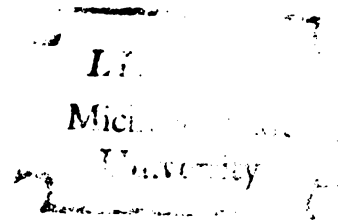


MECHANICAL STRENGTH AND DAMAGE
ANALYSIS OF NAVY BEANS

Thesis for the Degree of Ph. D.
MICHIGAN STATE UNIVERSITY
MAKOTO O. HOKI
1973



This is to certify that the
thesis entitled
MECHANICAL STRENGTH AND DAMAGE
ANALYSIS OF NAVY BEANS

presented by

MAKOTO O. HOKI

has been accepted towards fulfillment
of the requirements for

Ph.D degree in Agricultural
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Leroy H. Pickett
Major professor

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ABSTRACT

Mechanical Strength and Damage Analysis of Navy Beans

by

Makoto O. Hoki

Studies were conducted to evaluate those properties of the navy bean which are associated with its strength and mechanical damage. Basic mechanical properties of navy beans measured under quasi-static loading were utilized in an analysis of the mechanical behavior of beans under quasi-static loading and for prediction of mechanical damage under impact loading. Young's modulus and ultimate strength were separately determined for the seed coat and the cotyledons, the two principal components of the bean. Force-deformation measurements for quasi-static loading were made for bean moistures from 10 percent to 19 percent (wet basis) under conditions of equilibrium relative humidity and room temperature. Young's modulus and ultimate strength of the seed coat were determined from tensile tests of narrow specimens cut from the seed coat. Results from force-deformation tests of rings cut from the seed coat near the center of the bean were used to verify the values obtained for Young's modulus from the tensile tests. Young's modulus and ultimate strength of the cotyledon were determined from tests on small specimens of rectangular cross-section. Deformation of the whole bean was calculated for compressive loading by using the contact theory and

the measured material constants. The results of whole bean compression tests were used to compare with the predicted deformation.

The contact theory incorporated with the impact theory was used to predict damage from impact loading by using measured values of Young's modulus and ultimate strength. Whole bean impact tests at velocities of 2000 fpm and 3000 fpm were conducted for beans with specific moisture contents and compared with the results of theoretical predictions.

Theoretical analysis using the contact theory shows promise for prediction of mechanical damage to navy beans. By knowing the loading conditions and the physical properties of navy beans it was possible to predict when mechanical damage is to be expected.

Approved: Leroy K. Pickett
Major Professor

Approved: D.R. Heldman 2/7/73
Department Chairman

MECHANICAL STRENGTH AND DAMAGE ANALYSIS OF
NAVY BEANS

By

MAKOTO O. HOKI

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TABLE OF CONTENTS

	Page
LIST OF TABLES	vi
LIST OF FIGURES	vii
Chapter	
I. INTRODUCTION	1
1.1 Current Problems in Bean Production	1
1.2 Objective and Thesis Problem	2
II. REVIEW OF LITERATURE	3
2.1 Seed and Grain Damage	3
2.2 Mechanical Properties of Beans	4
2.3 Measurements of Mechanical Properties of Biological Materials	7
2.4 Structural Characteristics of Navy Beans	9
III. THEORETICAL CONSIDERATIONS	11
3.1 Strain Energy in Bending	11
3.2 Bending of Thin Plate	13
3.3 Thin Wide Ring with Rigid Section	16
3.4 Contact Theory	20
3.5 Assumptions for the Contact Theory	21
3.6 Impact of a Sphere with a Flat Surface	22
3.7 Maximum Shear Stress of Sphere	25
IV. APPARATUS	28
4.1 Seed Coat Tension Tests	28
4.2 Cotyledon Specimen Compression Tests	28
4.3 Seed Coat Ring Tests	28
4.4 Whole Bean Compression Tests	32
4.5 Whole Bean Impact Tests	32

