1 - polymer latexes increase the air content in cement-based materials. An antifoaming agent should be used to control the air content in latex modified CFRC;

2 - the increase in latex content of CFRC composites results in an increase in the water-binder ratio required for maintaining workability at acceptable levels;

3 - fly ash has relatively small effects on the performance of latex- modified CFRC composites;

4 - based on the trends observed in the effects of matrix constituents on the composite material performance, the following proportions were selected for latex modified CFRC composites:

silica fume/binder = 0.2 superplasticizer/binder = 0.032 set retarder/binder = 0.005 antifoam/binder = 0.015 grade 40 silica sand (volume fraction) = 25% carbon fiber (volume fraction) = 3% carbon fiber length = 1.5 mm (1/16 in.) water-binder ratio = 0.37 at

a latex-binder ratio of 0.1, and increasing or decreasing with increasing or decreasing latex-binder ratio;

5 - the mixing procedure selected for the manufacture of latex modified CFRC consisted of: (a) preparation of a dispersant mixture without latex (consisting of silica fume, and a fraction of water and (b) the silica sand, remainder of the water and chemical admixtures, and latex were then added and mixed until a uniform mixture was achieved; (c) the process was concluded with the addition of cement and some further mixing at higher speeds, and all the specimens prepared in this phase of study were dry-cured;

6 - a number of different latex types were observed to perform favorably in CFRC composites; among these two styrene butadiene latexes manufactured by Dow Chemical and BASF were selected for use in the remainder of this study;

7 - the removal of set retarder together with the use of finer aggregates were found to substantially enhance the strength characteristics of latex modified CFRC composites.

CHAPTER 4

MIX OPTIMIZATION AND PHYSICAL CHARACTERIZATION

4.1 GENERAL

In the previous chapter it was mentioned that major improvements in the flexural strength of latex-modified carbon fiber reinforced cement could be achieved by removing the set retarder and using finer aggregates. it was also mentioned that the effects of these adjustments in mix proportions on other properties of the material are to be investigated. This chapter presents test results on the effects of set retarder removal and use of finer aggregates on the composite material performance.

4.2 MATERIALS, ADJUSTED MIX PROPORTIONS, MANUFACTURING PROCEDURES, AND THE TECHNIQUES

4.2.1 Materials

The materials used were cement, silica fume, silica sand, superplasticizer, anti-foaming agent, carbon fiber, latex polymer and regular tap water. A brief description of these materials is presented below.

a-Cement: Regular type I portland cement was used.

b-Silica Fume: Silica fume in CFRC mixture helps with the dispersion of carbon fibers and also contributes to the hardened material performance. It is a fine, highly reactive pozzolanic material.

c-Silica Sand: Grade 100 silica sand, provided by Unimin Corporation, was used in this investigation. The maximum particle size was .0117 in. (.300 mm), and the gradation of this sand is presented in Table 4.1.

Table 4.1 Gradation of Grade 100 Silica Sand

U.S. Sieve	50	70	100	140	200
% Passing	99.4	86	38	10	.8

d- Superplasticizer: Daracem-100 from W.R. Grace a superplasticizer with naphthalene formaldehyde sulfonate as the active ingredient was used to improve the workability of the mixture, which tends to be adversely influenced by the presence of fibers and relatively high silica fume contents.

e-Antifoaming Agent: Anti-Foam B Emulsion Class 2 from Dow Corning was used and is identified as Polydimethyl Siloxane. This material is a surface active agent which reduces the surface tension of the mix so that bubbles generated in the mixing process burst; thus, the fraction of air voids in cement will be reduced. This polymer is very nonreactive and nonpolar.

f-carbon fibers: Carboflex carbon fibers were supplied by the Carbon Fiber Division of Ashland Petroleum Company. The pitch-based fibers used have a reported average length of 0.063 in. (1.6 mm) and a diameter of 10 - 12 microns. These fibers have a tensile strength of 81 ksi (560 MPA) when tested with a gage length of 0.7 in. (18 mm), a Young's modulus of 6 - 8 million psi (41 - 55 PGA), and specific gravity of 1.57.

g-Latexes: Two latex types were used in this part of the research. Table 4.2 introduces the basic properties of these two latices.

Table 4.2 Properties of Latex Polymers

Label	Product Name	Polymer Type	%Solids by wgt.	PH	Viscosity cps	Unit Weight (lb/gal)	Particle Size (Å)
Type A	BASF	Styrene Butadiene	47	9.5	26	8.4	——
Type B	Dow Chemical Modifier A	Styrene Butadiene	47.5	10.6	37	8.7	1950

4.2.2 Adjusted Mix Proportions

The mix proportions used in the earlier phases of this project for latex-modified carbon fiber reinforced cement were adjusted through the removal of the set retarder and the use of finer aggregates. The adjusted mix proportions are shown in Table 4.2.

Table 4.3: Adjusted Mix Proportions:

MIXED PROPORTIONS

	0% Latex	10% Latex
Water/Binder	.306	.37
Silica Fume/Binder	.2	.2
Latex/Binder	0	.1
Superplast./Binder	.032	.032
Anti Foam (% Binder)	.2	1.5
Fiber Content (% of volume)	3	3

FOR TYPE A AND B LATEXES

4.2.3 Manufacturing Procedure

Latex-modified carbon fiber-cement mixtures were manufactured in a 12- liter mortar mixer.

The mixing procedure selected for the manufacture of latex modified CFRC composites was as follows:

1. Charge the mixer with all the silica fume and 3/4 of the liquid (water + chemical admixtures), and mix at low speed for about 2 minutes until a uniform mixture is achieved;

2. Add the fibers gradually as the mixer is running over a period of about 2 minutes;

3. Add the silica sand followed by the remainder of water;

4. Add the latex slowly to maintain the homogeneity of the mixture, and then mix for another 1 minute;

5. Add the cement, then mix for 2 minutes;

6. Stop the mixer for about 30 seconds;

7. Change the mixing speed to medium, and mix for about 2.5 minutes.

The specimens were cast in molds, and were vibrated externally on a vibrating table. They were kept inside the molds under a plastic sheet for 24 hours and were then demolded and exposed to a regular laboratory environment until the test age of 14 days. This was the standard curing condition referred to as dry curing. Other curing conditions were also used and are described in the next section of this chapter.

4.2.4 Test Techniques

The latex-modified carbon fiber reinforced cement composites prepared in this phase of the study were characterized in the fresh state through the performance of the flow table test (ASTM C-87). The void content of the fresh mix was also obtained by the volumetric method (ASTM C-173).

A computer-based data acquisition system (Figure 4.1) was used to monitor both the forces and deformations throughout the flexural and compression tests. The flexural and compression tests were performed after 14 days of curing. Three flexural specimens 1.5 x 1.5 x 6 in. (38.1 x 38.1 x 152.4 mm) were tested for each mix by four-point loading on a span of 4.5 in. (114.3 mm). The compression specimens were 3 in. (76.2 mm) in di-

ameter and 6 in. (152.4 mm) high. Three compression specimens were tested for each mix.

The other experiments conducted on latex-modified CFRC were:

1. Time of setting (ASTM C-403) (the apparatus is shown in Figure 4.2)

2. Impact resistance on 6 in. (152.4 mm) diameter by 2.5 in. (63.5 mm) high cylindrical specimens.

3. Specific gravity (ASTM C-567)

4. Water absorption (ASTM C-567); and

5. Drying shrinkage (ASTM C-926), using a comparator (Fig. 4.3) for length measurements.

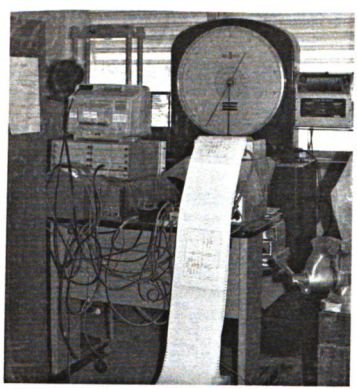


FIGURE 4.1 Computer-Based Data Acquisition System .

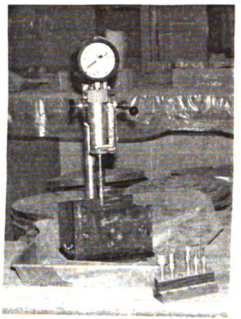


FIGURE 4.2 Apparatus For Time of Setting Measurement.

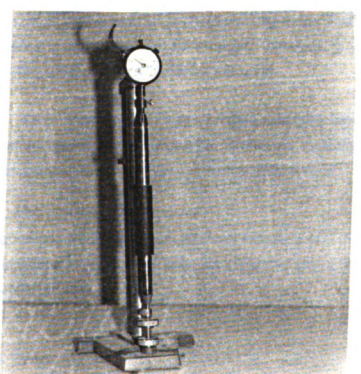


FIGURE 4.3 Comparator used for length measurement in the drying shrinkage experiment.

4.3 EXPERIMENTAL RESULTS

The generated test date on performance characteristics of latex- modified carbon fiber reinforced cement are presented in this section in two parts. First the effects of removing the set retarder on some key material properties are discussed, and then different aspects of the material performance with modified mix proportions (no set retarder) are reviewed.

4.3.1 Effects of Set Retarder

The set retarder used in the experimental work presented in the previous chapter is a combination of glucose, lignin sulfonate, and tri-ethanol amine. These materials combine to coat cement particles and provide a physical barrier to water. The hydration reaction is therefore limited by the diffusion rate of water through the coating. This coating also gives the particles a slight negative charge yielding some superplasticizing effects. The set retarder is displaced from the surface of the cement particles after twenty-four hours. At ages greater that two days, the strength of the retarded mix is greater than the same mix without set retarder, because a better hydrated cement paste structure results from a slower rate of hydration. In the presence of latex, however, the set retarder could interact with latex preventing the hydration of cement. The set retarder might be held at the cement particle surface by the latex, thus preventing the material strength from developing to the level it does in cement without set retarder. Therefore, in the presence of latex, the set retarder may have undesirable effects (Ref. 12).

4.3.2 Performance Characteristics of the Adjusted Material

The effects of the type and content of latex on different aspects of CFRC material properties, using the adjusted mix proportions, are discussed below:

4.3.2.1 Time of Setting

The time of setting for latex A was obtained following ASTM C-403 test procedures. Figure 4.4 indicates an increase in both the initial and final times of setting resulting from the introduction of latex.

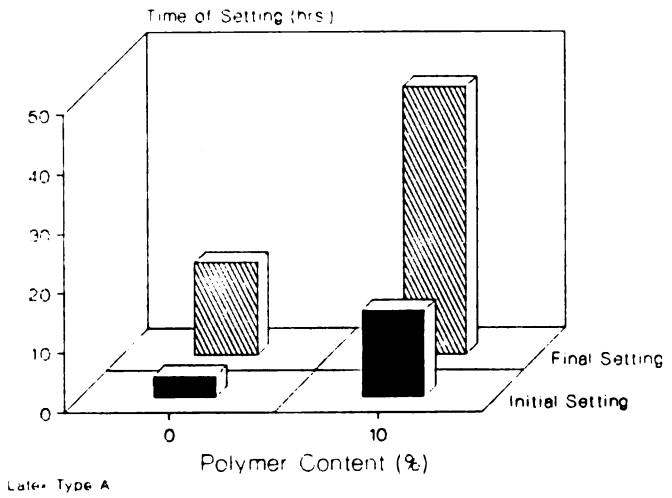


FIGURE 4.4 **Effect of Polymer Content On Time of Setting.**

4.3.2.2 Compressive and Flexural Behavior

The effects of latex modification on the flexural load-deflection and compressive stress-strain relationships of air-dried carbon fiber reinforced cement are shown in Figures 4.5 and 4.6, respectively. Latex modification is generally observed to increase the ductility and energy absorption capacity of carbon fiber reinforced cement, but to reduce the strength and stiffness of the material.

Figure 4.7 presents the effects of polymer content on flexural strength. Latex modification seems to have relatively small effects on the flexural strength of carbon fiber reinforced cement.

Figure 4.8 shows a decrease in the compressive strength of carbon fiber reinforced cement with increasing polymer content.

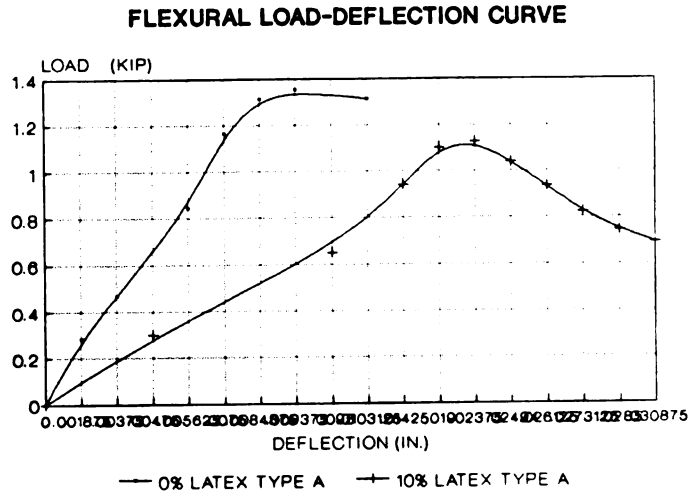


FIGURE 4.5 Effects of Latex Modification On the Flexural Load-Deflection Curve.

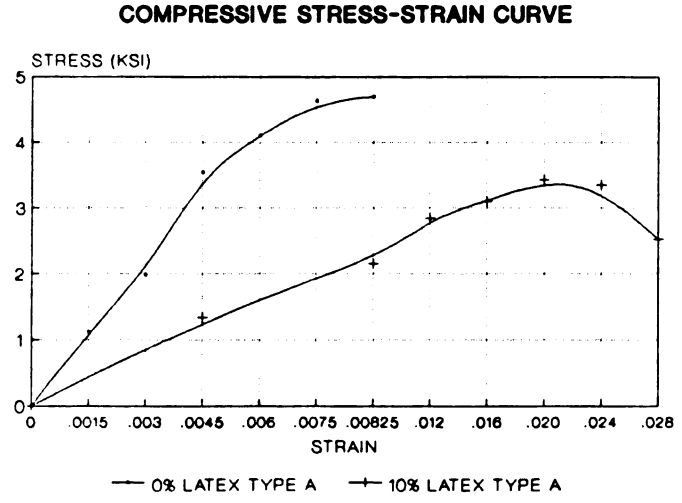


FIGURE 4.6 Effects of Latex Modification On Stress- strain Relationship in Compression.

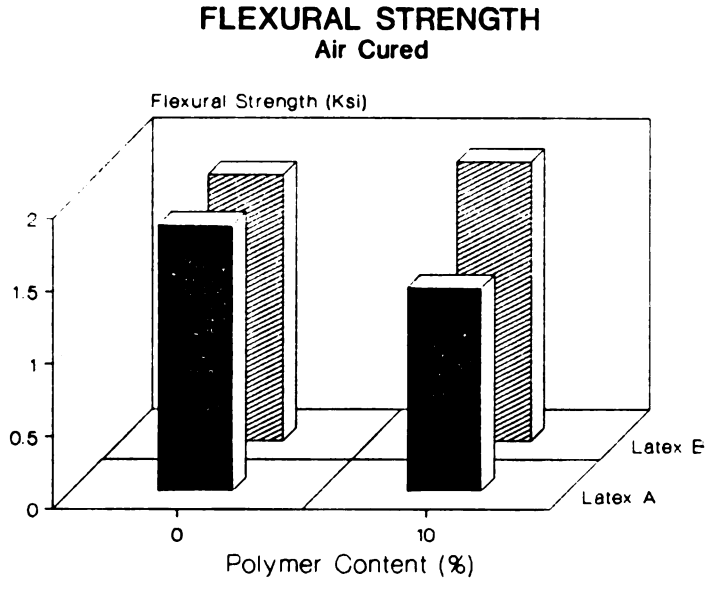


FIGURE 4.7 **Effects Of Polymer Latex Content On Flexural Strength.**

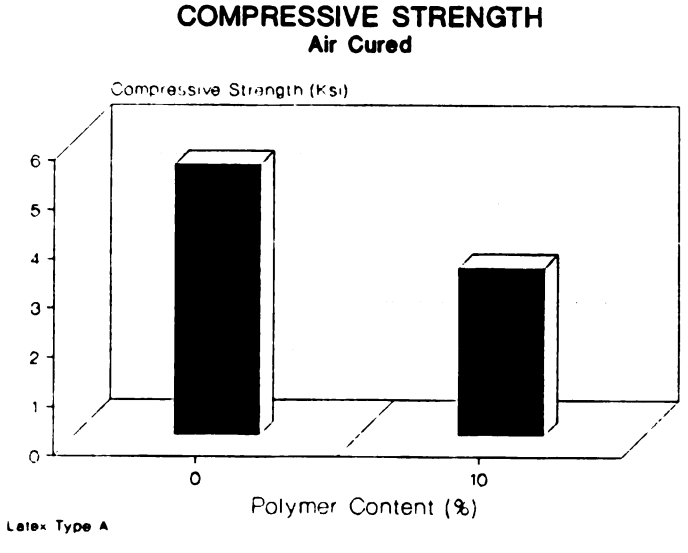


FIGURE 4.8 **Effects of Polymer Latex Content On Compressive Strength.**

The flexural toughness, defined as the area underneath the flexural load-deflection curve up to a deflection equal to 1/50 times the span length, is observed in Figure 4.9 to increase as a result of polymer modification. Figure 4.10 shows that compressive toughness, defined as the area underneath the compressive stress-strain curve up to a strain of 0.25%, also tends to increase with increasing polymer content.

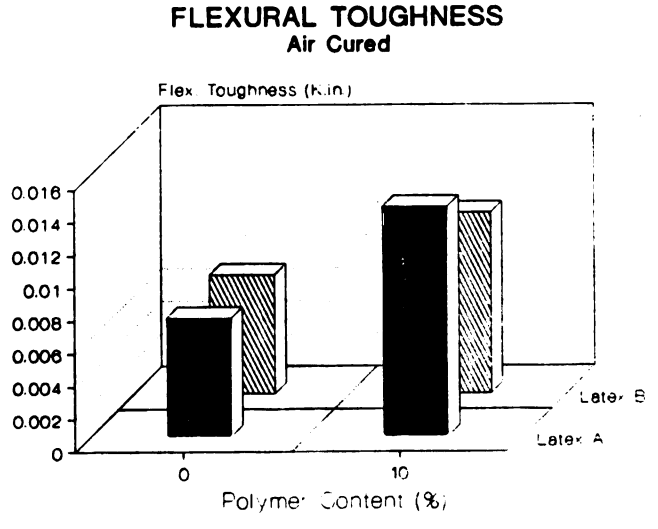


FIGURE 4.9 Effects Of Polymer Content On Flexural Toughness.