Chapter	Page
V. METHOD AND PROCEDURE	36
5.1 Sample Preparation	37
5.1.1 Specimens for seed coat tests	37
5.1.2 Specimens for cotyledon tests	39
5.2 Seed Coat Tension Tests	39
5.3 Cotyledon Specimen Compression Tests	39
5.4 Seed Coat Ring Tests	40
5.5 Whole Bean Compression Tests	40
5.6 Whole Bean Impact Tests	40
VI. RESULTS AND DISCUSSION	42
6.1 Homogeneity and Isotropy	42
6.2 Equilibrium Moisture for Seed Coat and Cotyledon	43
6.3 Dimension and Weight Change of Beans	43
6.4 Bean Seed Coat Strength	45
6.5 Seed Coat Ring Compression Tests	47
6.6 Bean Cotyledon Compressive Strength	50
6.7 Evaluation of the Assumptions for Contact Theory	55
6.8 Whole Bean Compression	57
6.9 Whole Bean Damage Analysis During Impact	60
6.10 Summary of Results	65
VII. CONCLUSIONS AND RECOMMENDATIONS	67
REFERENCES	70
APPENDICES	74

LIST OF TABLES

Table	Page
A.1 Young's modulus and ultimate strength of seed coat for two different cuts under moisture content of 16.2 percent.	75
A.2 Relative change of bean dimensions and weight for medium beans with hours of natural drying under room temperature.	76
A.3 Radii of curvatures of the two sides of medium beans.	77
A.4 Mechanical strength of bean seed coat at various moisture contents	78
A.5 Mechanical strength of bean cotyledon at various moisture contents	79
A.6 Young's modulus of bean seed coat calculated from thin ring theory	80
A.7 Calculations of internal maximum shear stress of the cotyledon and maximum shear stress on the seed coat at 2000 fpm	81
A.8 Calculations of internal maximum shear stress of cotyledon and maximum shear stress on the seed coat at 3000 fpm	82
A.9 Calculations of maximum shear stresses on the bean seed coat	83

LIST OF FIGURES

Figure	Page
2.1 Navy bean structure.	10
3.1 Bending of a bean.	14
3.2 Bending of a thin plate.	14
3.3 Thin wide ring with rigid section.	17
3.4 Impact of a sphere against a flat surface.	23
3.5 Stress components below the surface as a function of the maximum pressure for contacting bodies.	26
4.1 Instron University Testing Machine with the chamber connected to Aminco-Aire unit.	29
4.2 Seed coat strip clamped for tension test.	30
4.3 Rectangular cotyledon specimen (left) and seed coat ring specimen (right).	31
4.4 Rectangular cotyledon specimen under compression test.	31
4.5 Loading device for seed coat ring.	33
4.6 Seed coat ring under compression test.	33
4.7 Whole bean under compression test (side loading).	34
4.8 Bean holding disk and tip on impact disc.	34
5.1 Beans imbedded in plastic.	38
5.2 Parallel one side blades used for making cotyledon specimens (from left 0.232 inches, 0.074 inches and 0.052 inches apart respectively).	38
6.1 Equilibrium moisture content of seed coat and cotyledon.	44

Figure		Page
6.2	Effect of moisture content on Young's modulus of seed coat.	46
6.3	Effect of moisture content on the ultimate strength of seed coat.	48
6.4	Young's modulus of seed coat calculated by using thin ring theory	49
6.5	Typical stress-strain curves for cotyledon. .	51
6.6	Effect of moisture content on the Young's modulus of cotyledon.	52
6.7	Effect of moisture content on the ultimate strength of cotyledon.	53
6.8	Force-deformation curve for the whole bean at low moisture content (11.6%).	58
6.9	Force-deformation curve for the whole bean at high moisture content (18.8%).	59
6.10	Seed coat shear strength and damage for impact loading	62
6.11	Cotyledon shear strength and damage for impact loading.	63

I. INTRODUCTION

1.1 Current Problems in Bean Production

Among the bean growing states in the United States, Michigan has been a leading producer of beans. More than one-third of 173,850,000 cwt of edible dry beans produced in 1970 in the United States were grown in Michigan (United States Department of Agriculture, 1971). Beans produced in Michigan have a large domestic market and an increasing international market. From 15 to 20 percent of the total production is exported to more than 25 countries in the world. Mechanized harvesting and handling has made great contributions to the efficient bean production, promising more profit to the growers, processors and canning industries. The mechanically harvested or handled beans, however, receive increased damage which is at least partly due to impact loading. Recently Judah (1970) reported that up to 13 percent of the beans were damaged by the time they reached the combine bin. Several other studies on mechanical damage of beans during threshing and handling have been reported (Dorrell, 1968, Fiscus, et al., 1971, and Green, et al., 1966).

Beans initially damaged during harvest are likely to be more susceptible to damage from subsequent handling and processing. Mechanically damaged beans, including those which are split or have seed coat checks, are of less commercial value because of reduced canning and cooking quality. Mechanical damage not only affects market value of the bean but also impairs germination vigor.

Recent increases in bean export have increased the chances of mechanical damage before they reach the consumers. Export beans are subjected to an increased number of impacts because of increased mechanical handling. Also with more handling and shipping during winter, damage to the beans is increased because of low temperature (Hoki and Pickett, 1972).

Increased concern has been shown by bean growers, processors, and shippers, to minimize the mechanical damage to beans caused by impact loading during harvesting and handling.

1.2 Objective and Thesis Problem

The primary objective of this study was to make theoretical and experimental analysis of mechanical damage to navy beans. The study was undertaken to theoretically determine the stress in the bean resulting in damage under specific impact velocities. It was necessary to obtain data on the mechanical properties of beans which depended upon moisture content, and other parameters such as weight, dimensional factors and temperature.

Specific objectives of the thesis were:

1. To measure seed coat strength and cotyledon strength using uniform specimens cut from beans.
2. To formulate the theory for predicting mechanical damage to navy beans.
3. To evaluate the applicability of the formulated theory for predicting seed coat checks and bean splits under specific moisture content and impact seed.

II. REVIEW OF LITERATURE

2.1 Seed and Grain Damage

Numerous studies have been conducted on the damage analysis of various seeds and grains. They are mostly experimental studies applicable to specific seed and grain handling. King and Riddolls (1960 and 1962) studied the relationship between damage, threshing drum speed, and concave clearance, using wheat and pea seeds. They pointed out that wheat and pea seed damage could be kept to low levels by avoiding high drum speed even at fairly low moisture contents, but concave clearance had a minor effect. Similar results on mechanical damage of wheat during threshing was reported by Kolganov (1958). He concluded that the main cause of grain damage during harvesting was the severe threshing process. Arnold (1964) and Arnold and Lake (1964), who studied damage to wheat and barley, concluded that the threshing done by severely impacting the crop caused most damage.

More specific studies on the relation between impact velocity, orientation, energy absorption, and seed damage were made by several researchers. Turner et al. (1967) pointed out that the impact velocity required to damage peanuts depended upon the moisture content and orientation. He found that the coefficient of restitution was different depending on the orientation. Bilanski (1966) found that the energy required to damage soybeans, corn, wheat, barley and oats under low and high velocity impact loads was different depending on the

orientation. He also pointed out that more energy was required to cause grain damage under high moisture contents. Clark et al. (1967) investigated the effect of high velocity impact on cotton seed damage while controlling seed orientation. He found that the maximum impact velocity was 5000 fpm to maintain at least 80 percent germination. Fiscus et al. (1971) investigated mechanical damage to wheat, soybeans and corn, in bucket elevators, grain throwers, free fall impacts and spouting drops. He found that dropping grain from heights greater than 40 ft. caused more damage than any other handling method tested. Impact of the grain on concrete caused more breakage than grain on grain. The breakage was greater at low grain moistures and temperatures.

2.2 Mechanical Properties of Beans

Not much work has been reported on mechanical properties of beans which is applicable to damage analysis. Likely this is in part due to the difficulty of measuring the strength of the small bean seeds experimentally or dealing with the discontinuities between cotyledons analytically. The earliest work on the mechanical properties of beans was undertaken by Brown (1955). He measured the force required to crack navy beans having 6.9 percent to 9.2 percent moisture content. Forces required to crack beans, when loaded across the flat side using a quasi-static loading device, varied from 11 to 42 pounds. Forces of 2 to 45 pounds were required to crack similar beans loaded across the edges.

Experimental evaluation of navy bean damage due to impact was conducted by Solorio (1959). He used a rotary paddle wheel to impact individual beans being dropped into its path and examined visible

damage consisting of seed coat checks and splits. He found 7.2 percent visible damage for beans with 15.5 percent moisture and 70.3 percent damage for those with 9.7 percent moisture. No attempt was made to control bean orientation.

Perry (1959) conducted two types of impact tests to analyze damage to navy beans. In one set of tests, he utilized a bean dropping system to determine the damage to beans dropped through three heights; 11.25 ft., 22.5 ft., and 45 ft. He found that damage, consisting of splits and seed coat checks, was about proportional to height of drop. Damage was reduced considerably for higher moisture content and higher temperature. In the other tests he impacted oriented beans individually with a wooden-faced bar. The beans were restricted by a small movable wooden block at the opposite side of impact. Impact velocities varying from 29.2 to 34.4 fps did not cause damage unless the beans were restricted at the other end. A high speed movie camera was used to determine velocities, deformations and time of impact. Values for maximum impact force and kinetic energy dissipation during impact were calculated. Deformation was found to be largely elastic under the impact loadings.