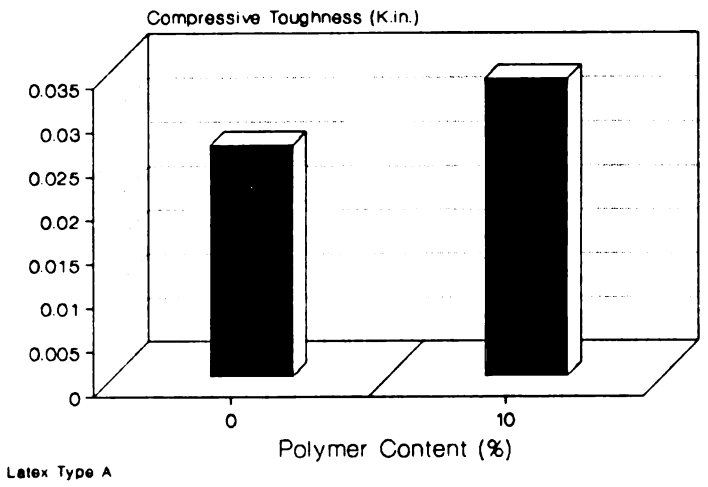
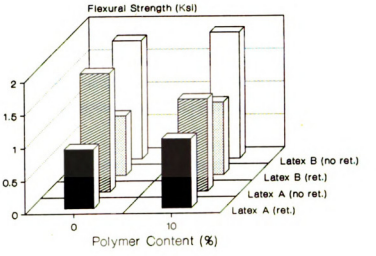


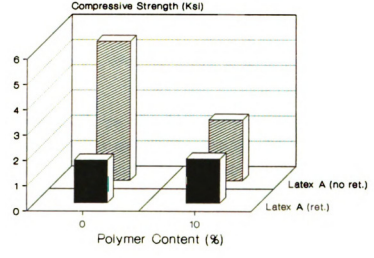
FIGURE 4.10 Effects Of Polymer Content on Compressive Toughness.

The improvements in material properties of latex-modified carbon fiber reinforced cement resulting from the removal of set retarder (accompanied by the use of fine aggregates) are shown in Figure 4.11. The flexural strength of carbon fiber reinforced cement of different latex contents can be increased by about 50% with the removal of set retarder (Figure 4.11a). Figure 4.11b shows major improvements in compressive strength resulting from the removal of set retarder. The time of setting, which tends to increase in the presence of both latex and set retarder, can be reduced through the removal of set retarder (Figure 4.11C).

(a) Flexural Strength



(b) Compressive Strength



(c) Setting Time

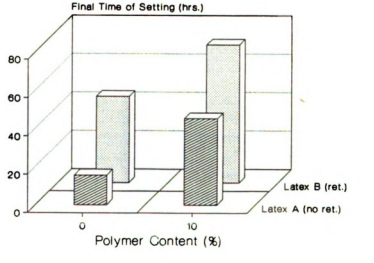


FIGURE 4.11 Improvements in Material Properties Resulting From The Removal of Set Retarder.

4.3.2.3 Effects of Curing Conditions

The conclusions presented so far were derived based on the results of tests on air-dried specimens. In order to investigate the effects of curing conditions on mechanical properties of latex-modified carbon fiber reinforced cement, three different curing conditions were applied to the material (all specimens were covered by wet burlap and plastic for 24 hours after casting):

1. Air Curing: The specimens were air cured continuously until tested at 14 days of age.

2. Wet Curing: The specimens were air-cured for four days then placed in water saturated with lime until tested 14 days of age.

3. Moist Curing: The specimens were air-cured for four days and the moist-cured (at 100% relative humidity) until tested at 14 days of age.

The following results summarize the effects of curing conditions on the material behavior.

Figure 4.12 shows that wet curing, as described above, increases the flexural strength of unmodified carbon fiber reinforced cement over the air- cured values, but produces flexural strength test results for latex modified composites which are comparable with those obtained with air curing. Moist curing does not seem to produce desirable flexural strength for unmodified and especially latex-modified carbon fiber reinforced cement

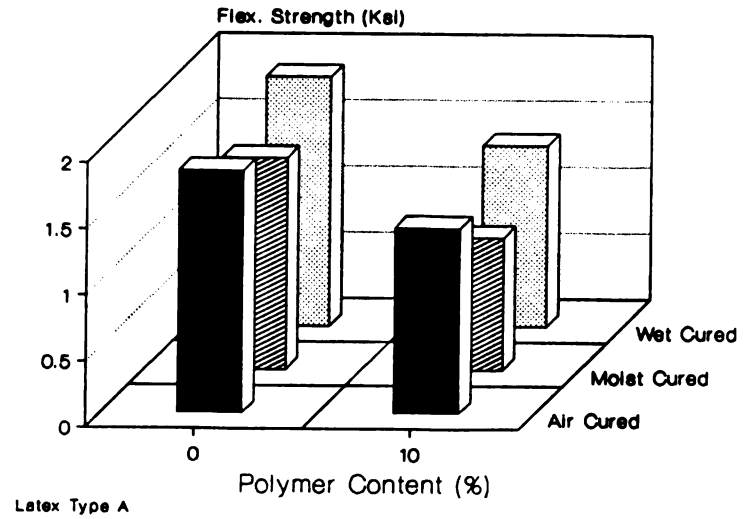


FIGURE 4.12 Effects Of Curing Conditions On Flexural Strength.

As far as the effects of curing conditions on flexural toughness are concerned, one may conclude from Figure 4.13 that wet cured latex-modified carbon fiber reinforced cement produces the best toughness values. For the unmodified material, however, wet curing has adverse effects on flexural toughness.

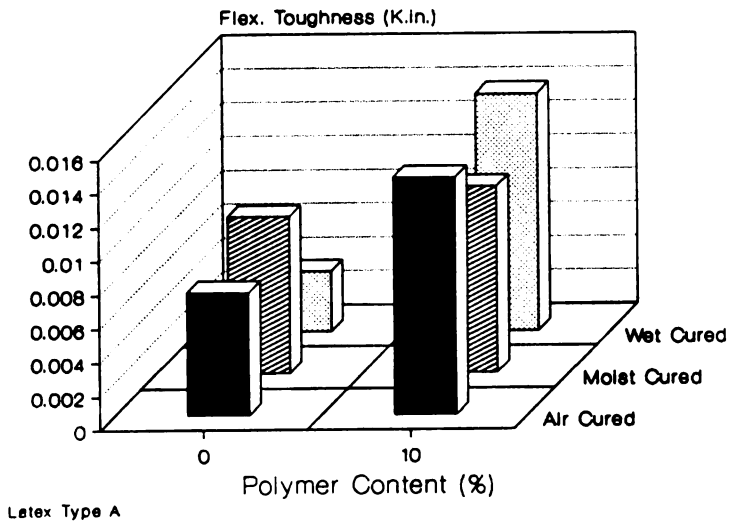


FIGURE 4.13 Effects Of Curing Conditions On Flexural Toughness.

One may conclude from Figures 4.12 and 4.13 that wet curing increases the flexural toughness and decreases the flexural strength of latex-modified carbon fiber reinforced cement, while the reverse is true for the unmodified material. This observation could be justified by the fact that immersion in water can reduce the effectiveness of latex, (e.g., in improving the fiber- matrix interfacial bond). Hence, the latex modified fibrous material tends to have less flexural strength after immersion in water (due to the reduced bonding) but increased toughness resulting from the energy absorbed by the material during fiber pull out (rather than fiber rupture) in condition with reduced bond strength.

4.3.2.4 Impact Resistance

Air cured unmodified and latex-modified carbon fiber reinforced cements are observed in figure 4.14 to produce comparable first-crack and ultimate impact strengths.

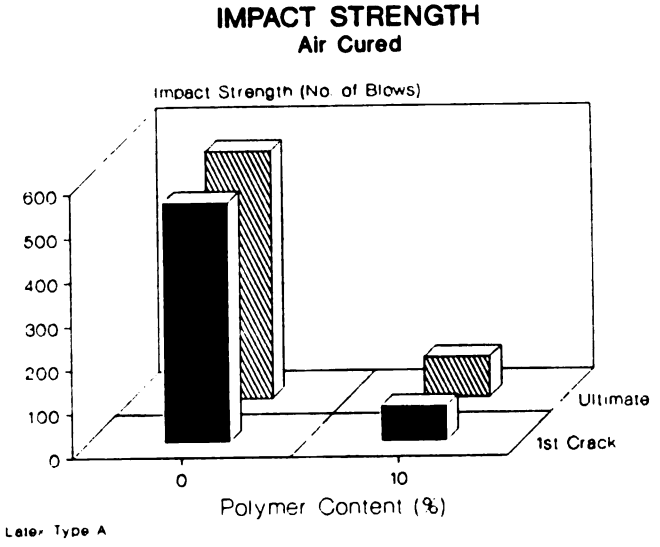
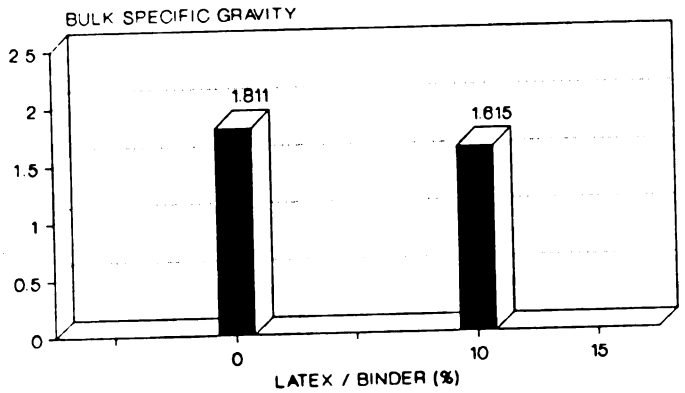


FIGURE 4.14 Impact Resistance Test Result.

4.3.2.5 Specific Gravity

The specific gravity measurements were performed on oven-dried specimens following ASTM C-567. Both latex A and B are observed in Figure 4.15 a and b to slightly reduce the specific gravity of CFRC composites.

(a) Latex Type A



(b) Latex Type B

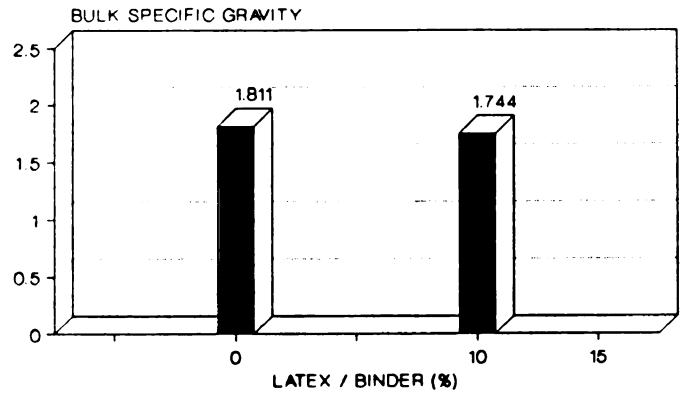
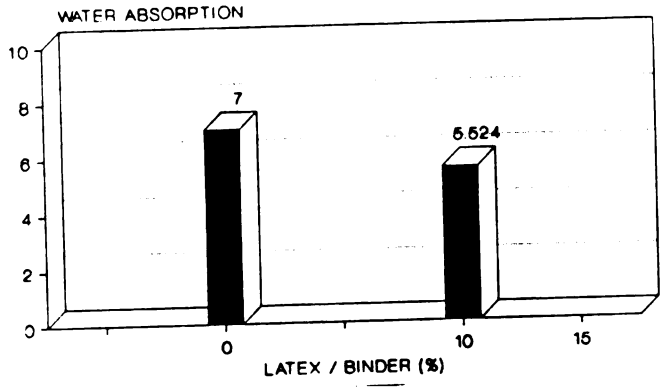


FIGURE 4.15 Effects of Latex Modification On Bulk Dry Specific Gravity of CFRC Composites.

4.3.2.6 Water Absorption

The water absorption test results (ASTM C-567) performed on latex- modified CFRC composites (Figure 4.16) indicate that latex types A and B at a latex-binder ratio of 10% are effective in reducing water absorption by about 10% and 17%, respectively.

(a) Latex Type A



(b) Latex Type B

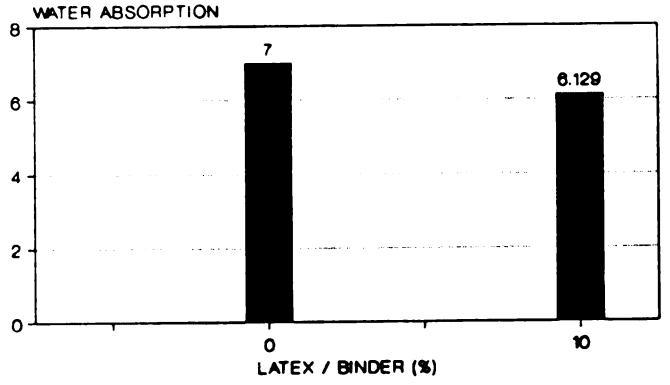
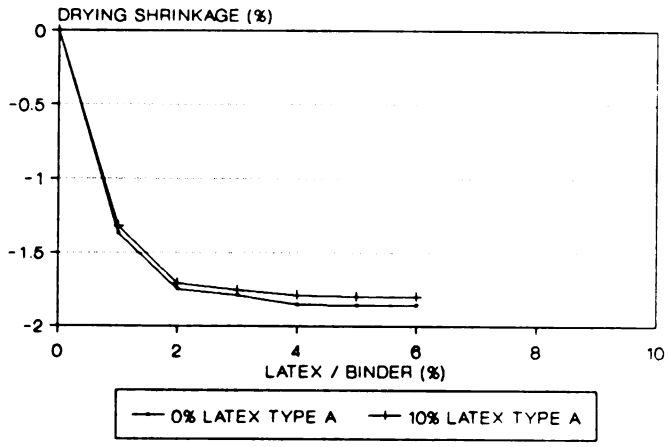


FIGURE 4.16 Effects of Latex Modification On The Water Absorption Capacity of CFRC Composites.

4.3.2.7 Drying Shrinkage

Figure 4.17 shows the reduction in drying shrinkage of carbon fiber reinforced cement due to the incorporation of 10% polymer latex. This aspect of latex effect on carbon fiber reinforced cement, together with the increase in ductility and strain capacity of the material in the presence of latex, have important practical implications in the control of shrinkage cracking in cement-based materials.

(a) Latex Type A



(b) Latex Type B

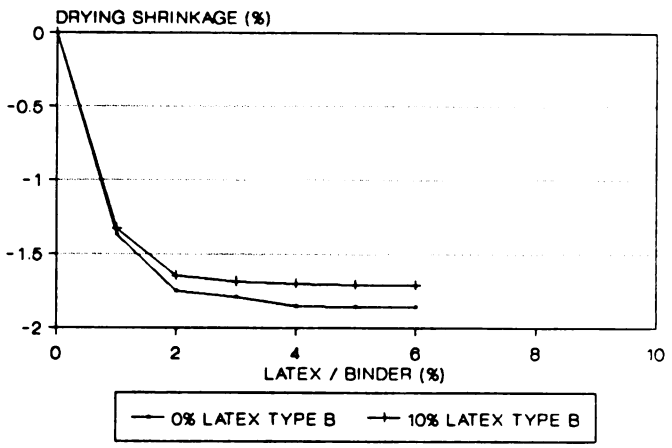


FIGURE 4.17 Effects of Polymer Content On The Drying Shrinkage Of CFRC.

4.4 SUMMARY AND CONCLUSIONS

An adjustment of the latex-modified carbon fiber reinforced cement mix composition was investigated. Set retarder was removed from the mix, and the maximum particle size of silica sand was reduced.

A comprehensive experimental characterization of the adjusted latex- modified carbon-reinforced cement was conducted in order to investigate the effects of adjustments in mix proportions, and to assess different aspects of the performance characteristics of adjusted latex-modified carbon fiber reinforced cement composites. The two latexes used in this phase of research were both Styrene Butadiene: Type A (produced by BASF) and Type B (produced by Dow Chemicals).

The latex contents used in this experimental program were 0% and 10%. The curing procedures were: air curing, wet curing (in water after a short period of air curing), and moist curing (in moist environment after a short period of air curing). The following tests were performed:

fresh mix air content; fresh mix flow; time of setting; compressive strength and stress-strain performance; flexural strength and load-deflection performance; specific gravity; water absorption; drying shrinkage.

From the test results it could be concluded that:

1) The initial and final times of setting of carbon fiber reinforced cement tend to increase due to the incorporation of polymer latex.

2) An increase in the flexural and compressive ductility and toughness of the material was observed in the presence of polymer latex.

3) The flexural and compressive stiffness and strength of carbon fiber reinforced cement tends to be reduced as a result of latex modification.

4) Latex-modified and unmodified carbon fiber reinforced cements have comparable impact strengths.

5) Important reductions in drying shrinkage of carbon fiber reinforced cement can be obtained through latex modification. The improved ductility and strain resistance, together with the reduced free shrinkage, have important implications in reducing the generally troublesome shrinkage cracking of cement-based materials.

6) Latex modification leads to reduced water absorption in carbon fiber reinforced cement.

7) The adjustments made in the mix proportions of CFRC, involving the removal of set retarder and use of finer aggregates, had positive effects on the physical performance of the material.

CHAPTER 5

FREEZE-THAW DURABILITY OF CARBON FIBER REINFORCED CEMENT

5.1 GENERAL

It is generally accepted now that in designing structures the durability characteristics of the material under consideration should be evaluated as carefully as other aspects such as mechanical properties and initial cost. It is estimated that in industrially developed countries over 40% of the total resources of the building industry are applied to repair and maintenance of existing structures and less than 60% to new installations . The escalation in replacement costs of structures and the growing emphasis on life cycle cost rather than first cost are forcing engineers to become durability conscious. There is also a realization that a close relation exists between durability and ecology. Conservation of natural resources by making materials last longer is certainly a positive ecological step.

The durability of cement-based materials can be defined as their ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration. Among the weathering actions with major disintegrating effects, repeated freezing and thawing has particularly disruptive effects on cementitious materials.

Ordinary concrete has many air-filled cavities that cannot be readily filled with water even upon immersion in water. The pressures developed during freezing resulting from the increase in the volume of water) are probably more than sufficient to force water into the various cavities, so that after repeated wetting and freezing a large part of these cavities become filled. A few additional cycles of freezing and thawing, after a critical degree of saturation, can cause a rapid disintegration of concrete.

The freeze-thaw damage in cementitious materials can take several forms. The most common is cracking and spalling of the material that is caused by progressive expansion of cement past matrix under repeated freeze- thaw cycles (Figure 5.1a). Concrete slabs exposed to freezing and thawing in the presence of moisture and dicing

chemicals are susceptible to scaling (Figure 5.1b), i.e., the finished surface flakes or peels off.



(a) Deterioration Along The (b) scaling of a Concrete Surface Saturation Line

FIGURE 5.1 Types of Frost Action Damage In Concrete (Ref. 5).

The freeze-thaw damage in concrete can be controlled through the adjustment of the pore system and strength characteristics of the material and controlling its degree of saturation. Small, well-distributed air bubbles provide escape boundaries for the expanding water in freezing condition and reduce the internal pressure associated with ice formation. Increased tensile strength can also postpone the internal pressure which should be exceeded to cause rupture and deterioration. Impermeable cementitious materials which maintain a low degree of saturation are also expected to suffer less severe frost damage.

Deleterious effects of frost action on cement and concrete depend not only on the characteristics of the material but also on specific environmental conditions. The temperature range, the rate of variation in temperature, the humidity conditions and the frequency of exposure to freeze-thaw cycles are among the critical environmental factors; hence,

a cementitious material that is frost resistant under a given freeze-thaw conditions, can be destroyed under a different condition. It is rather difficult to reproduce the actual weathering action in accelerated laboratory tests. The laboratory durability test results, thus, only provide means of approximate comparative studies on the weathering resistance of different materials.

Carbon fibers which consist of more than 90% elemental carbon are the most chemically inert of various fibers for the reinforcement of cementitious materials, and are not corroded in cement. The network of carbon fibers in cement may help in frost resistance through the restraint of frost expansion and by increasing the tensile strength and strain capacity of cement paste.

As far as the latex modification effects are concerned, the reduction in permeability and adjustments in the pore system characteristics of cement paste are expected to positively influence the freeze-thaw durability of cementitious materials. Latex effects on increasing the tensile strain capacity and improving the fiber-matrix interfacial bond characteristics are other factors which potentially enhance the frost resistance of carbon fiber reinforced cement.

This chapter presents a comprehensive background on the freeze-thaw durability of cement and concrete materials and reviews the test data generated in this study regarding the effects of latex modification on the freeze-thaw durability of carbon fiber reinforced cement. The pore system of unmodified and latex-modified carbon fiber reinforced cements are also compared in relation to the frost resistance of the material. The background information presented on freeze-thaw durability covers: the mechanism of freeze-thaw deterioration, experimental methods, and effects of different factors (air content, latex modification, fiber, ...) on the freeze-thaw resistance of cementitious materials.

5.2 MECHANISM OF FREEZE THAW DETERIORATION

The mechanism of frost action in cement paste can be described as follows (Ref. 14): when water begins to freeze in a capillary cavity, the increase in volume accompanying the freeze of water requires a dilation of the cavity equal to 9% of the volume of frozen water, or forcing of the excess water out through the boundaries of the specimen, or a combination of both effects. During this process, hydraulic pressure is generated, and the magnitude of the pressure depends on the distance to an "escape boundary", the permeability of the surrounding material, and the rate at which ice is formed. Experience shows

that disruptive pressures will be developed in a saturated specimen of paste unless every capillary cavity in the past is not farther than three or four thousandths of an inch from the nearest escape boundary. Such closely spaced boundaries are provided by the correct fuse of a suitable air entraining agent. A diagrammatic illustration of this hypothesis is shown in Figure 5.2.

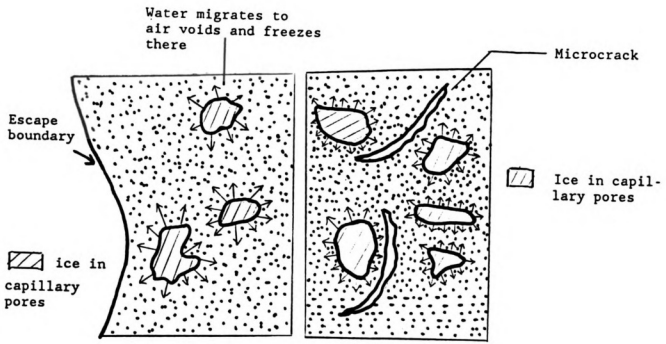


FIGURE 5.2 Capillary Cavities and Escape Boundaries (Ref. 14).

In addition to the hydraulic pressure caused by the freezing of water in large cavities, the osmotic pressure resulting from partial freezing of the solution in capillaries can be another source of destructive expansions of cement paste. Water in the capillaries contains several soluble substances, such as: alkalies, chlorides and calcium hydroxide.

Solutions freeze at lower temperature than pure water; generally, the higher the concentration of a salt in a solution, the lower the freezing point. The existence of local salt concentration gradients between capillaries may be considered as a source of osmotic pressure.

The hydraulic pressure due to an increase in the specific volume of water freezing in large cavities and the osmotic pressure due to salt concentration differences in the pore fluid do not appear to be the only causes of expansion of cement pastes exposed to frost action. Expansion of cement paste specimens has been observed even when benzene, which contracts on freezing, was used as a pore fluid instead of water. A capillary effect, involving large-scale migration of water from small pores to large cavities, is another important cause of expansion in porous bodies. According to this theory, the rigidly held water by the C-S-H (both inter-layer and absorbed in gel pores) in cement past cannot rearrange itself to form ice at the normal freezing point of water because the mobility of water existing in an ordered state is rather limited. Therefore, when a saturated cement past is subject to freezing conditions, while the water in large cavities turns into ice, the gel pore water continues to exist as liquid water. This creates a thermodynamic non-equilibrium between the frozen water in capillaries (in a low- energy state) and the liquid water in gel pores (in a high-energy state). This condition forces the liquid water to migrate to the lower- energy sites (large cavities) where it can freeze. This fresh supply of water from the gel pores to the capillary pores steadily increases the volume of ice in the capillary pores until there is no room to accommodate more ice. Any subsequent tendency for the liquid water to flow toward the large cavities would cause internal pressure and expansion of the system.

A similar phenomenon occurs when ice lenses form in large concrete voids (which could be microcracks or voids occurring under reinforcement of large aggregate particles due to segregation or poor compaction) and an external supply of water that can readily migrate to these voids is available. Mechanical damage occurs when the rate of moisture transport is considerably less than demanded by the conditions (temperatures gradient, permeability, degree of saturation...).

It may be noted that during frost action on cement paste, the tendency for certain regions to expand is balanced by other regions that undergo contraction (e.g., due to the loss of adsorbed water from C-S-H). The net effect on a specimen (overall expansion or contraction) is the result of these two opposite tendencies.

Using the mechanisms described above it can be shown that the resistance to freezing and thawing depends on the permeability, the degree of saturation of the paste, the amount of freezeable water, the rate of freezing, and the average maximum distance from any point in the paste to a free surface where ice can form safely. Partially dry concrete will not suffer freeze-thaw damage because the larger cavities are now empty and provide the necessary free space throughout the paste. The critical degree of saturation has been found to be close to 0.80 of the total freezeable water and about 0.85 if expressed as a fraction of the total evaporable water (which includes gell pore water, which does not freeze). Air entrainment is thus required for protection only for concrete that is frozen in near-saturated condition. The entrained air bubbles do not readily fill with water except when the concrete is immersed for long periods of time. Concrete should develop a certain strength in order to withstand frost damage. Fresh concrete can be damaged by freezing even when air entrained.

5.3 EXPERIMENTAL METHODS

The numerous disruptive mechanisms in nature are diverse and complex. If one has the time, the most dependable durability test involves exposure to the actual environment. Since the time factor makes this impractical, either accelerated laboratory tests or severe natural tests can be used to obtain behavior information which then has to be interpreted. Laboratory test can reveal valuable information on probable durability.

A number of different tests have been developed to assess the long term frost resistance of concrete. These involve subjecting concrete to different freeze-thaw cycles and measuring the progressive internal damage by monitoring weight loss, length change (dilation), and decrease in strength or dynamic modulus of elasticity. Tables 5.1 gives a brief summary of several test methods currently in use. These tests differ in the nature of freeze- thaw cycle used and the condition of the specimen just prior to and during the test.

The potential for frost damage in actual field conditions depends on the rate of freezing, water-cement ratio, time of moist curing, and degree of saturation; these may vary widely in service conditions. Thus, predictions from freeze-thaw tests are not always a good indication of actual service performance, and results should be treated with caution.

Standard laboratory freeze-thaw tests for concrete provide valuable tools in comparing concrete materials. Direct comparisons can be made between sources of aggre-

gate, sources of cementitious materials and various admixtures. A given material can also be tested and compared with "Standard Control Mixes" for which field service has been established. For these purposes, the correlation between standard laboratory freezing and thawing exposures and actual field exposure is academic. When specific materials are being considered for a particular structure, however, it may be desirable that freezing and thawing tests simulate the actual field exposure.

The standard method of test described in ASTM C-666 prescribes a cooling and heating cycle between 40 and 0°F/h (4.4 and 17.8°C) at a rate of cooling in the range of 22 to 26°F/h (12.2 to 1.4.°C/h). Freezing can be done while the specimen is in air (procedure A) or immersed in water (procedure B), but thawing is done in water in both cases. The test is continued (either continuously or intermittently) until 300 cycles or until the dynamic modulus has reached 60% of its initial value, whichever occurs first. A durability factor (D.F.) Can then be calculated: D.F. = P*N/300; where P is the percentage of the initial dynamic modulus after N cycles. There are no definite values of the durability factor for acceptance or rejection of the concrete subjected to this test. A value of less than 40 suggests that the concrete may be unsatisfactory, whereas above 60 it is likely to perform well, but there is no guarantee that this prediction will hold true.

Table 5.1 - Freezing and Thawing Test Methods

TEST METHOD	TYPE OF SPECIMEN	MEASURE OF DETERIORATION	TYPE OF EXPOSURE
ASTM C-666 procedure B	Width 3 to 5 in. Depth 3 to 5 in. Dia. 3 to 5 in. Lgth. 11 to 16 in (Prism or Cyldr.)	Loss in dynamic modulus of elasticity	Rapid freezing and thawing in water
ASTM C-666 procedure A	Same as above	Loss in dynamic modulus of elasticity	Rapid freezing in air and thawing in water
Corps of Engineers C-10-54	3.5 x 4.5 x 16 in prism	Loss in dynamic modulus of elasticity	Rapid freezing and thawing in air and water
USBR Method	3 x 6 in. cylinder	Expansion and weight loss	Rapid freezing and thawing in water
Powers Method	4.5 x 3 in. cylinder	Expansion	Controlled freezing

A major objection to ASTM C-666 is the unrealistically high rate of freezing; since in the field, rates exceeding 5°F/h (3°C/h) are rarely encountered. ASTM C-671 overcomes this objection by specifying one freeze- thaw cycle every 2 weeks, employing this rate of freezing with a rapid thawing regime. Damage is monitored by measuring linear expansion during the tests, which is continued until critical dilation (i.e., until dilation begins to increase sharply) or the desired number of cycles is completed. This test allows

the user to specify the curing history of the specimen and the exposure conditions to nearly match the expected service conditions.

5.4 FACTORS INFLUENCING CONCRETE FREEZE-THAW DURABILITY

The ability of concrete to resist damage due to frost action depends on the characteristics of both the cement paste and aggregates. In each case, however, the outcome is controlled actually by the interaction several factors, such as the location of escape boundaries (the distance by which water has to travel for pressure relief), the pore structure of the system (size, number, and continuity of pores), the degree of saturation (amount of freezeable water present), the permeability of the material, the rate of cooling, and the tensile strength of the material that must be exceeded to cause rupture.

This section describes the effects of pore system characteristics, latex, fibers, and some other factors on the resistance of concrete materials to the actions of freeze-thaw cycles.

5.4.1 Effects of Pore System Characteristics

In general, during the process of freezing hydraulic pressure will exist throughout the paste. This pressure will be higher for points further away from an escape boundary. If a point in the paste is sufficiently remote from an escape boundary, the pressure will be high enough to stress the surrounding gel beyond its elastic limit, or beyond its tensile strength, thus in proportion to the square of the distance from the void. By reducing the distance between voids to the point where the protected zones overlap, generation of disruptive hydraulic pressures during the freezing of water in the capillaries can be prevented. It is thus not the total area, but void spacing of the order of 0.00394 to 0.00787 in (0.1 to 0.2 mm) within every point in the hardened cement, which is necessary for protection of concrete against frost damage. By adding small amounts of certain air entraining agents to cement paste it is possible to incorporate 0.002 to 0.04 in. (0.05 to 1 mm) bubbles. Thus, for a given volume of air depending on the size of air bubbles, the number of voids, void spacings, the degree of protection against frost action can vary a great deal. For example, silica fume (a by product of the Ferro-silicon industry) can alter the microstructure of the hydration products in the cement paste and also at the sand-cement interfaces in cement mortar, producing a large increase in the volume of protective pores and thus greatly improving the freeze-thaw resistance of cement paste and especially cement mortars (Ref. 22).

It has been suggested that protective pores existing at the sand- cement interface provide protection against freeze-thaw action in the same manner as does air entrainment, and that a uniform distribution of various amounts of sand can control the spacing of these pores (Ref. 22).

Although the volume of entrained air is not a sufficient measure for protection of concrete against frost action, assuming that mostly small air bubbles are present, it is the easiest criterion for the purpose of quality control of concrete mixtures. Since the cement paste content is generally related to the maximum aggregate size, lean concretes with large aggregates have less cement paste than rich concretes with small aggregates; therefore, the latter will need more air entrainment for an equivalent degree of frost resistance.

The aggregate gradation also effects the volume of entrained air, which is decreased by an excess of very fine sand particles. Addition of mineral admixtures such as fly ash, or the use of very finely ground cements has a similar effect. In general, a more cohesive concrete mixture is able to hold more air than either a very wet or a very stiff concrete. Also, insufficient mixing or over-mixing, excessive time of handling and transportation of fresh concrete, and over-vibration tend to reduce the air content.

Portland cement pastes of lower water cement ratios tend to be more resistant to the build up of hydraulic pressure and the growth of capillary ice because there are fewer capillaries in the paste. It has been shown, on the other hand, that even where there are fewer capillaries in the portland cement paste, these capillaries must be protected by air voids should they become filled with water (Ref. 14). If this protection is not provided, the development of hydraulic pressure from the existing capillaries, although not as extensive as in pastes of higher water cement-ratios, would be sufficient to cause deterioration. Any paste should thus be protected to some extent by the proper amount of air entrainment. Approximately, the same durability has been found with pastes of different water-cement ratios and different cement contents with proper air entrainment (see Figure 5.3)

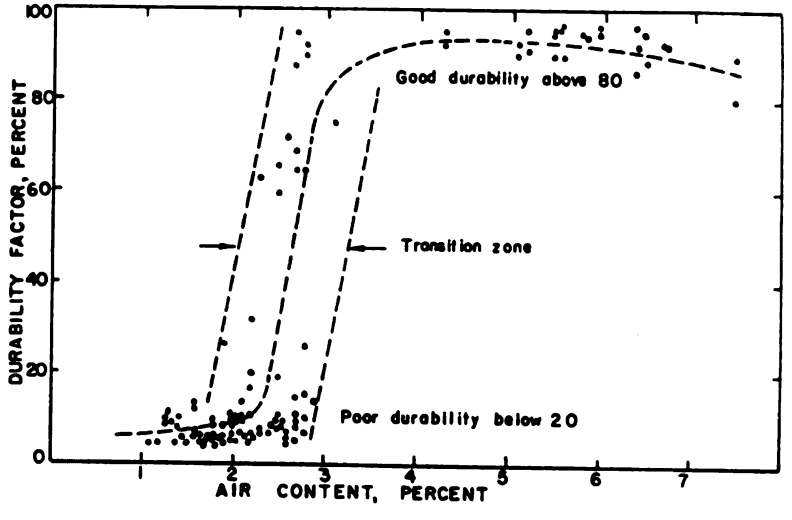


FIGURE 5.3 Freeze-Thaw Durability of Concretes Containing Various Aggregates, Cement Contents and Air Contents.

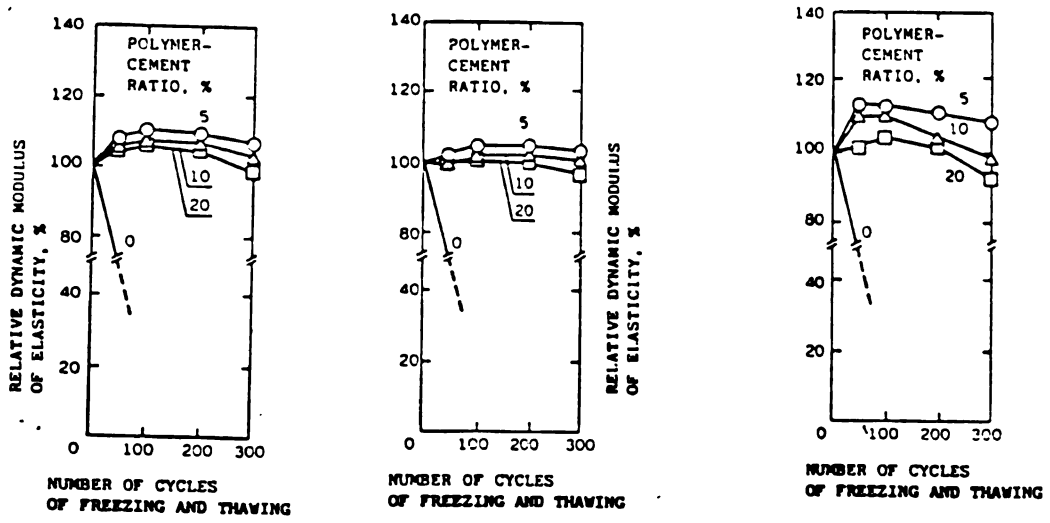
It is worth mentioning that, although there is generally a direct relationship between strength and durability, this does not hold in the case of frost damage. For example, when comparing non-air entrained with air entrained concrete, the former may be of higher strength, but the latter will have a better durability to frost action because of the protection against development of high hydraulic pressures.