Zoerb's (1958) work on navy beans included measuring static and time-dependent rheological properties. He obtained load-deformation curves for beans with 10.6 and 18.5 percent moisture (d.b.) using a 0.267 ipm loading velocity. Using bean core specimens at 6.4 percent moisture (d.b.) he obtained stress-strain curves to evaluate maximum strength and modulus of elasticity. Shear strength was measured by punch tests on thin bean slabs at four moisture contents. A pendulum

impact test was used to measure energy required for impact shear to compare with static shear tests. From measurements of time dependent characteristics he found that the behavior of navy beans could be represented by two parallel Maxwell units.

Narayan (1969) used column stability theory to compute the stability modulus and elastic modulus of navy beans under quasi-static loading. The moisture was varied from 11.5 to 28.2 percent. He found that varying loading velocity between 0.2 ipm and 0.05 ipm for quasi-static tests had little effect on measured strength. Two types of impact tests were conducted; low velocity impact by a falling weight and high velocity impact by a rotating arm. Impact forces required to cause checking were measured and impact energies were computed. A comparison was made of the energy measured for the two types of impact tests. He found that the optimum moisture content range for minimum checking of seed coats was 13.4 to 15.6 percent.

The research results reported are not directly applicable for use in an analytical approach to the bean damage problem. Reasons for this can be summarized as follows:

1. The difference in strength between the cotyledons and the seed coat was not considered in most tests and analysis.
2. The material constants obtained were only for particular moisture contents or test conditions and were not generally appropriate for theoretical analysis.

No attempt has been made to theoretically analyze the stress conditions in beans during impact. Also no attempt has been made to use experimentally measured mechanical properties for predicting the damage to beans for specific moisture and loading conditions.

2.3 Measurements of Mechanical Properties of Biological Materials

Many types of measuring techniques have been developed for specific agricultural products. However, structural complexity and variation in product size and shape have made it very difficult to use uniform test techniques. Therefore no standardized method has been established for agricultural products.

The measuring techniques which have been used can be divided into quasi-static and dynamic methods. The quasi-static methods used commonly for determining basic mechanical properties are compression and tension tests. Uniaxial compression tests of cylindrical specimens have been conducted for grains by Zoerb (1960), apples by Mohsenin et al. (1963), and white potatoes by Finney et al. (1967). Very few tension tests have been made because of difficulties in tightly gripping the ends of the specimen without breaking the tissues. Huff (1967) obtained data on tensile stress-strain properties of potato skin to analyze the cracking mechanism of potatoes during handling. He used rectangular specimens with a reduced middle section. Tension tests of corn were made by Mammerle (1968) for rectangular specimens of the horny endosperm at various moisture contents.

Most dynamic tests have been employed for the practical purpose of determining mechanical damage rather than determining mechanical properties of products. Therefore impact forces were usually applied to the whole products. Dynamic tests may be classified according to impact method as free dropping, pendulum, falling weight, and rotating arm. The free dropping method was employed by Perry (1959). This method does not permit control of the orientation of seed and high velocities are hard to obtain. Bilanski (1966) and Mohsenin and

Gohlich (1962) used a swinging pendulum device. With this method it was difficult to obtain high impact velocity, consequently a resistance block was required on the other side of seed to give enough force to damage seeds. The falling weight method was employed by Narayan (1969). With this method a drop weight was used to apply impact to an oriented navy bean seed. Neither the pendulum method nor the falling weight method simulates free impacts during threshing or handling. Also maximum impact velocity is limited to low values for each method. The limited applicability of the above three methods led to the development of high velocity impact devices driven by variable speed motors. Rotating arm methods, employed by Mitchell and Rounthwaite (1964) and Bilanski (1966) were designed to provide controlled high velocity impact to the seeds but the orientation of seeds was not controlled. Clark (1967) combined a rotating arm method with a vacuum seed holding device to have desired seed orientation. Burkhardt and Stout (1969) developed an impact arm with force transducer which made just one revolution to accelerate the arm up to a desired impact velocity before hitting an oriented sample and stopped by electro-magnetic brake within one and a half revolutions after impacting. With the use of an oscilloscope, this system was able to measure the impact force. Hoki and Pickett (1972) developed a high speed impact tester which consisted of a rotating impact disk and vacuum bean holding disk. The tester permits continuous operation for large numbers of beans. It was used to evaluate mechanical damage at various impact velocities and moisture contents.