5.4.2 Effects of Latex Modification

Latex modification alters the pore system of concrete in a manner which leads to reduced permeability of the material (Ref. 16). Latex also provides concrete with increased tensile strength and strain capacity.

Ohama (Ref. 16) has reported freeze-thaw durability test results for latex modified mortars incorporating different latex types at different fractions. The SBR, PAE, and EVA

latexes are observed in Figure 5.4 to substantially improve the freeze-thaw durability of mortar.



(a) SBR Modified (b) PAE Modified (c) EVA Modified

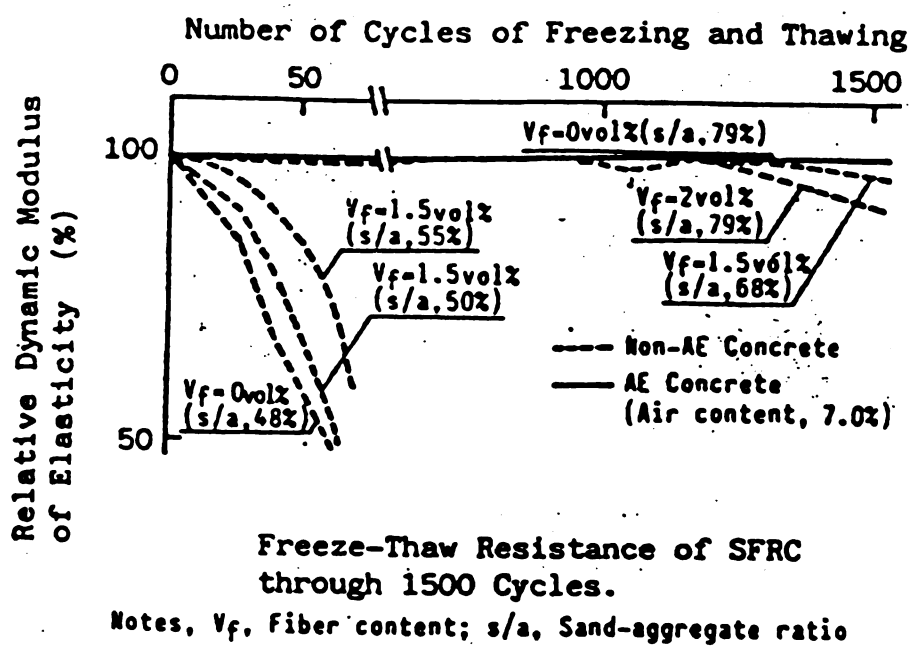
FIGURE 5.4 Freeze-Thaw Resistance of Plain and Latex Modified Mortars.

The test data reported in Reference 18 for latex modified concrete confirms the highly desirable resistance of latex concrete to freeze-thaw damage as compared to ordinary concrete. It is further stated that additional enhancements of the freeze-thaw resistance of latex concrete can be achieved by treating the material at elevated temperature.

5.4.3 Fiber Effects

The durability characteristics of fiber reinforced concrete materials are influenced by the durability of fibers, cementitious matrices and the interfaces between them. Ohama (Ref. 20) has reported these results on the performance of steel fiber reinforced con-

crete under the action of up to 1500 freeze-thaw cycles (Figures 2.5). Freeze-thaw resistance of steel fiber reinforced concrete with a high sand-to-aggregate ratio is observed in Figure 5.5 to be nearly equal to that of air entrained concrete (i.e., concrete with seven percent air content). This superior freeze-thaw resistance is attributed to a decrease in spacing factor due to increase in the sand-to- aggregate ratio, and also to the restraint of frost expansion by the network of steel fibers in concrete (Ref. 17)



Freeze-Thaw Resistance of SFRC through 1500 Cycles.

Notes, V_f, Fiber content; s/a, Sand-aggregate ratio

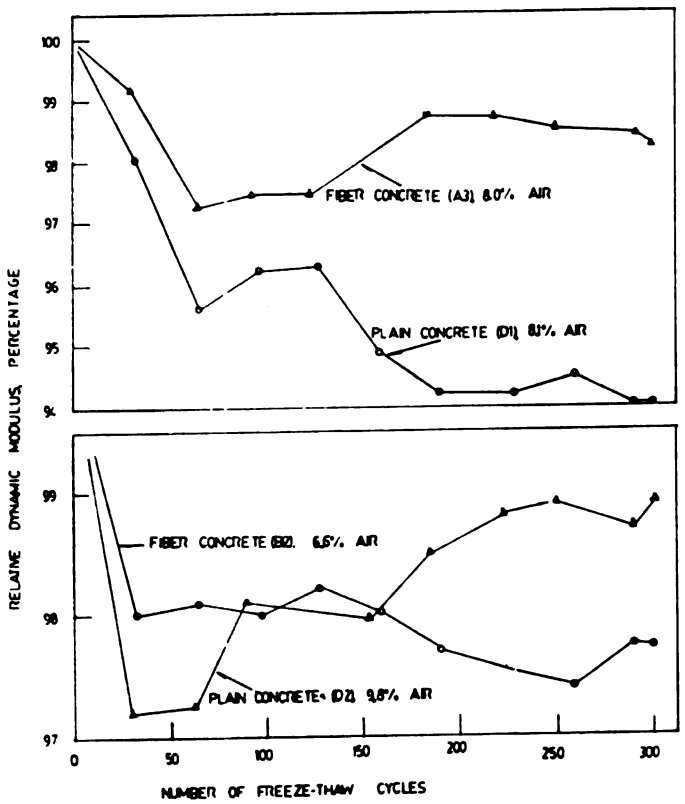
FIGURE 5.5 Freeze-Thaw Resistance of Steel Fiber Reinforced Concrete (Ref. 20).

Balaguru and Ramakrishnan (Ref. 19) have also reported results of an experimental study on the freeze-thaw resistance of steel fiber reinforced concrete. In this specific study, at relatively high air contents (Figure 5.6a), fiber reinforced concrete exhibited slightly better freeze-thaw durability than plain concrete (both fibrous and plain materials showed excellent durability). At lower air contents also, fibrous specimens generally

showed better freeze-thaw durability when compared with plain specimens. Here again, fibers seem to have relatively small effects freeze- thaw durability.

Long-term exposure of steel fiber reinforced concrete to freezing and thawing environments have shown similar freeze-thaw durability characteristics for plain and steel fiber reinforced concrete (Schupack) (Ref. 21). One may conclude from the data on freeze-thaw durability of steel fiber reinforced concrete presented above that the matrix durability is a dominant factor in deciding the composite material durability. Direct benefits of steel fibers to freeze- thaw durability seem to be relatively small. The fact that fibrous mixtures typically have higher sand contents and thus smaller spacing factors, however, seems to positively influence the freeze-thaw durability of steel fiber reinforced concrete. Ohama (Ref. 16) suggest that polypropylene, glass, and carbon fiber reinforced concretes all possess desirable freeze-thaw durability characteristics (see Figure 5.7 for carbon fiber reinforced cement).

(a) Higher Air Content



(b) Lower Air Content

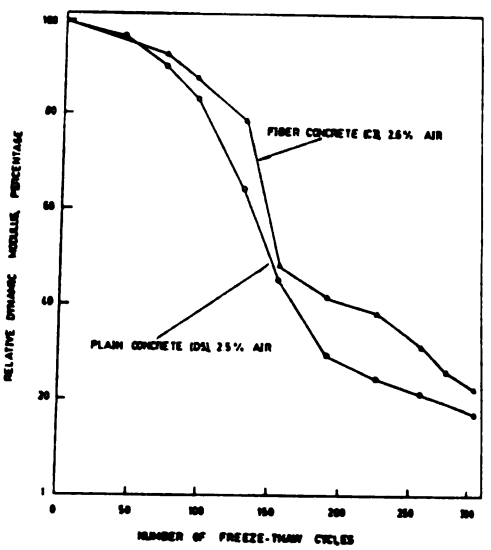


FIGURE 5.6 Effects of Steel Fibers on Freeze- Thaw Durability (Ref. 19).

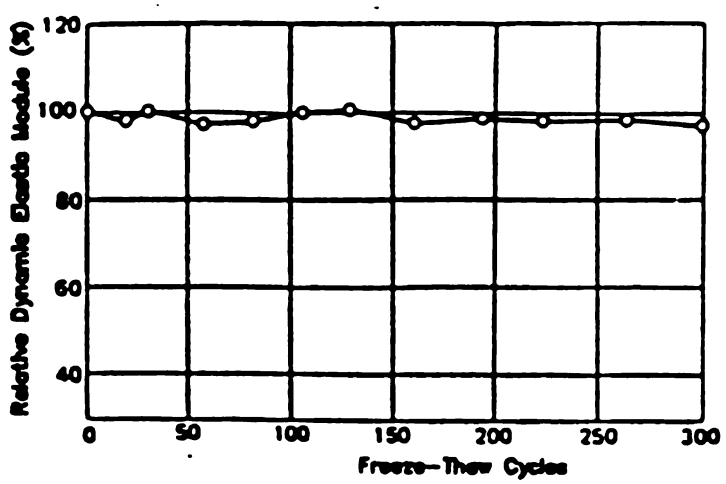


FIGURE 5.7 Freeze-Thaw Durability of Carbon Fiber Reinforced Cement.

5.4.4 Effects of Other Factors

The freeze-thaw durability of concrete also depends on a number of factors besides the air content and the presence of latex polymers and fibers. A brief review of these factors is presented below.

Water Content: Additional water in excess of the amount required for hydration of the paste leaves capillary cavities within the hardened paste. The use of minimum amount of water in fresh concrete is, therefore, highly desirable.

Aggregates: The pore structure of some rocks is such that water is absorbed by the aggregate particles and when frozen, this water will be forced to the outside surface. Other rocks have pore spacings within the rock itself similar to entrained air bubbles. If one assumes that the water which is forced from the voids as freezing takes place must find its way to the outside surface of the rock, the size of the rock itself becomes critical. Experience has shown that very porous rocks do not deteriorate when exposed to freez-

ing and thawing; they allow the movement of water rapidly enough so that internal pressure does not develop. Rocks with relatively fine pores, on the other hand, are more susceptible to fracturing unless the rock particles are small enough. In the case of mortar, Reference 22 suggests that the increase in sand-cement ratio improves frost resistance due to the formation of protective pores (in the range of 1 to 10 μm) at sand-matrix interfaces, and also because the spacing of sand particles in the paste matrix allows close spacing of pores at the interfaces of sand particles.

Water Reducing Admixtures:The water content of concrete mix may be reduced by the use of water reducing admixtures. The dispersion of cement particles by these admixtures densifies the cement paste by reducing the amount of uncombined water within the paste. This may result in fewer capillary voids in the gell in the presence of water reducing admixtures, even at the same water-cement ratio. Reference 15 reports gains up to 39% in freeze-thaw durability with the use of water-reducing admixtures.

Retarding Agents: Set retarding admixtures may also influence the durability of concrete by reducing the number of capillary voids in the cement paste. The heavier ingredients of fresh concrete tend to settle in the plastic mix. Water, being the lightest ingredient rises to the surface. This process in known as bleeding. If the time of set is retarded, more of the mixing water bleeds to the surface, thus reducing the number of voids caused by excess uncombined water. As water rises to the surface, small capillary passages may develop, however, and excessive bleeding may provide easy access to surface water.

Pozzolans and Mineral Admixtures: The use of Pozzolans in concrete reduces its porosity and permeability. The finely ground reactive silica Pozzolans combine chemically with the calcium hydroxide resulting from cement hydration. This produces a silica gel which occupies pore space initially occupied by the soluble alkalies and water. We could assume that the use of Pozzolans tends to increase freezing and thawing resistance by reducing capillary voids in much the same manner as an increase in portland cement. Test results, however, indicate that this is not necessarily true.

Fly ash concrete can have a freeze-thaw durability comparable to that of conventional portland cement concrete if the fly ash effects on reducing air content are overcome through the use of higher dosages of air entraining agent (Ref. 23).

In the case of silica fume mortar, frost resistance can be increased at a water-binder ratio of 0.60 by the addition of 10% silica fume to mortar when the sand-cement ratio is 2.25 or greater. Blow this sand-cement ratio, frost resistance is not improved by the addition of silica fume. It is concluded in Reference 22 that relative inaccessibility of

pores to water in mortar contributes to frost resistance; this can be provided in the case of mortar by the impermeable structure formed in the presence of silica fume at a water-binder ratio below 0.70.

In reference to the effects of finely divided mineral fillers on freeze-thaw durability, Reference 15 hints at the decrease in permeability of concrete in the presence of such fillers. The reduction in permeability is accomplished because of

the increased surface area and reduction in the size of capillary voids. This reduces the rate of the flow of water under pressure, but does not preclude the saturation of concrete if exposed to moisture for a sufficient length of time. Moreover, the movement of water from the capillaries is also retarded and greater hydraulic pressure is developed as concrete freezes.

5.5 EXPERIMENTAL PROGRAM AND TEST RESULTS

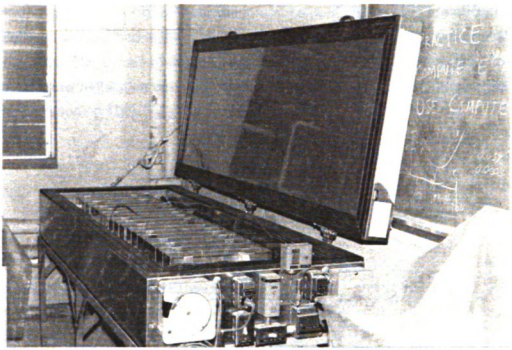
Unmodified and latex-modified (10% latex/binder ratio, with both latexes Type A and B presented in Table 1.2) carbon fiber reinforced cement mixtures with three percent volume fraction of 1/16 in. (1.5 mm) fibers were manufactured, and tested for freeze-thaw durability at the age 14 days.

A mortar mixer was used to manufacture all the composite materials, as illustrated in Section 1.3.3 of Chapter 1. The specimens were coated with wet burlap inside their molds for 24 hours after construction, and were then demolded and air cured until the test age of 14 days. The mix proportions for unmodified and latex-modified carbon fiber reinforced cements were the same as the ones used in earlier characterization studies discussed in Chapter 1 (see Table 1.3). The air content of all fresh mixtures was also measured following the gravimetric method of ASTM C-138. The unmodified mixture had an air content of 8% and the latex-modified mixtures with types A and B latex had air contents of 11% and 10%, respectively.

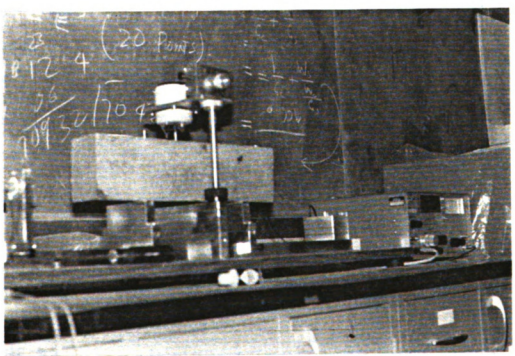
The freeze-thaw test specimens were prismatic with a 3 x 4 in. (76.2 x 101.6 mm) cross section, and a length of 14 in. (355.6 mm).

Freeze-thaw tests were performed following the procedure B (both freezing and thawing in wet environment) of ASTM C-666. The freezing and thawing cycles were applied in an automated machine (Figure 5.8a), and the freeze-thaw damage was assessed through the measurement of the fundamental transverse frequency of specimens simply supported on a span of 7.728 in. (196.3 mm), from which the dynamic modulus of elastic-

ity was derived. The equipment used for the measurement of the fundamental frequency is shown in Figure 5.8b. The frost damage in the material would be represented by the drop in the dynamic modulus of elasticity. The weight loss of the specimens at increasing number of cycles was also measured as another representative of the frost damage to the material. A maximum number of 300 cycles was selected as representing a typical frost action on the material throughout the life span of structures (ASTM C-666).



(a) Freeze-Thaw Equipment



(b) Fundamental Frequency Equipment

FIGURE 5.8 Freeze-Thaw and Fundamental Frequency Test Equipment.

The effects of freeze-thaw cycles on the dynamic modulus of elasticity of unmodified and latex-modified carbon fiber reinforced cement composites are shown in Figure 5.9. Both unmodified and latex-modified composites are observed to perform very satisfactorily under 300 cycles of freezing and thawing. Latex modification tends to improve the freeze-thaw resistance of carbon fiber reinforced cement at later stages (the number of cycles exceeding 100).

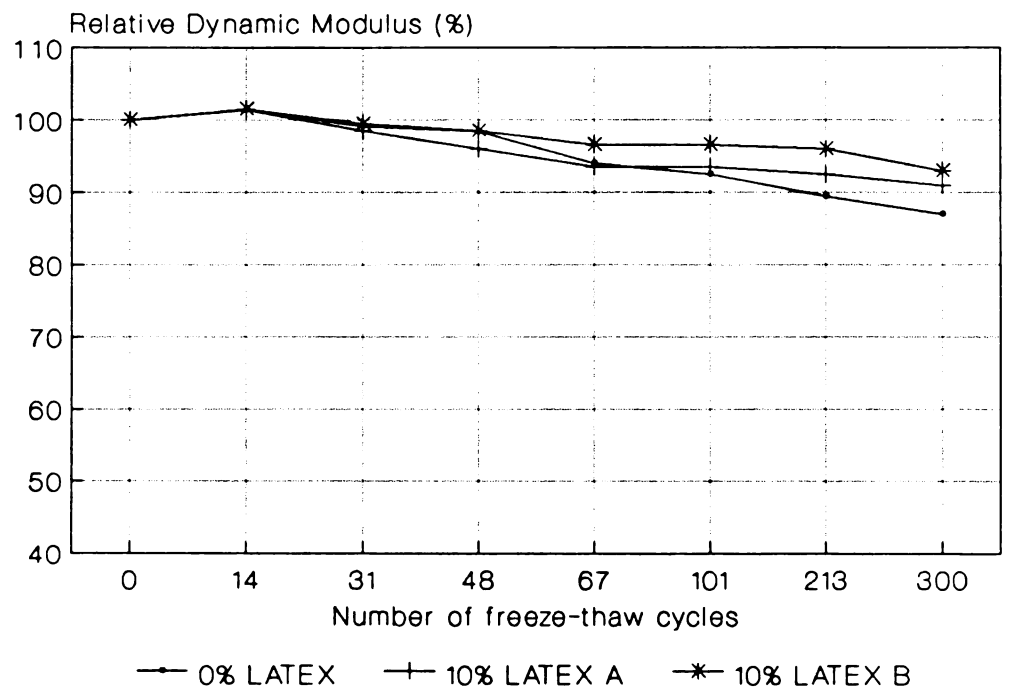


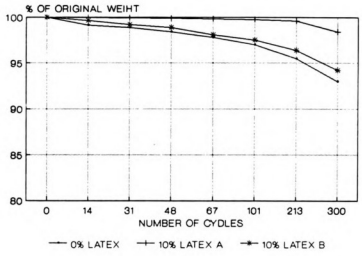
FIGURE 5.9 Effects of Freeze-Thaw Cycles on Dynamic Modulus of Elasticity.

The durability factor (D.F.) Is defined in ASTM C-666 as: D.F. = P*N/300, where P is the percentage of the initial dynamic modulus of elasticity after N cycles, and N is 300 cycles in this study (it could be less if the dynamic modulus had reaches 60% of its initial

value in less than 300 cycles). ASTM C-666 suggests that materials with a durability factor of above 60 are likely to perform well under freeze-thaw cycles. The durability factors calculated in this study were 86.97, 90.90, and 93.00 for unmodified, Type A latex-modified, and Type B latex-modified carbon fiber reinforced cements, respectively. These durability factors confirm the desirable freeze-thaw resistance of all composites and the improvements obtained through latex modification.

The results of weight loss measurements at different freeze-thaw cycles are presented in Figure 5.10a. This figure indicative of an excellent performance with only minimal weight loss even at later stages of the test. It should, however, be noted that weight loss measurements tend to overestimate the freeze-thaw durability of fiber reinforced concrete. The tendency towards spalling was observed on the surface of the specimens tested in this study towards the end of the freeze-thaw test. The loose pieces on the surface, however, were tied to the specimen by carbon fibers (Figure 5.10b), and thus this surface damage phenomenon did not result in weight loss in fibrous specimens.

Carbon fiber reinforced cement and particularly latex-modified carbon fiber reinforced cement were generally observed to possess a highly desirable freeze-thaw resistance. This can be attributed to: (1) the high tensile strain and stress capacity (and thus resistance to cracking and internal damage) provided by both carbon fibers and latex polymers; and (2) reduced porosity and permeability of cementitious materials resulting from latex modification (which reduces the permeation of water into the specimen and thus lowers the internal pressure associated with ice formation inside the material). Figure 5.11 typically compares the pore systems of unmodified and latex-modified carbon fiber reinforced cements. Latex modification is observed to seal many of the pores existing in cementitious materials, leading to a pore structure consisting of isolated pores which do not allow an easy flow of water into the latex modified cementitious material.



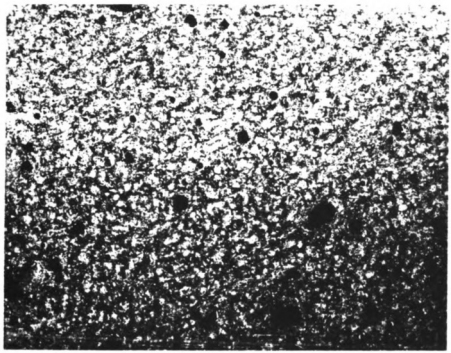
(a) Weight Loss



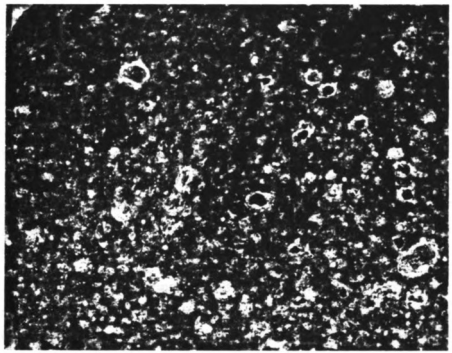
(b) Surface Damage (x20)

FIGURE 5.10 Weight Loss Measurements and Surface Damage for Freeze-Thaw Specimens.

Carbon fiber reinforced cement and particularly latex-modified carbon fiber reinforced cement were generally observed to possess a highly desirable freeze-thaw resistance. This can be attributed to: (1) the high tensile strain and stress capacity (and thus resistance to cracking and internal damage) provided by both carbon fibers and latex polymers; and (2) reduced porosity and permeability of cementitious materials resulting from latex modification (which reduces the permeation of water into the specimen and thus lowers the internal pressure associated with ice formation inside the material). Figure 5.11 typically compares the pore systems of unmodified and latex-modified carbon fiber reinforced cements. Latex modification is observed to seal many of the pores existing in cementitious materials, leading to a pore structure consisting of isolated pores which do not allow an easy flow of water into the latex modified cementitious material.



(a) Unmodified



(b) Modified With Latex B

FIGURE 5.11 Effect of Latex Modification on the Pore System Characteristics of Carbon Fiber Reinforced Cement (10X Magnification).

5.6 SUMMARY AND CONCLUSIONS

A review of the mechanisms of freeze-thaw deterioration, the freeze- thaw test methods, and the key factors influencing the freeze-thaw durability of concrete is presented. The test results reported in the literature regarding the effects of latex modification and fiber reinforcement on the freeze-thaw resistance of cementitious materials are also summarized.

The results of an experimental study on the freeze-thaw durability of carbon fiber reinforced cements, with and without latex polymers, is presented. All the materials considered in this experimental study incorporated 3% volume fraction of 1/16 in. (1.5 mm) carbon fibers. The latex- modified materials had 10% latex/binder ratios (latex Types A and B were used, see Table 1.2). Table 1.3 in Chapter 1 presents the mix proportion of the unmodified and latex modified carbon fiber reinforced cements. The freeze- thaw test was performed according to procedure B (both freezing and thawing in wet environment) of ASTM C-666. The freeze-thaw damage in specimens was quantified through the measurement of the dynamic modulus of elasticity and the weight loss after different number of freeze-thaw cycles. The freeze-thaw tests started when the specimens were 14 days old. The following conclusions were derived from the freeze-thaw test results:

1) Carbon fiber reinforced cement performs desirably under freeze-thaw cycles. Latex modification generally improves the freeze-thaw durability of carbon fiber reinforced cement.

2) Latex modifies the pore system characteristics of carbon fiber reinforced cement, thus reducing the interconnection between pores. This reduces water permeation into the material, a factor which potentially reduces internal damage associated with ice formation under frost action. Increased tensile strain and stress capacity of cementitious materials resulting from both latex modification and carbon fiber-reinforcement can also be used to illustrate the desirable freeze-thaw durability of latex-modified carbon fiber reinforced cement; and

3) Weight loss measurements seems to overestimate the freeze-thaw durability of fiber reinforced cement composites. Although a certain level of surface damage was observed in carbon fiber reinforced cement specimen, the loose parts on the measured weights included these spelled segments which could hardly contribute to the strength of the material.

CHAPTER 6

RESISTANCE TO ACID ATTACK AND HOT-HUMID ENVIRONMENTS

6.1 GENERAL

Acid attack on concrete can occur in various ways: (a) concrete materials cast against soil can be attacked by the acid present in natural ground water or dumped as chemical waste from industrial processes; (b) leakage and random spillage of acids can occur in industrial environments resulting in localized deterioration of concrete; (c) in sewage systems, especially in hot climates, concrete might be subjected to acid attack; and (d) acid rain can affect the long term durability of exposed concrete structures on a wide scale. In the northern United States and Eastern Canada, precipitation in 1987 exhibited average pH. Levels between 4.0 and 4.5 (Ref. 26). Acid precipitation has also been detected recently in Southeastern United States.

Acid attack in concrete is a process of structural change which starts at the surface and progresses inwards. For example, in the case of sulfuric acid, the reaction between the cement constituent of concrete and sulfuric acid results in the conversion of calcium hydroxide to calcium sulfide (gypsum) which, in turn, may be converted to calcium sulfoaluminate (etringate). All these reactions involve volume increase, and the formation of calcium sulfate leads to softening (decrease in density) of concrete. This simultaneous increase in volume and lowering of density creates a condition in which acid attack does not necessarily lead to weight loss. In order to quantify the acid attack effects in concrete it is thus important to measure the variations in weight as well as those in dimensions.

The acid attack on concrete tends to be more pronounced in environments with higher acidity (lower pH), especially when concrete is exposed to cycles of wetting and drying. The deterioration of concrete when subjected to acid attack tends to be reduced for concrete of higher strength and also for air entrained concrete (possibly due to better compaction and denser structure) ; measures aimed at reducing the permeability of concrete for ingestion of chemical solutions are found to be highly efficient in improving the acid resistance of concrete. Another consideration in assessing the durability of concrete

materials, especially those incorporating latex polymer and certain fiber types, relate to the performance of material when subject to hot and humid environments for extended time periods.

6.2 TEST METHODS FOR DETERMINING THE ACID RESISTANCE OF CONCRETE

In the acid resistance tests on concrete reported in literature, acidic solutions with different concentrations (e.q.i., sulfuric acid with pH = 1) (Ref. 25), 1.03% sulfuric acid with pH = 1.83 (Ref.26), of 3.03% sulfuric acid with pH = 1.47 (Ref. 26), or 5% hydrochloric acid) at different pH levels (ranging from 1 to 5) have been employed the specimens are commonly immersed in these solution (a typical ratio of specimen volume to solution volume is 0.277) (Ref. 26), at ambient temperature (typically between 22°C to 26°C, 72°F to 79°F) (Ref. 26, 27) for periods ranging from 8 hours up to 100 days (Ref.25), some investigations involving repeated wetting involved alternate acid immersion and drying of test specimens (Ref. 25). The specimens at the initiation of the acid resistance test are typically at an average age of 28 days (Ref. 25, 26, 28).

Attiogibe and Rizkalla (Ref. 25) oven-dried the specimen at 100°C, 212°F for 24 hours to a constant weight, and measure the weight and thickness of the specimens prior to the start of the acid attack program the concrete specimens used for acid resistance test are typically 2 in (51 mm) cubes or 4 in. (100 mm) by 0.5 in. (12 mm) by 0.25 in. (6 mm) prisms cut out of cylindrical specimens (Ref. 25). Specimens with large surface area to volume ratio may be preferred for acid resistance test since acid attack is a surface phenomenon (Ref. 25).

The measurements made for quantifying the effects of acid attack on concrete include: (a) weighing at regular time intervals after oven drying or some time after soft brushing and rinsing in tap water, followed by towel- drying for the removal of loose surface material and simulating the mild by erosive effects of direct rain fall (Ref. 26); (b) assessment of dimensional changes at regular intervals; (c) inspection of the specimen color and general appearance (photographing) throughout the test; (d) compression test (typically at the completion of the test produce); and (e) microstructure study (SEM, energy-dispersive x-ray analysis). As for the durability characteristics of cementitious materials in hot and humid environments are concerned, the laboratory durability tests reported in the literature (Ref. 29) generally involve the immersion of specimens in hot water (tem-

perature of about 75°C, 167°F). Measurements are made in this durability test on strength and toughness characteristics (typically in flexural) of the specimens.

6.3 ACID RESISTANCE OF CONCRETE

This section briefly reviews the effects of latex modification and some other factors related to mix proportioning on the acid resistance of concrete material.

6.3.1 Effects of Latex Modification

Latex modified concrete has recently found applications under chemically moderate corrosive or erosive conditions in building chemical plants ocean structure (Ref. 30). Such applications, which rely on the water tightness and acid resistance of latex modified concrete, have encouraged investigations into the resistance of latex modified concrete to acids.

Ohama, et. al. (Ref. 30) have reported the results of acid resistance test and concrete modified with styrene-butadiene rubber (SBR) latex, ethylene vinyl acetate (EVA), and polyacrylic ester (PAE) emulsions at polymer/cement ratios of 0, 10, and 20%. All the mixtures were designed (through the adjustment of water-cement ratio) as a result, the latex modified mixture at lower water contents when compared with the unmodified material.

Cylindrical concrete specimens 4 x 8 in. (10 x 20 cm) were molded, and were subjected to two days of moist drying followed by 5 days of immersion in water and 21 days of air drying. The cured concrete specimens were immersed in 2% hydrochloric acid and 5% sulfuric acid solutions at 68°F (20°C) for 28 days for acid attack. Approximately 146.5 in^3. (2400 ml) of each test solution was employed for each concrete specimen. The test solutions were changed every seven days up to an immersion period of 28 days.

After 28 days of immersion in acid solutions the attacked portions of concrete specimens, and their weight compressive strength and corrosion depth were measured. The pH of the concrete specimens was also determined at their surfaces, boundaries between the attacked and unattacked portions, and central portions.

The appearance after cleaning the attacked portions of polymer modified concrete immersed in 2% Hcl is shown in Fig. 6.1. Except for PAE modified concrete with a polymer-cement of 10%, the exposed course aggregate in the polymer modified concrete are not observed at all. By contrast, many course aggregate are exposed by severe attack of 2% Hcl in unmodified concrete.

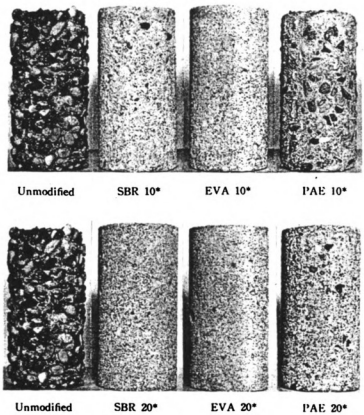


FIGURE 6.1 Appearance After Cleaning of Attacked Portions of Polymer Modified-Concrete Immersed in 2% Hcl for 28 Days.

Figures 6.2 and 6.3 represent the weight change and erosion depth of polymer modified concrete immersed in 2% Hcl solution, respectively. Except for PAE modified concrete with polymer-cement ratio of 10%, the weight change of the polymer modified concrete is less than one fourth of that for unmodified concrete. Regardless of the type of

polymer the weight change tends to decrease with an increase in polymer content the increase in polymer content is observed in Fig. 6.3 to produce relatively small reductions in the erosion depth which can be explained by the fact that the attacked portions of polymer modified concrete can not be completely cleaned because of the formation of polymer film network structure, though their large erosion depth is measured.

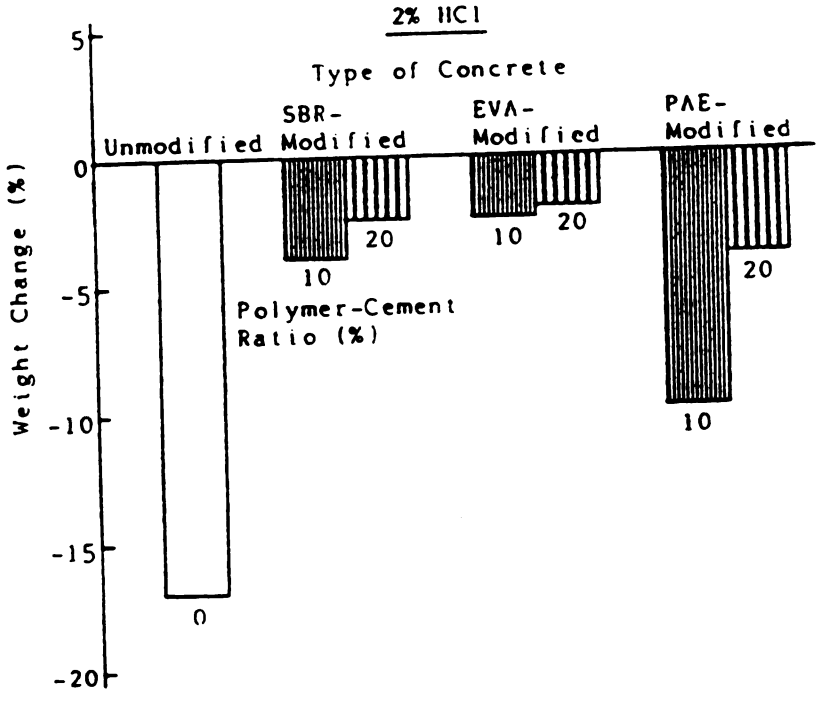


FIGURE 6.2 Weight Change After Cleaning of Attacked Portions of Polymer Modified Concrete Immersed in 2% Hcl for 28 Days.

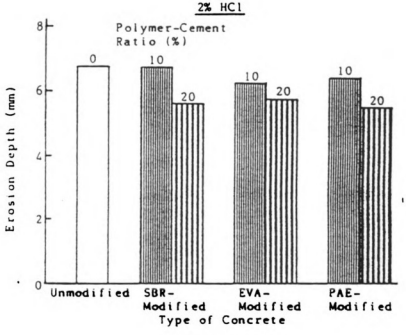


FIGURE 6.3 Erosion Depth of Polymer-Modified Concrete Immersed in 2% Hcl for 28 Days.

Figure 6.4 illustrate the relative compressive strength of polymer modified concrete immersed in 2% Hcl (with respect to the corresponding strength value, prior to acid attack). In general, the relative compressive strength of polymer modified concrete is 70% to 90%, and smaller that of unmodified concrete. It should, however, be noted that the absolute value of the compressive strength of attacked polymer-modified concrete is generally larger than that of the attacked unmodified concrete regardless of the polymer type.

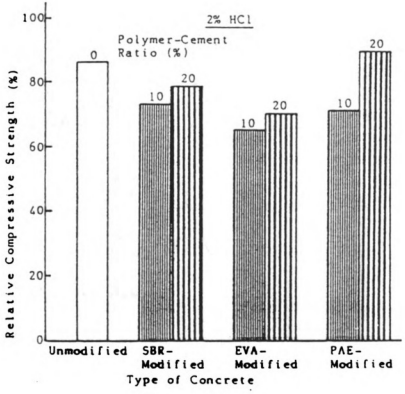


FIGURE 6.4 Relative Compressive Strength of Polymer- Modified Concretes Immersed in 2% Hcl for 28 Days.

In the case of specimens immersed in 5% H_2SO_4 solutions, Fig. 6.5 shows that both polymer modified and unmodified concrete are initially swollen, and considerably attacked by 5% H_2SO_4 , leading to exposure of course aggregate. In particular, PAE modified concrete is remarkably eroded by 5% H_2SO_4 compared to other concrete.