2.4 Structural Characteristics of the Navy Bean

Some structural details of navy beans must be understood for analyzing the damage process and for making appropriate assumptions necessary for the application of elastic theory.

A navy bean seed is nearly ellipsoidal in shape with an average size bean approximately 0.31 inches long, 0.20 inches wide and 0.23 inches high, Figure 2.1. The bean consists of two cotyledons of semi-ellipsoidal shape enclosed in a thin seed coat of about 0.003 inches thick. Details of the bean structure are described by Esau (1953). The section in the plane perpendicular to the long axis, A-A in Figure 2.1a, is shown in Figure 2.1b. The two palisade layers occur in the hilum region. The outer of these is derived from the funiculus and the inner is extended from the epidermis. The hilum region, therefore, becomes thick and rigid. The thick region developed at the hilum is extended to the seed coat region gradually decreasing the thickness. The seed coat thickness decreases until a point about 30 degrees from the vertical plane B-B (Figure 2.1b) between the two cotyledons. The cotyledon tissue is made of various sizes of polygonal cells arranged randomly (Powrie et al., 1960).

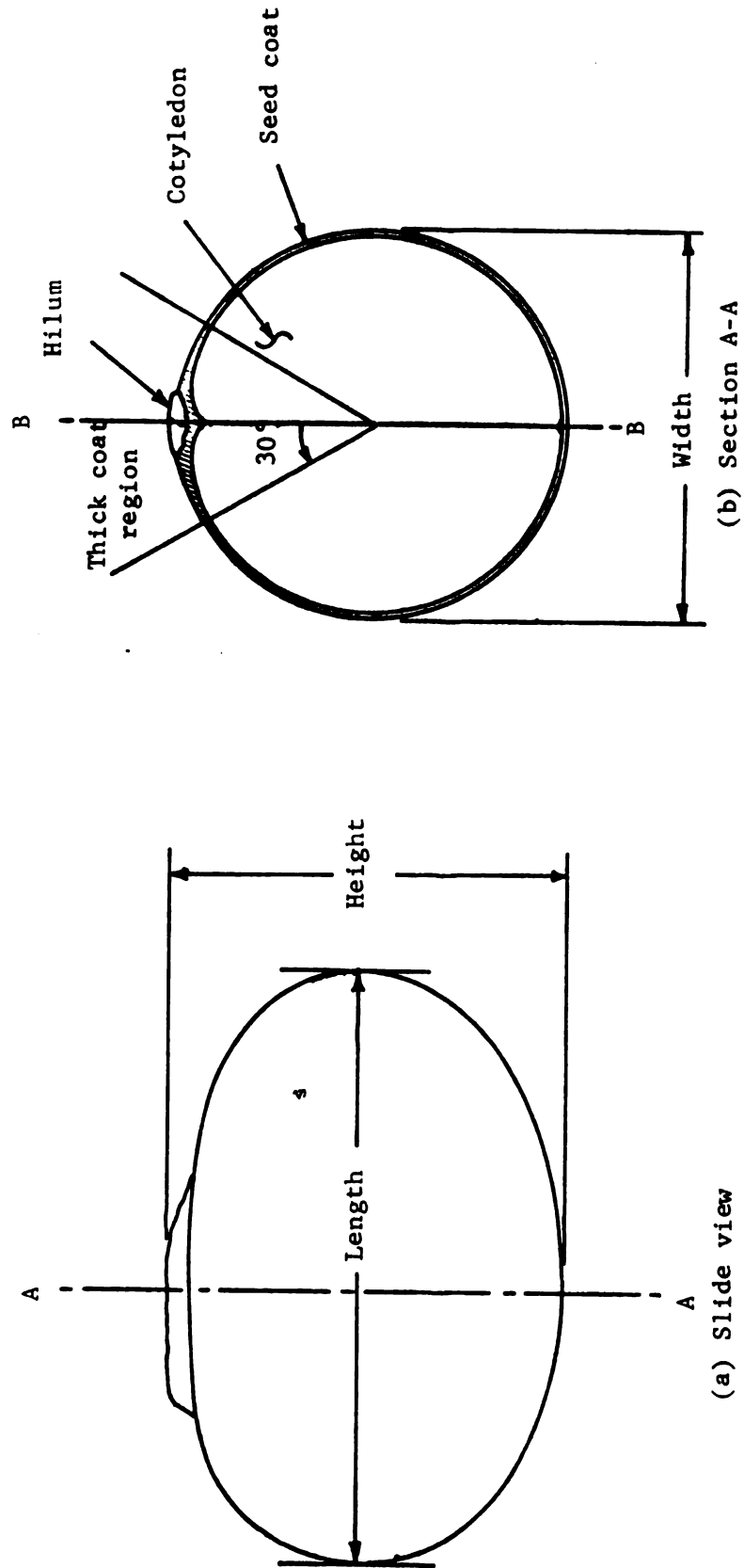


Figure 2.1 Navy bean structure.

III. THEORETICAL CONSIDERATIONS

For a long time mechanics of deformable solids has been based upon linear elasticity. However the behavior of most materials including metal, concrete, and biological products are not linearly elastic, except within specified limitations. Nevertheless, most stress analysis is still based on linear elasticity because of its simplicity and practical applicability.

Basically this approach was used in the present study. The analysis of the bean seed coat strength was based upon the thin ring theory derived using the strain energy theorem. For the analysis of deformation of the whole bean, Hertz's contact theory was applied. The contact theory was extended to predict maximum force and maximum shear stress acting on the bean during impact. Because of reduced complexity and small differences in calculated results, the contact theory for a sphere rather than an ellipsoid was used to represent the bean for impact loading by a flat surface. The calculated maximum shear stress is increased by only 3 percent by using ellipsoidal contact theory for the case when the minor radius to major radius ratio is 0.34 (Timoshenko and Goodier, 1951).

3.1 Strain Energy in Bending

When an elastic body is deformed by the action of external forces, work is done by these forces. The work done in straining such a body is regarded as energy stored in the body and is called the strain energy. The strain energy theory is discussed in any strength of