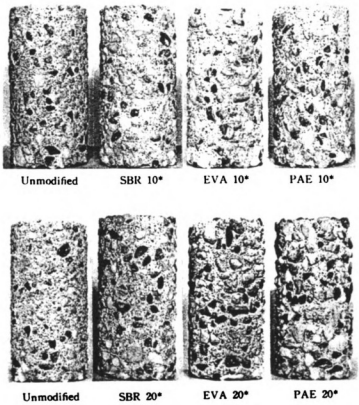


FIGURE 6.5 Appearance After Cleaning of Attacked Portions of Polymer-Modified Concrete Immersed in 5% H_2SO_4 for 28 days.

Figures 6.6 and 6.7 indicate that the weight change and erosion depth, respectively, of polymer modified concretes immersed in 5% H_2SO_4 solutions tend to increase with increasing polymer content. Especially the PAE-modified concrete with a polymer-cement ratio of 20% shows the lowest resistance to 5% H_2SO_4 attack. The reason for the poor resistance in H_2SO_4 attack. The reason for the poor resistance in H_2SO_4 solutions might be the poor sulfuric acid resistance of cement hydrate and polymers as binders. The formation of etringite by sulfuric acid attack tends to cause expansion in polymer-modified concrete (Ref. 30).

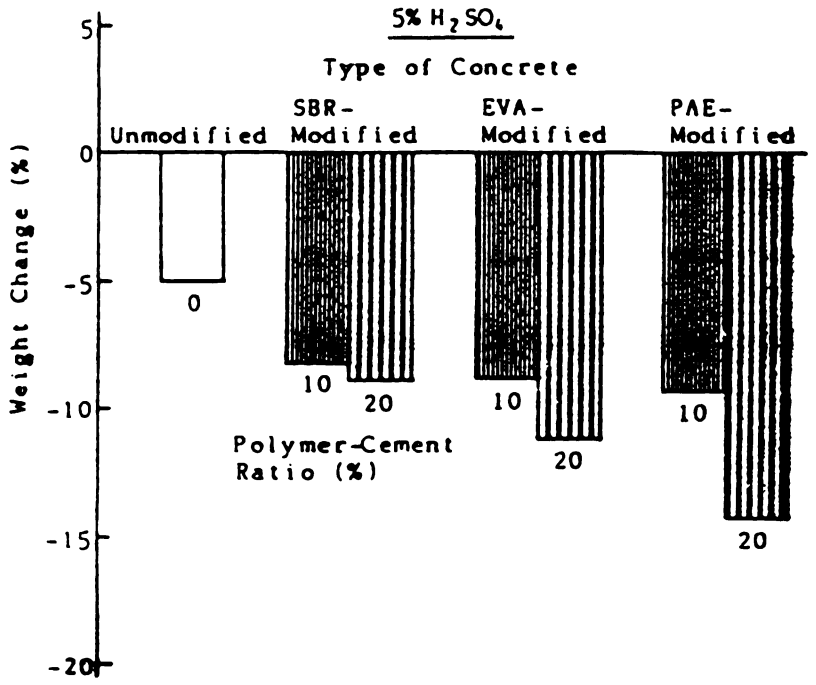


FIGURE 6.6 Weight Change After Cleaning of Attacked Portions of Polymer-Modified Concrete Immersed in 5% H_2SO_4 for 28 Days (Ref. 30).

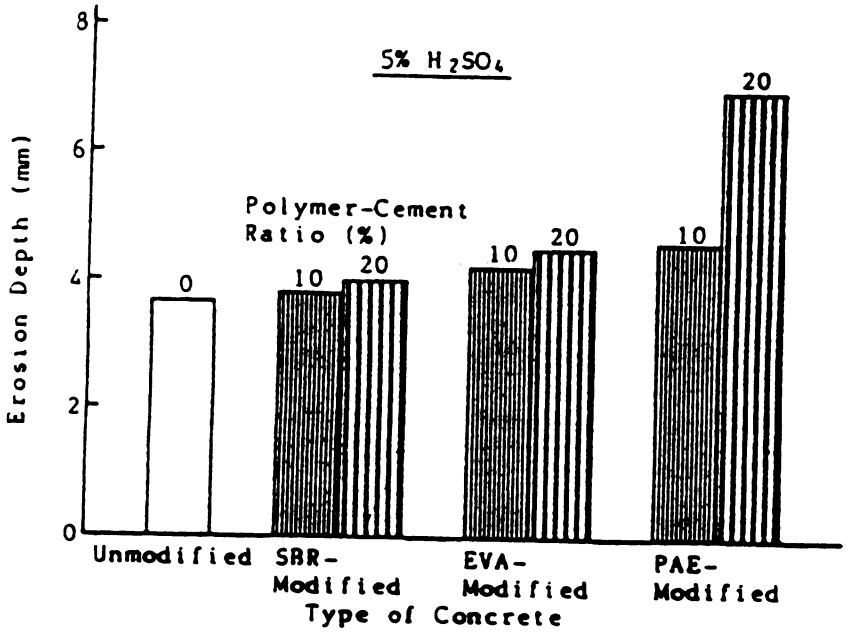


FIGURE 6.7 Erosion Depth of Polymer-Modified Concrete Immersed in 5% H_2SO_4 for 28 Days (Ref. 30).

Figure 6.8 shows that the relative compressive strength of polymer- modified concrete immersed in 5% H_2SO_4 (like 2% HCL) is 70% to 90%, and smaller than that of unmodified concrete. Except for EVA modified concrete, the attacked polymer-modified concretes exhibit a large compressive strength than the unmodified concrete.

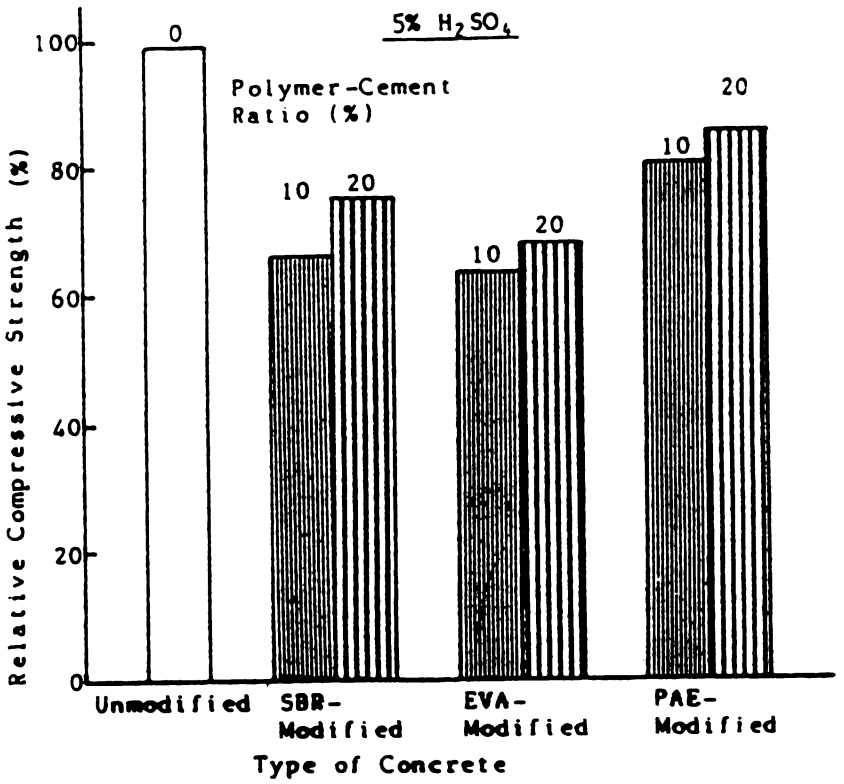


FIGURE 6.8 Relative Compressive Strength of Polymer-Modified Concrete Immersed in 5% H_2SO_4 for 28 Days.

The pH measurement at the surface boundaries and central portions of polymer-modified concrete immersed in 2% Hcl and 5% H_2SO_4 solutions show that the pH of polymer-modified concrete is nearly constant at each region, irrespective of the polymer type and content. The pH was observed in increase with additional depth below the surface.

The acid resistance test results presented above indicate that the resistance of most polymer-modified concrete to 2% HCL is improved to some extent when compared to unmodified concrete. In the other hand, the resistance of most polymer modified concrete to 5% H_2SO_4 is hardly improved in comparison with unmodified concrete.

The effectiveness of SBR latex modification in improving the hydrochloric acid resistance of concrete is conformed by test results reported in Ref. 28. In these tests our cured (28 days) unmodified and SBR modified concrete cylinders were placed in 5% HCL solutions (with the top end of cylinders out of contact with the acid) Fig. 6.9 shows that the unmodified (control) concrete deteriorated rather severely, while the latex modified specimens did not show any obvious deterioration after 8 hours of immersion.



FIGURE 6.9 Hydrochloric Acid Attack on Unmodified and SBR-Latex Modified Concrete.

Fattuli and Hughes (Ref. 27) have reported the results of tests on the performance of Polyregional Alcohol (PVA) modified concretes in 1% and 3% sulfuric acid solutions. They concluded that the addition of PVA to cement paste or mortar results in considerable expansion in the surface layers of the cubes that are penetrated by the acids. Preliminary test results indicated that the PVA keeps the matrix together after it is attacked by the acid, resulting in a lower rate of deterioration.

6.3.2 Effects of Concrete Mix Proportions

Fattuli and Hughes (Ref. 27) have reported that the weight loss of mortar and concrete cubes in 1% and 3% sulfuric acid solutions tends to increase with an increase in cement content. This was less marked for the 1% solution. The loss in weight also increased with an increase in acid concentration reduction in water cement ratio through the use of a superplasticizer, however, resulted in reduced weight loss of concrete. The effect of water cement ratio was more significant when the concrete was subjected to the lower acid concentration of 1%.

Kong and Orbison (Ref. 26) have reported the results of an accelerated laboratory test program conducted to evaluate the response of concrete cylinders to simulated acid precipitation solutions a total of 140 specimens was placed in acidic solutions prepared by adding concentrated sulfuric and nitric acid to distilled water in a 2 to 1 ratio, representing precipitation composition in northern United States and Canada, with pH levels ranging from 2 to 5. The immersion period was 3 months. The response of the specimens, made using Type I portland cement and having design compressive strength of 3000 psi (20.7 MPA) to 9000 psi (62.1 MPA), was evaluated through visual evaluation, weight changes, and compressive strength changes, and compressive strength changes. The loss of specimen surface materials generally increased with increasing acidity of the simulated acid precipitation solution. However, the pH 3 solution apparently produced greater surface deterioration in all but the 9,000 psi (62.1 MPA) specimens, were the degree of deterioration was similar to the high strength specimens, those with design compressive strengths of 7000 psi (48.3 MPA) and above, experienced the greatest deterioration in the form of a relatively uniform erosion of surface material. This can be attributed to the higher cement content of these materials.

The lower strength specimens were somewhat less susceptible to uniform surface deterioration relative to the high strength specimens, but displayed a moderate degree of sulfate attack characterized by expansion, cracking, and spalling at the edges in all of the acidic solution. In addition, all the acidic solutions produced this discoloration of the specimens, with a degree of discoloration generally increasing with both solution acidity and design strength of the specimen.

6.4 DURABILITY IN HOT-HUMID ENVIRONMENT

In some environments materials should withstand long-term efficient high temperatures and high humidity levels. Laboratory studies have indicated that carbon fiber rein-

forced cement possesses excellent durability characteristics when subjected to hot-humid environments for long time periods (Ref. 29). Carbon fiber reinforced cement has also performed well in actual field applications in hot-humid environments.

6.5 EXPERIMENTAL PROGRAM

Unmodified and Latex modified (10% Latex-Binder ratio, with both Type A and Type B latexes (only Type A was used in hot water durability) presented in table 4E carbon fiber reinforced cement mixtures with 3% volume fraction of 1/16 in. (1.5 mm) fiber were manufactured and tested for acid resistance and hot water durability. The specimens were manufactured in a conventional mortar mixer and were compacted inside molds thru external vibration. They were demolded after 24 hours (during which they were covered by a plastic sheet), were then air-cured until the test age of 14 days. The mix proportions for unmodified and latex modified carbon fiber reinforced cements were similar to those described earlier (see table 4.3). The fresh mix air content were 8%, 11%, and 10% for the unmodified carbon fiber reinforced cement and those modified with latex Types A and B, respectively.

The acid resistance test specimens were 2 inches (51 mm) cubes, and the hot water durability test specimens were 1.5 in. x 1.5 in. x 6 in. (38.1 x 38.1 x 152.4 mm). Four acid resistance and 12 hot water durability test specimens were manufactured for each mix composition noting that the assessment of hot water durability involves testing at different ages.

In the acid resistance test, the 14 days old specimens were immersed in water for 3 days, and were then surface dried and photographed and their color was recorded. The specimens were then placed in 5% HCL solution for a period of 24 hours, with about 1 in. (25.4 mm) of the specimen height outside the solution (for handling purposes). The specimens were then removed from the solution and were flashed with water.

The loose materials were then carefully brushed off the specimens and the specimens were weighed and photographed with their color recorded. The erosion depth was also measured by taking 4 measurements in 2 perpendicular directions, and the compressive strength was obtained.

In the hot water durability test the 14 days old specimens were immersed in hot water at temperature of 158°F (70°C). The specimens were tested in flexure on a span of 4.5 in. (1143 mm) using the 4 point loading method of ASTM C-1018 after 0, 4, 8, and 14 days of immersion in hot water. Both load and deflection at the load point were monitored

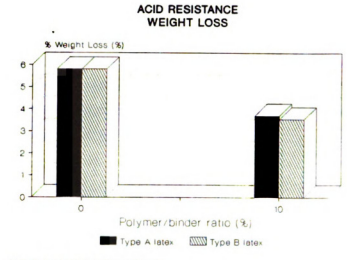
in flexure test in order to asses the effects of exposure to hot water and the flexural strength as well as the toughness of the material.

6.6 EXPERIMENTAL RESULTS

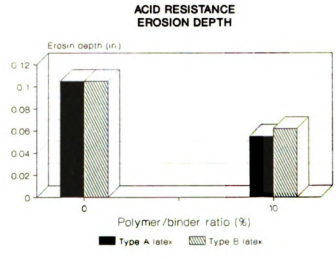
The acid resistance test results are presented in Fig. 6.10. As shown in Fig. 6.10 a and b, the weight loss and erosion depth under acid attack, respectively tend to be reduced by latex modification of carbon fiber reinforced cement. The improvements in acid resistance from these points of view are rather significant with about 50% reduction in weight loss and erosion depth both latexes Type A and Type B performed similarly in reducing the weight loss and erosion under acid attack.

Fig. 6.10 c shows the effects of acid attack on the compressive strength of unmodified and latex modified carbon fiber reinforced cements. The relative compressive strength in this figure is defined as the ratio of compressive strength after immersion in acid solution to that prior to immersion. The results presented in Fig. 6.10 C indicate that latex Type A has relatively small effect on the compressive strength loss under acid attack, while latex Type B can impart improvements is this aspect of the acid resistance of carbon fiber reinforced cement.

(a) Weight Loss



(b) Erosion Depth



(c) Relative Compressive Strength

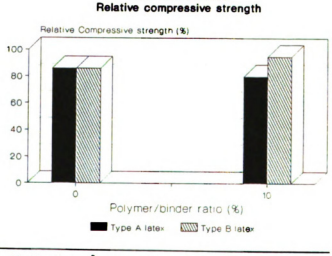
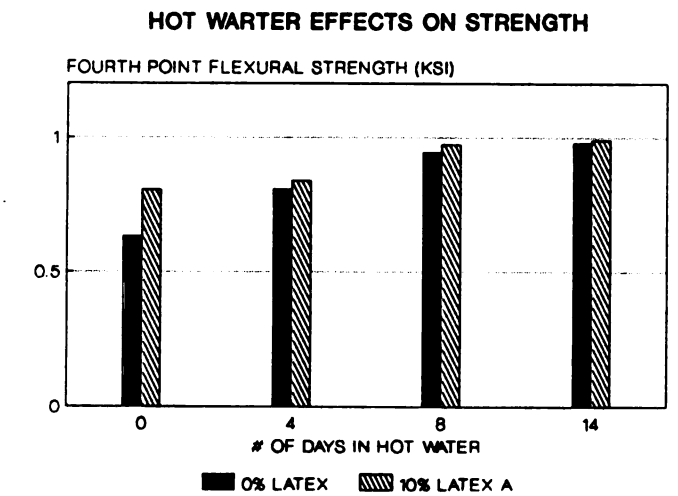


FIGURE 6.10 Effects of Latex Modification on the Acid Resistance of Carbon Fiber Reinforced Cement.

The hot water durability test results for unmodified and latex modified carbon fiber reinforce cement, are presented in Fig. 6.11. The flexural strength is observed to increase with extended immersion in hot water with latex modification having relatively small positive effect. The flexural toughness (area underneath the flexural load-deflection cure), however, is observed in Fig. 6.11 b to decrease as a result of exposure to hot water. Latex modification seems to have relatively important effect in maintaining the toughness of carbon fiber reinforced cement under extended exposure to hot water.

(a) Flexural Strength



(b) Flexural Toughness

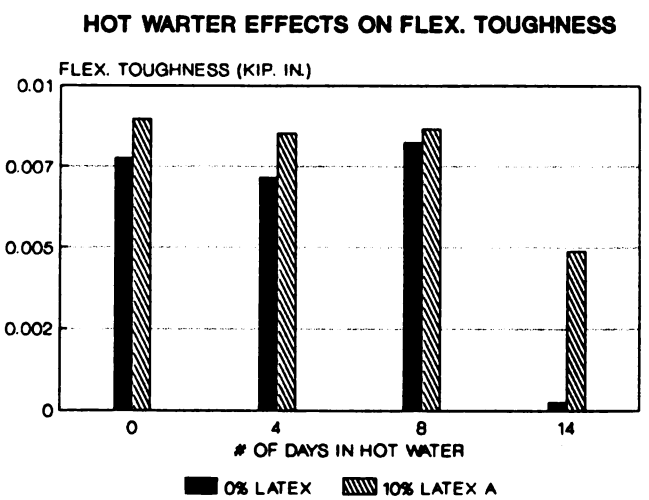


FIGURE 6.11 Effects of Extended Immersion in Hot Water on Flexural Performance of Carbon Fiber Reinforced Cement.