materials textbook (Timoshenko and Young, 1965). A summary of the strain energy concepts is presented here for the succeeding discussion of thin wide ring theory to be used for bean seed coat strength evaluation.

Elastic materials obey Hooke's law within the elastic limits. In the case of pure bending of a prismatic bar in a principal plane (Figure 3.1a) the angle θ of rotation of one end with respect to the other is proportional to the bending moment M (Figure 3.1b). Hence, the strain energy of bending, equal to the total work produced by the moment M , is

$$U = \frac{M\theta}{2} \quad (3.1)$$

Using for θ the known formula

$$\theta = \frac{M\ell}{EI} \quad (3.2)$$

in which ℓ is the length of the beam and EI is flexural rigidity, the strain energy may be represented in either of the following two forms:

$$U = \frac{M^2 \ell}{2EI} \quad (3.3)$$

or

$$U = \frac{\theta^2 EI}{2\ell} \quad (3.4)$$

The strain energy may be presented either as a function of the acting forces, in this case the bending moment M , or as a function of the quantity θ defining the deformation. In the case of a prismatic beam subjected to the action of transverse loads in a plane of symmetry, we have strain energy due to both bending and shear deformation.

However, the strain energy due to shear is small compared with that due to bending, and the former is usually neglected in structural analysis (Timoshenko and Young, 1965). Considering only bending, we obtain the strain energy in an element of the beam of length dx from Equations (3.3)

and (3.4) by substituting dx for ℓ and $d\theta/dx$ for θ/ℓ . Thus, for one element,

$$dU = \frac{M^2 dx}{2EI} \quad (3.5)$$

$$dU = \frac{EI}{2} \left(\frac{d\theta}{dx} \right)^2 dx \quad (3.6)$$

Then, to obtain the strain energy in the entire beam, expressions (3.5) and (3.6) are summed over the entire length ℓ of the beam. Utilizing the relationship for small deformations, $\theta \approx dy/dx$, the strain energy is:

$$U = \int_0^\ell \frac{M^2 dx}{2EI} = \int_0^\theta \frac{M^2 r d\theta}{2EI} \quad (3.7)$$

$$U = \frac{EI}{2} \int_0^\ell \left(\frac{d^2 y}{dx^2} \right)^2 dx \quad (3.8)$$

3.2 Bending of a Thin Plate

Assume that a rectangular plate of uniform thickness t is bent to a cylindrical surface (Figure 3.2a). It is sufficient to consider only one strip of unit width as a beam of rectangular cross section (Figure 3.2b). When the deflection of the middle plane is small compared with the thickness t , the following assumptions can be made (Wang, 1953).