6.7 SUMMARY AND CONCLUSIONS

In certain exposure conditions cementitious materials are subjected to acid attack or long-term effect of hot-humid environments. The effects of latex modification on these aspects of the durability characteristics of carbon fiber reinforced cement were assessed experimentally. The acid resistance test involved immersion of 2 in. (51 mm) cube specimens in 5% HCL solution. The weight loss, erosion depth and loss in compressive strength were used as measures of acid attack. Latex modification was observed to reduce the weight loss and erosion depth of carbon fiber reinforced cement by about 50%. The overall effects of latex modification on the loss of compressive strength under acid attack were relatively small. Extended immersion in hot water led to an increase in flexural strength together with a decrease in flexural toughness of carbon fiber reinforced cement. Late modification reduced the loss in flexural toughness of carbon fiber reinforced cement under hot water exposure.

CHAPTER 7

REPAIR TECHNIQUES

7.1 GENERAL

Coating and spraying repair techniques, which are applicable to latex modified carbon fiber reinforced cement, are suitable in conditions of concrete cavitation, dormant cracks, crazing, form stabing, small and large holes, permeability, scaling, and spalling. The spraying or pneumatic application of latex modified carbon fiber reinforced cement involves shooting the mortar under pressure into the cavity or onto the surface of the concrete to be repaired. Spraying is practical on either vertical or horizontal surfaces; where the cavities are comparatively shallow. The surface profile should preferably be somewhat irregular and rough texture.

The filling of cavities or application of a repair uniform layer of repair material can also be achieved by troweling. It is often used to repair deteriorated surfaces of concrete structures that are basically sound structurally.

The spraying and troweling repair technique applied in field conditions do not necessarily produce cementitious materials with pore system characteristics and compaction levels comparable with those obtained in laboratory molding and external vibration. Hence, it is important to verify that the materials obtained from the actual repair application technique possess properties resulting from laboratory processing methodology.

7.2 EXPERIMENTAL PROGRAM

The experimental study conducted in this phase of the research was concerned with the assessment of the material properties of unmodified and latex modified carbon fiber reinforced cements produced by the spraying and troweling application techniques.

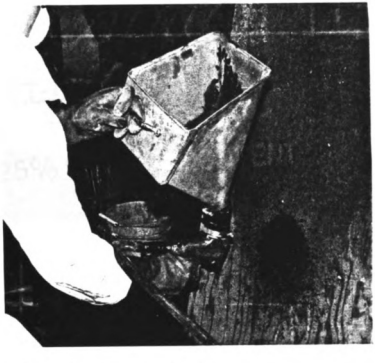
The mix proportions for carbon fiber reinforced cements with and without latexes were similar to those used earlier in laboratory manufacture by molding technique (see table 4.3). All the materials had 3% volume fraction of 1/16 in. (1.5 mm) carbon fibers. The latex modified materials had a polymer-binder ratio of 10% (Only Type A latex (BASF styrene butadiene) was used in this phase of study. The composite was premixed using a mortar mixer, again following the procedure described in chapter 4 for laboratory manufacturing. The fresh fibrous mix was then either sprayed or troweled in order to make the test specimen. The spraying and troweling techniques followed in this study for the appli-

cation of unmodified and latex modified carbon fiber reinforced cement are described below.

Spraying Technique: The fresh fibrous cement mixture was fed into the container above the spraying gun (Fig. 7.1a), and was sprayed through the larger whole of the gun (6 mm) (Fig. 7.1b). The material was sprayed into a 10 in. cube wood box, and was moist cured for 24 hours and was exposed to the regular laboratory environment until the age of 14 days at this age, 1.5 in. x 1.5 in. x 6 in. (38.1 x 38.1 x 152.4 mm) prismatic were saw cut from the 10 in. (254 mm) (Fig. 7.2). Three specimens were cut out of one cube fro each mix composition. They were used for flexure test by 4-point loading on a span of 4.5 in. (114.3 mm) (ASTM C-1018). The broken flexure specimen were used to conduct specific gravity and water absorption tests (ASTM C-567).



(a) Fresh Fibrous Cement



(b) Spraying Gun in the Container

FIGURE 7.1 Spraying Application Technique.

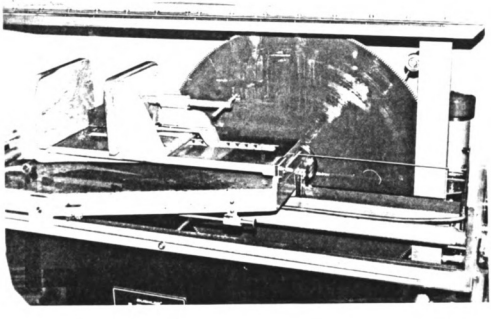
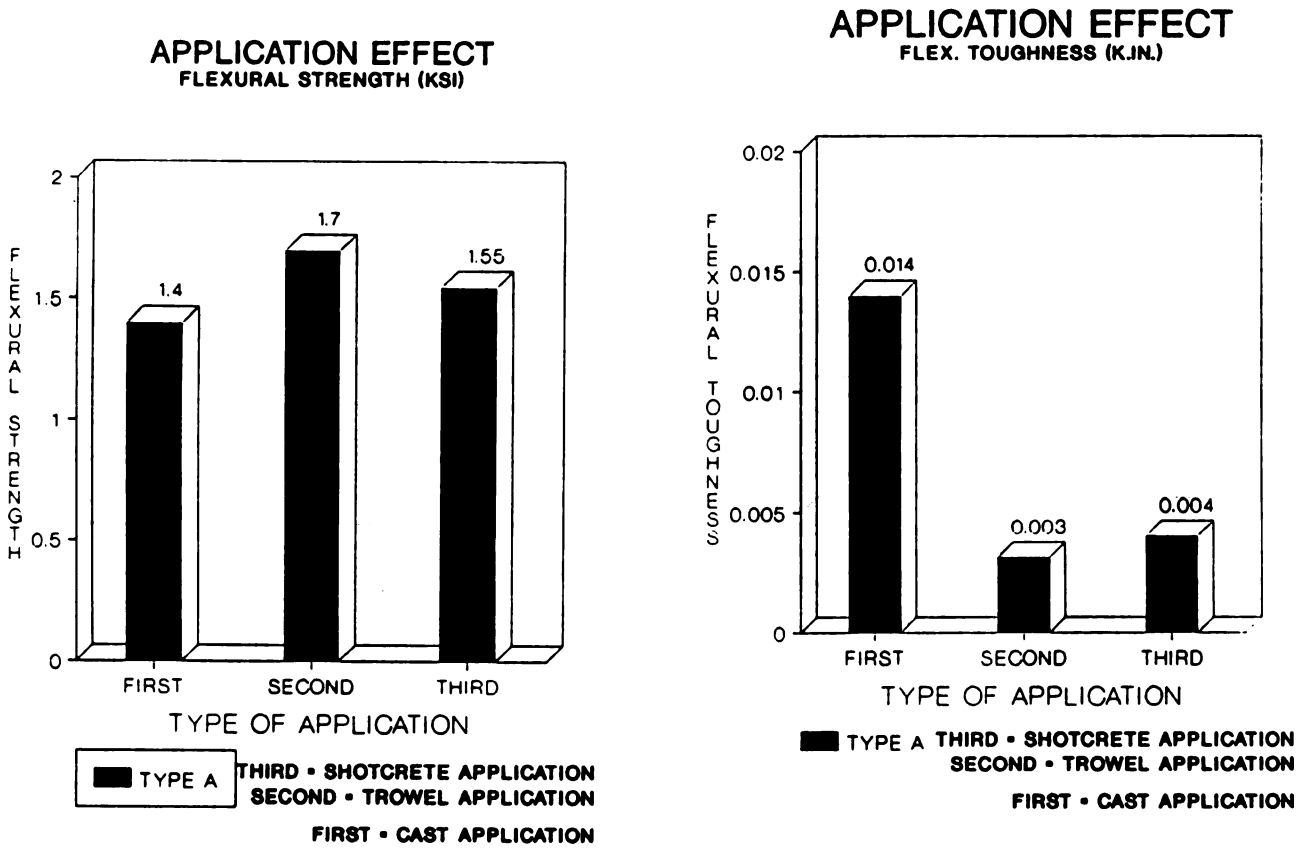


FIGURE 7.2 Saw-Cutting of Sprayed Specimens.

troweling Procedure: In this method the premixed unmodified and latex modified fibrous cements were simply troweled into a 10 in. (254 mm) cube wood box with no vibration applied. The curing, saw cutting of test specimens and experimental procedures followed the same method described for the sprayed material.

7.3 TEST RESULTS

The flexural strength and toughness test results obtained for the molded, troweled and sprayed latex modified carbon, fiber reinforced cements are presented in Figs. 7.3a and b, respectively. The flexural strength is observed to be higher in the case of sprayed and particularly troweled composite when compared with the molded ones. The flexural toughness is, however, the highest for conventionally molded materials. The sprayed and troweled composites in spite of their desirable flexural strength, have low toughness characteristics. It is worth mentioning that in actual field conditions the repair application on deteriorated concrete surfaces are generally by troweling and spray. Hence, the material properties, obtained for sprayed and troweled composites are more representative of the properties expected in field conditions.



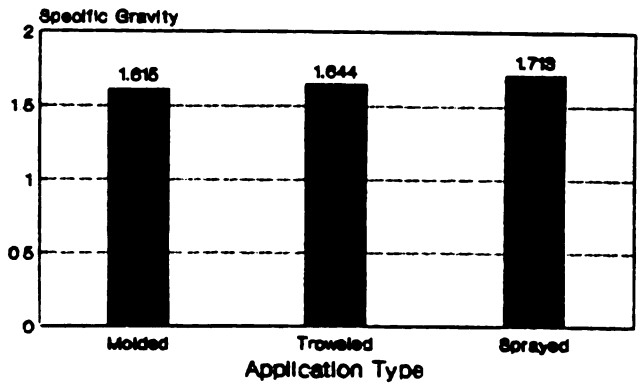
(a) Flexural Strength (b) Flexural Toughness

FIGURE 7.3 Comparison of the Flexural Properties of Molded, troweled, and Sprayed Latex Modified Carbon Fiber Reinforced Cements.

The specific gravity and water absorption test results for the molded, troweled, and sprayed latex modified carbon fiber reinforced cements are presented in Figs. 7.4 a and b, respectively. There seems to be relatively small differences between the specific gravities of the composites produced with different processing techniques (see Fig. 7.4a). The troweled specimens, however, were observed in Fig. 7.4b to poses relatively high water absorption capacity. This conclusion is not conclusive in the use that relatively

large variations were observed in the limited water absorption test performed on the troweled latex modified carbon fiber reinforced cement.

(a) Specific Gravity



(b) Water Absorption

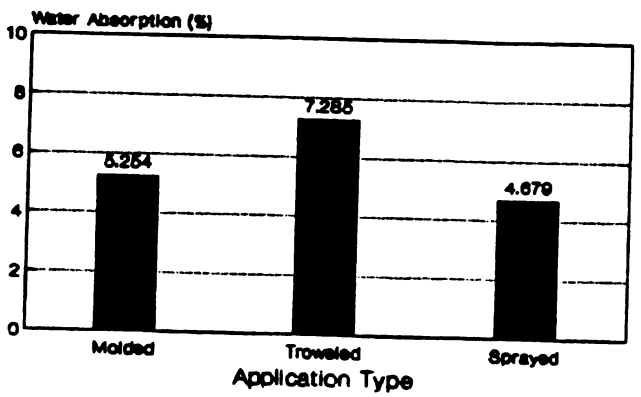


FIGURE 7.4 Specific Gravity and Water Absorption Test Results.

7.4 SUMMARY AND CONCLUSIONS

The application methodology of a repair material is one of the factors deciding the final material property. Laboratory test on cementitious materials are generally performed using specimens constructed by molding (casting and external vibration) of premixed materials. The actual repair of deteriorated concrete surface, however, involves the application of cementitious materials by the troweling and spraying methodology.

This phase of the study was concerned with the effects of the troweling and spraying versus molding application technique and the performance characteristic of latex modified carbon fiber reinforced cement. The materials used all had similar mix proportions (the optimal ones decided earlier), and were all premixed in a mortar mixer. The effects of the application methodology on the flexural performance, specific gravity, and water absorption of latex modifies carbon fiber reinforced cement were assessed thru tests on similarly premixed materials which were either molded, troweled, or sprayed. The following conclusions were derived from the generated test results:

1) The flexural strength of latex modified carbon fiber reinforced cement was highest for troweled materials, followed by the sprayed and molded materials;

2) The troweling and spraying application technique produce composite with lower toughness when compared with the molding application method.

3) The specific gravity of latex modified carbon fiber reinforced cement is comparable for molded, troweled, and sprayed materials, and

4) The water absorption capacity of the molded and sprayed composite were comparable. The results for the water absorption capacity of the troweled composites were not conclusive.

One may conclude from the results of this phase of the study that the actual field repair application technique may positively or negatively influence the final property of a repair material. These effects should be considered in the selection of materials and methodology for repair projects.

CHAPTER 8

GUIDELINES FOR THE SELECTION OF REPAIR MATERIALS

8.1 GENERAL

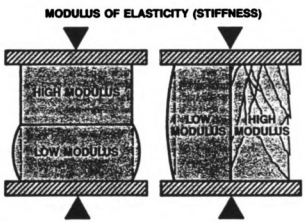
The wide array of specialty and conventional repair materials available today give the concrete repair contractor the opportunity to match material property with job demands. While bond and compressive strength values typically receive much attention in the selection of repair materials, characteristic, such as the dimensional stability, thermal expansion, stiffness and permeability of the material as well as its durability in the specific job conditions can be of equal or greater importance. These critical considerations in the selection of repair materials are described in this chapter. Alternative repair materials are also introduced, and practical guidelines for the selection of one of these alternatives in a specific job are presented. The information given in this chapter together with the information on material property of latex modified carbon fiber reinforced cement given in earlier chapter can be helpful in making the proper decision responding the suitability of composite material developed in this study for specific repair jobs.

8.2 CONSIDERATIONS IN THE SELECTION OF REPAIR MATERIALS

One of the primary requirements for a successful repair is to provide good bond between the new material and the underlying concrete or substrate. Bond failure between new and old concrete is not usually caused by the incapability of new concrete to adhere to a properly prepared substrate. It is usually caused by shrinkage. Most repairs are made on older concrete that will not under go much further shrinkage. Hence, the repair material also be essentially shrinkage free or else be able to shrink without loosing bond. Latex modified carbon fiber reinforced cement shows relatively small shrinkage movements, and its desirable tensile strain capacity can delay cracking under strain shrinkage. These are different advantages in repair applications. Other cementitious repair materials may use construction procedure, such as dry packing, dry-mix shotcreting and aggregate preplacing which reduce water requirement and minimize shrinkage potentials. Another

way to overcome shrinkage problem is to use repair products that actually expand in volume once they are mixed.

Coefficient of thermal expansion in another important property of repair materials. All materials expand and contract with changes in temperature. When making large or thick patches or when placing an overlay, it is important to use a material with a coefficient of thermal with a coefficient of thermal expansion similar to that of the concrete being repaired. When a composite of two materials of widely varying thermal coefficient undergoes a significant temperature change, difference in volume change can cause failure either at the bond line or within the section of lower strength material. Latex modified carbon fiber reinforced cement possesses a coefficient of thermal expansion which is comparable to that of conventional concrete? This is another advantage of this new material in repair application. Depending on the repair condition, the similarities of material stiffness can be an important concern in the selection of repair materials. When the external load is perpendicular to the bond line (Fig. 8.1a), a difference in modules usually does not cause problems. However, when the load is applied parallel to the bond line (Fig. 8.1b), deformation of the lower modulus material transfers load to the higher modulus material which may then fracture. Latex modified carbon fiber reinforced cement has lower modulus of elasticity when compared with conventional concrete is, however, typically used in thin layers and thus provides little load bearing capacity. Hence, the relatively low modulus of the material is not necessarily a disadvantage in many repair jobs.



(a) Load Applied Perpendicular To Bond Live

(b) Load Applied Parallel To Bond Live

FIGURE 8.1 Composites of Two Materials With Different Moduli Under Load (Ref. 31).

Good quality concrete is relatively impermeable to liquids but freely transmits vapors. Impermeable repair materials can protect substrate from exposure to water and the aggressive chemicals it transports. On the other hand, entrapped moisture vapor that passes up thru the repair material this can be a particularly troublesome problem with stabs on grade that are subject to freezing and thawing. The impermeability of latex modified carbon fiber reinforced cement is at an advantage when a substrate needs to be protected in aggressive environments. This project has not produced data on vapor transmission property of the material.

Latex modified carbon fiber reinforced cement, due to the presence of carbon fibers is a highly conductive cementitious material. This is an advantage in repair jobs involving damage due to corrosion of reinforcing bars. The use of nonconductive repair materials in such conditions can concentrate the transmission of electric current (associated with steel corrosion) in a smaller section of concrete, leading to an increased rate of corrosion.

The durability of a repair material is certainly a prime consideration, noting that the need for repair is generally a sign of aggressive environments. It has been establish in this research project that latex modified carbon fiber reinforced cement can stand the action of repeated freeze-thaw cycle, hot-humid environment, and acid attack quiet satisfactory. This durability in a variety of severe exposure conditions is a distinct advantage of the new material developed in this study for repair applications. Besides the material property certain applications and service condition should also be considered in the selection of repair materials. These factors are briefly discussed below:

1) Thickness of the repair surface as relate the maximum aggregate size and the heat generating property of the repair materials.

2) Moisture content of the substrate which may affect the curing of the repair material and may cause a destructive steam due to the heat generated during the curing of the repair material.

3) Temperature of repair material application as relate to the desirable curing condition for the repair material.

4) Ventilation level of fire safety concerns at repair site can prevent the use of volatile and combustible repair materials.

5) With the repair section on a vertical surface or underneath a horizontal member, very flowable repair materials which do not adhere to substrate without siding are not preferred.

6) If repair materials should be put into service rather quickly rapid strength gain characteristics are essential.

7) The need for color matching or duplication of original concrete texture may be critical in the selection of repair material for certain job conditions.

8.3 ALTERNATIVE CEMENTITIOUS REPAIR MATERIALS

It is desirable to maintain uniform structural property within individual members to be repaired therefore, where an existing member is being packed. It is desirable to make new materials to the original as closely as possible. Use of aggregate and other composition ingredients similar to those used when the original structure was constructed is desirable. Likewise it is advisable to make the original mix proportion as closely as possible, with the exception of a reduction in water content (Ref. 32).

Where new members are being constructed design of a mix which contains the minimum freezable amount of water should be considered. Concrete mixtures designed for minimum shrinkage should have a low total water content, and contain a larger possible amount of aggregate consistent with the required workability. Also, the largest size aggregate that can be handled and placed should be used, as mixes containing large-size aggregate have more total aggregate and thus less pore space requiring less cement paste then those containing small size aggregate. Shrinkage is also influenced by the type of aggregate. Hard aggregate are difficult to compress and, therefore, provide more restraint regardless of shrinkage of the cement paste.

The cementitious materials used for different repair applications can be categorized on the basis of constituent materials as superplasicized, latex modified and fiber reinforced concrete and mortar. Based on the construction technique employed, the cementitious repair material can be categorized as dry pack, preplaced aggregate, low-strength, and vacuum-dewatered concrete and mortar, or shotcrete. Brief description for these alternative repair cementitious material are given below in order to provide a basis for the comparison of latex modified carbon fiber reinforced cement with other alternatives in the selection of repair materials for specific jobs.

8.3.1 Superplasticizers:

The use of superplasticizers in concrete permits 20% to 30% less water in a given concrete mixture without any loss in the plasticity or workability. Because of the significantly lower amount of water required for a given mix, reduction in cement content of 10% to 15% is possible without any loss in strength because of large reduction in required mixed water the drying shrinkage is reduced.

8.3.2 Latex Modification:

Latex composition can be added to any cementitious mixture. The addition of such compounds can promote many desirable properties, including low permeability and high bond strength. Latex modified compositions require special mixing and handling, and this special equipment and knowledge are required in their use, except in the case of small patches. As they have the advantage of repairing only one day of wet during they are particularly well suited for use where many small patches are required over a large expense of relatively inaccessible areas, such as on the walls of high rise building.

8.3.3 Fiber Reinforcement:

Inclusion of some fibers in concrete limits shrinkage and thus provides for improved bond. Fiber reinforcing also leads to substantial improvement in ductility. A variety of fibers are in common usage including fibers made from glass, plastic, steel, and carbon. The extent of fiber reinforced concrete use in repair application is expanding rapidly in spite of the fact that more information on the actual field behavior of some fibers materials are needed.

The principal limitation in the use of cementitious composition with water contents sufficiently low to preclude damaging shrinkage is the inability to compound such mixture with enough plasticity and workability to provide for proper placement. Thus, a number of construction techniques have been developed which enable placement of such compositions regardless of their lack of plasticity. In addition, there are methods available to reduce shrinkage thru removal of some of the mixed water immediately upon placement of the composition and prior to its initial set.

8.3.4 Drypack Mortar or Concrete:

Drypack mortar or concrete are compositions possessing the same constituents as regular concrete or mortar except that the water content has been reduced to the minimum quantity required to provide a cohesive mass when compressed or rammed into

place thus, while drypack materials can not be placed utilizing normal procedures, they do have a near optimum water content for sufficient hydration and are virtually shrinkage free. They are usually hand placed in small amounts at any given time, being tamped or rammed into place to the maximum obtainable density because such placing requirements are labor intensive, the procedure is not economical for large walls; however, it is well suited for small patches of repairs in remote locations, or in areas where inexpensive labor is available. Also, since such work does not require extensive use of skilled labor, it is particularly applicable for use in area where skilled labor is lacking and available laborer is relatively inexpensive. Because minimum water is required repairs made with drypack compositions are stable and durable.

8.3.5 Preplaced Aggregate Concrete:

Preplaced aggregate concrete is coast by pumping mortar into the pore spaces of previously placed large aggregate. There is virtually no limitation to the maximum size of aggregate although the minimum size is usually in the order of 3/8 inch (10 mm). The intrusion mortars most commonly used are composed of portland cement, fine sand (minus No. 8 mesh), and an expansion promoting additive. Because each piece of large aggregate in preplaced aggregate concrete is in intimate contact with the adjoint piece, and the introduced mortar expands after preplacement. The material is to some degree self stressing and thus provides high bond strength. It is, therefore, well suited for repair and restoration type work, especially where access is difficult or an unusually large congestions of reinforcing or other inserts exists.

8.3.6 Low-Slump Concrete:

Where very low-slum compositions are to be used for reducing the voter content special consideration must be directed to the placing and consolidation methods. For structural application the use of external vibration is a frequent expedient. Where, low-slump concrete for slabs or other flat work mechanical placing equipment and vibrating should enable efficient placement of essentially zero-slump materials.

8.3.7 Vacuum-Dewstered Concrete:

Although not frequently used in structural application, vacuum water removal is fairly well established method of removing surplus water from normal concrete, prior to their initial set. In practice, immediately following normal placing of the concrete, special filter pads are placed over the area to be treated. A suction mat is then placed over the filter pad and the edges are completely sealed. A vacuum is then created and the mats thru

use of a suction pump connected to the mat with a hose. The process can be applied to vertical and other formed surface by adoption of the filter and suction pads as reprinted and their subsequent placement in the forms prior to concrete placing. The use of vacuum- dewatering has been limited, but it has been proven practical in actual applications and is worthy of consideration in repair and retrofit work.

8.3.8 Drymix Shotcrete:

Drymix shotcrete process involving premixing of the cement and sand and transfer to the work site thru a hose in a stream of compressed air. The end of the hose is equipped with a suitable nozzle at which point water is injected and mixed with the material as it exits at high velocity. The water content can be adjusted at the nozzle and is restricted to approximately that reprinted for proper hydration of the cement. Because shrinkage is virtually eliminated due to the low water content together with the high impact force at which it is applied, properly installed drymix shotcrete possesses very high bond strength. The process is particularly suited to restoration work as the material is transported to the work site thru hose making its placement virtually unlimited by access construction.

8.4 SUMMARY AND CONCLUSION:

Selection of appropriate materials is an absolute requirement for obtaining durable repairs. To match properties of the base concrete as closely as possible, portland cement concrete or similar cementitious compositions are frequently, but not always, the best choice for the repair materials. Such factor as restricted work condition, requirements for rapid strength gain, needed improvements in resisting to chemical attack or the need to achieve aesthetically pleasing surfaces often mandate the use of other materials. A variety of different methods, relating to design of specific mixture, as well as placing techniques are available to offset deleterious effects of shrinkage and the consequent lack of bond normally experienced with cementitious materials. Shrinkage of new cementitious mixtures can be minimized thru careful proportion of individual mix constituents, and use of least amount of water in the mixture. Water reduction can be facilitated thru the use of superplasticizer. Composition shrinkage characteristics and bond capacity can be improved through fiber reinforcement or the inclusion of latex modifiers. Shrinkage of the final composition can be minimized or completely eliminated by use of drypack mortar or concrete, preplaced aggregate concrete, or drymix shotcrete. Low-slump concrete can be used with appropriate application consideration and surplus water can be removed

from any cementitious composition prior to initial set by means of vacuum water removal. The latex modified carbon fiber reinforced cement developed in this investigation as a new repair material should be carefully evaluated against the alternative repair material in order to make the proper selection of material for satisfying the requirements of a specific repair job, noting that almost every repair job has unique conditions and special requirements have been thoroughly examined can the final repair criteria be established. Once the repair criteria are known it will often be found that more than one material can be used with equally good results. Final selection of the material or combination of materials must then take into account the ease of application, cost, and available labor skills and equipment. In general, when choosing repair material the true repair professional considers three things: the conditions of the repair, the property of the repair materials, and the skill and equipment needed to do the job (Ref. 31).

CHAPTER 9

SUMMARY AND CONCLUSIONS

9.1 GENERAL

The results of a comprehensive study aimed at the development of latex modified carbon fiber reinforced cement for repair applications are described. A brief background has been presented on the mechanisms of action of carbon fibers and latex polymers in cement-based materials. Typical improvements in the performance characteristics of cement resulting from either latex modification or carbon fiber reinforcement are discussed. The potentials for joint action of latex polymers and carbon fibers in cementitious materials are introduced, and their potentials are evaluated using the test data generated in this investigation.

9.2 PRELIMINARY SELECTION OF MIX COMPOSITION AND LATEX TYPE

The results of an experimental study for a preliminary optimization of latex modified CFRC mixtures are presented. The matrix mix constituents and proportions, the latex type, and the manufacturing procedures are selected based on the results of this preliminary investigation. The experimental study was performed in two phases. First, the matrix mix proportions were decided by a trial and adjustment procedure based on strength test results, and then, for constant mix proportions, the effects of different latex types on the performance characteristics of CFRC composites were assessed, and two latex polymers were selected for use in future phases of the study. The following conclusions were derived from the experimental data generated in this part of study:

(a) polymer latexes increase the air content in cement-based materials. An anti-foaming agent should be used to control the air content in latex modified CFRC.

(b) the increase in latex content of CFRC composites results in an increase in the water-binder ratio required for maintaining workability at acceptable levels;

(c) fly ash has relatively small effects on the performance of latex- modified CFRC composites;

(d) based on the trends observed in the effects of matrix constituents on the composite material performance, the following proportions were selected for latex modified CFRC composites: silica fume/binder = 0.2 superplasticizer/binder = 0.032 set retarder/ binder = 0.005 antifoam/binder = 0.015 grade 40 silica sand (volume fraction) = 25% carbon fiber (volume fraction) = 3% carbon fiber length = 1.5 mm. (1/16 in.) water-binder ratio = 0.37 at a latex-binder ratio of 0.1, and increasing or decreasing with increasing or decreasing latex-binder ratio:

(e) the mixing procedure selected for the manufacture of latex modified CFRC consisted of: - preparation of a dispersant mixture without latex (consisting of silica fume and a fraction of water and chemical admixtures) in which the carbon fibers were dispersed; - the silica sand, remainder of the water and chemical admixtures, and latex were then added and mixed until a uniform mixture was achieved; - the process was concluded with the addition of cement and some

further mixing at higher speeds, and all the specimens prepared in this phase of study were dry-cured;

(f) - a number of different latex types were observed to perform favorably in CFRC composites; among these, two styrene butadiene latexes manufactured by Dow Chemical and BASF were selected for use in the remainder of this study;

(g) - the removal of set retarder together with the use of finer aggregates were found to substantially enhance the strength characteristics of latex modified CFRC composites.

9.3 MIX OPTIMIZATION AND PHYSICAL CHARACTERIZATION

An adjustment of the latex-modified carbon fiber reinforced cement mix composition was evaluated in this phase of the study; the set retarder was removed from the mix, and the maximum particle size of silica sand was reduced.

A comprehensive experimental characterization of the adjusted latex- modified carbon-reinforced cement was conducted in order to investigate the effects of adjustments in mix proportions, and to assess different aspects of the performance characteristics of adjusted latex-modified carbon fiber reinforced cement composites. The two latexes used in this phase of research were both Styrene Butadiene: Type A (produced by BASF) and Type B (produced by Dow Chemical).

The latex contents used in this experimental program were 0% and 10%. The curing procedures were: air curing, wet curing (in water after a short period of air curing), and moist curing (in moist environment after a short period of air curing). The following tests were performed:

- fresh mix air content
- fresh mix flow ? time of setting
- compressive strength and stress-strain performance
- flexural strength and load-deflection performance
- specific gravity
- water absorption
- drying shrinkage

From the test results it could be concluded that:

(a) The initial and final times of setting of carbon fiber reinforced cement tend to increase due to the incorporation of polymer latex.

(b) An increase in the flexural and compressive ductility and toughness of the material was observed in the presence of polymer latex.

(c) The flexural and compressive stiffness and strength of carbon fiber reinforced cement tends to be reduced as a result of latex modification.

(d) Latex-modified and unmodified carbon fiber reinforced cements have comparable impact strengths.

(e) Important reductions in drying

shrinkage of carbon fiber reinforced cement can be obtained through latex modification. The improved ductility and strain resistance, together with the reduced free shrinkage, have important implications in reducing the generally troublesome shrinkage cracking of cement-based materials.

(f) Latex modification leads to reduced water absorption in carbon fiber reinforced cement.

(g) The adjustments made in the mix proportions of CFRC, involving the removal of set retarder and use of finer aggregates, had positive effects on the physical performance of the material.

9.4 FREEZE-THAW DURABILITY

Reviews of the mechanisms of freeze-thaw deterioration, the freeze- thaw test methods, and the key factors influencing the freeze-thaw durability of concrete are presented. The test results reported in the literature regarding the effects of latex modification and fiber reinforcement on the freeze-thaw resistance of cementitious materials are also summarized.

The results of an experimental study on the freeze-thaw durability of carbon fiber reinforced cements, with and without latex polymers, is presented. All the materials considered in this experimental study incorporated 3% volume fraction of 1/16 in. (1.5 mm) carbon fibers. The latex-modified materials had 10% latex/binder ratios (latex Types A and B were used, see Table 1.2). Table 1.3 in Chapter 1 presents the mix proportion of the unmodified and latex modified carbon fiber reinforced cements. The freeze-thaw test was performed according to procedure B (both freezing and thawing in wet environment) of ASTM C-666. The freeze-thaw damage in specimens was quantified through the measurement of the dynamic modulus of elasticity and the weight loss after different number of freeze-thaw cycles. The freeze-thaw tests started when the specimens were 14 days old. The following conclusions were derived from the freeze-thaw test results:

(a) Carbon fiber reinforced cement performs desirably under freeze-thaw cycles. Latex modification generally improves the freeze-thaw durability of carbon fiber reinforced cement.

(b) Latex modifies the pore system characteristics of carbon fiber reinforced cement, thus reducing the interconnection between pores. This reduces water permeation into the material, a factor which potentially reduce internal damage associated with ice formation under frost action. Increased tensile strain and stress capacity of cementitious materials resulting from both latex modification and carbon fiber-reinforcement can also be used to illustrate the desirable freeze-thaw durability of latex- modified carbon fiber reinforced cement; and

(c) Weight loss measurements seem to overestimate the freeze-thaw durability of fiber reinforced cement composites. Although a certain level o surface damage was observed in carbon fiber reinforced cement specimens, the loose parts on the surface were tied to specimens by the fibers, an thus the measured weights included the spalled segments which could hardly contribute to the strength of the material.

9.5 RESISTANCE TO ACID ATTACK AND HOT-HUMID ENVIRONMENT

In certain exposure conditions cementitious materials are subjected to acid attack or long-term effect of hot-humid environments. The effects of latex modification on these aspects of the durability characteristics of carbon fiber reinforced cement were assessed experimentally.

The acid resistance tests involved immersion of 2 in. (51 mm) cube specimens in 5% Hcl solution. Weight loss, erosion depth and loss in compressive strength were used as measures of acid attack.

Latex modification was observed to reduce the weight loss and erosion depth of carbon fiber reinforced cement by about 50%. The overall effects of latex modification on the loss of compressive strength under acid attack were relatively small.

Extended immersion in hot water led to an increase in flexural strength together with a decrease in flexural toughness of carbon fiber reinforced cement. Latex modification reduced the loss in flexural toughness of carbon fiber reinforced cement under hot water exposure.

9.6 REPAIR TECHNIQUES

The application methodology of a repair material is one of the factors deciding final material properties. Laboratory tests on cementitious materials are generally performed using specimens constructed by molding (casting and external vibration) of premixed materials. The actual repair of deteriorated concrete surfaces, however, involves the application of cementitious materials by the troweling and spraying methodologies.

This phase of the study was concerned with the effects of the troweling and spraying versus molding application techniques on the performance characteristics of latex modified carbon fiber reinforced cement. The materials used all had similar mix proportions (the optimum ones decided earlier), and were all premixed in a mortar mixer.

The effects of the application methodology on the flexural performance, specific gravity, and water absorption of latex modified carbon fiber reinforced cement were assessed through tests on similarly premixed materials which were either molded, troweled, or sprayed. The following conclusions were derived from the generated test results:

(a) the flexural strength of latex modified carbon fiber reinforced cement was highest for troweled materials, followed by the sprayed and molded materials;

(b) the troweling and spraying application techniques produced composites with lower toughness when compared with the molding application method;

(c) the specific gravity of latex modified carbon fiber reinforced cement was comparable for molded, troweled, and sprayed materials; and

(d) the water absorption capacity of the molded and sprayed composites were comparable; the results for the water absorption capacity of the troweled composite were not conclusive.

One may conclude from the results of this phase of the study that the actual field repair application techniques may positively or negatively influence the final repair material properties. These effects should be considered in the selection of materials and methodologies for repair projects.

9.7 SELECTION OF REPAIR MATERIALS

Selection of appropriate materials is an absolute requirement for obtaining durable repairs. To match properties of the base concrete as closely a possible, portland cement concretes of similar cementitious composition are frequently, but not always, the best choice for concrete repair materials. Such factors as restricted work conditions, requirements for rapid strength gain, needed improvements in resisting to chemical attacks, or the need to achieve aesthetically pleasing surfaces often mandate the use of other materials.

A variety of different methods are available to offset deleterious effects of shrinkage and the consequent lack of bond normally experienced with cementitious materials. These methods relate to the design of mixture or placing technique. Shrinkage of new cementitious mixtures can be minimized through careful proportioning of individual mix constituents, and use of the least practical amount of water in the mixture. Water reduction can be facilitated through the use of superplasticizers. The shrinkage characteristics and bond capacity of the material can be improved through fiber reinforcement or the inclusion of latex modifiers. Shrinkage of the final composition can be minimized or completely eliminated by use of drypack mortar or concrete, preplaced aggregate concrete, or drymix

shotcrete. Low-slump concrete can be used with appropriate application techniques and surplus water can be removed from any cementitious techniques, prior to initial set by means of vacuum water removal.

The latex modified carbon fiber reinforced cement developed as a new repair material in this investigation should be carefully evaluated against the alternative repair materials for satisfying the requirements of a specific repair job, noting that almost every repair job has unique conditions, and special requirements. Only after these requirements have been thoroughly examined can the final repair criteria be established.

Once the repair criteria are known it will often be found that more than one material can be used with equally good results. Final selection of the material or combinations of materials must then take into account the ease of application, cost, and available labor skills and equipment. In general, when choosing repair materials, the repair professional should consider three things: the conditions of the repair, the property of the repair materials, and the skill and equipment needed to do the job.

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