1. The normals of the middle plane before bending are deformed into the normals of the middle plane after bending.
2. The stress σ_y is small compared with the other stress components and may be neglected in the stress-strain relations.

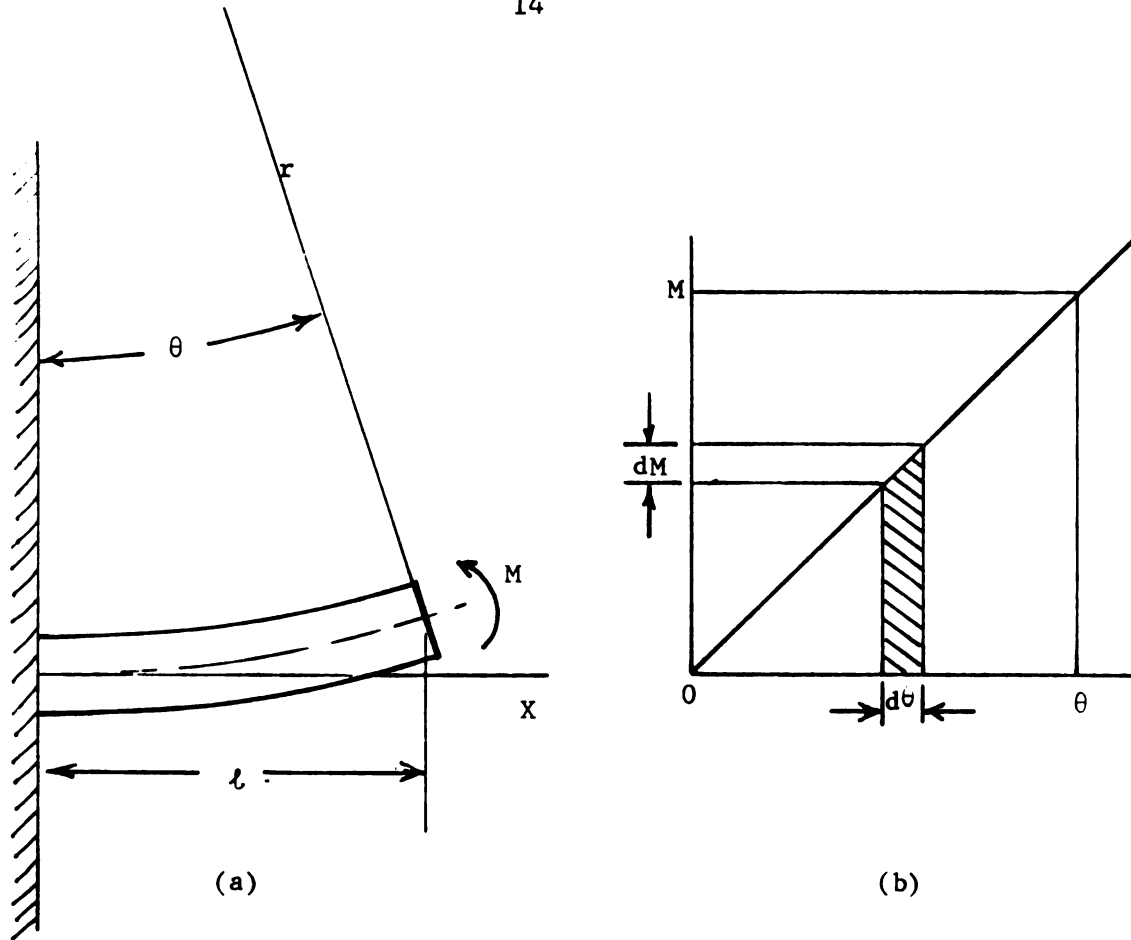


Figure 3.1 Bending of a beam.

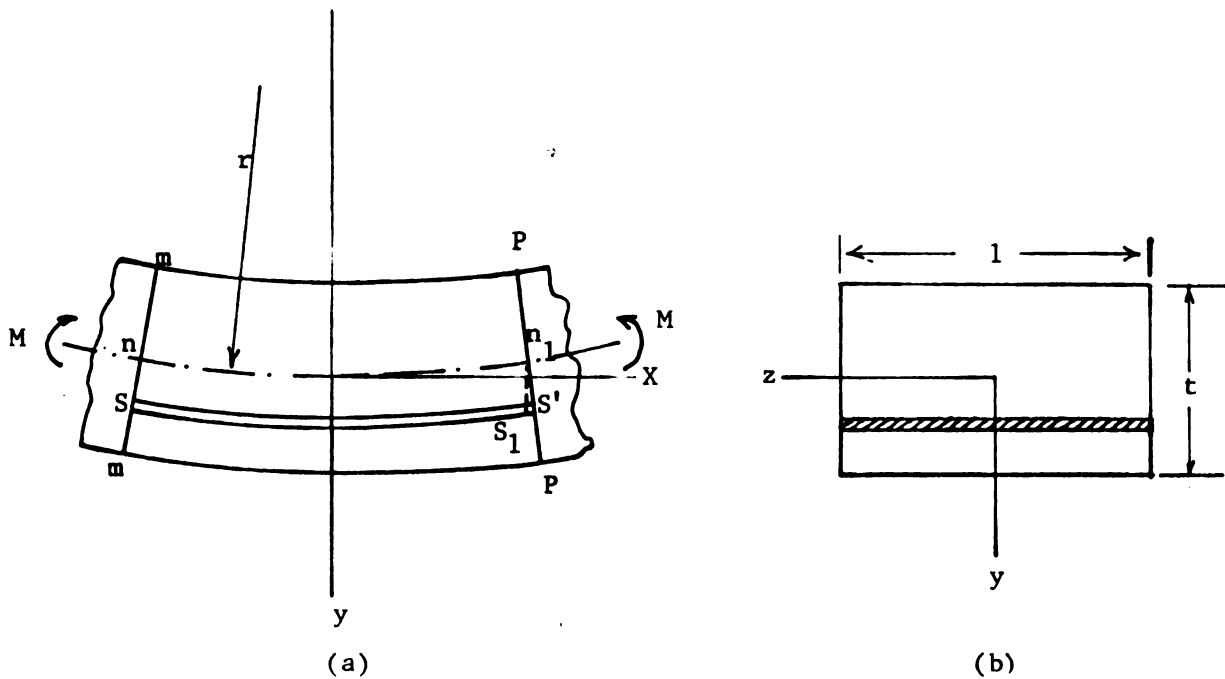


Figure 3.2 Bending of a thin plate.

3. The middle plane remains unstrained after bending.

Then a fiber lengthwise of the strip such as ss' (Figure 3.2a) is subjected not only to the longitudinal tensile stress σ_x but also tensile stress σ_z in the lateral direction, which must be such as to prevent lateral contraction of the fiber. Hence the strain components in the x and z directions are:

$$\epsilon_x = \frac{S_1 S'}{n n_1} = \frac{y}{r}; \quad \epsilon_z = 0 \quad (3.9)$$

While, if both stresses σ_x and σ_z act simultaneously the strains in the x and z directions are:

$$\epsilon_x = \frac{\sigma_x}{E} - \nu \frac{\sigma_z}{E} \quad (3.10)$$

and

$$\epsilon_z = \frac{\sigma_z}{E} - \nu \frac{\sigma_x}{E} \quad (3.11)$$

where: E = Young's modulus

ν = Poisson's ratio

From Equations (3.10) and (3.11)

$$\begin{aligned} \sigma_x &= -\frac{(\epsilon_x + \nu \epsilon_z) E}{1 - \nu^2} \\ \sigma_z &= \frac{(\epsilon_z + \nu \epsilon_x) E}{1 - \nu^2} \end{aligned} \quad (3.12)$$

From Equations (3.9) and (3.12) the corresponding stresses in the x and z directions are

$$\sigma_x = \frac{\epsilon_x E}{1 - \nu^2} = \frac{E y}{(1 - \nu^2) r}$$

and

$$\sigma_z = \frac{\nu \epsilon_x E}{1 - \nu^2} = \frac{\nu E y}{(1 - \nu^2) r}$$

Then the bending moment at any cross section of the strip is

$$M = \int_{-t/2}^{t/2} \sigma_x y dy = \frac{E}{(1 - \nu^2) r} \int_{-t/2}^{t/2} y^2 dy = \frac{Et^3}{12(1 - \nu^2) r}$$

from which

$$\frac{1}{r} = \frac{M}{D} \quad (3.13)$$

where

$$D = \frac{Et^3}{12(1 - \nu^2)} \quad (3.14)$$

The quantity D is called the flexural rigidity of a plate and is substituted for EI which is used in the discussion of bending of beams. Then the strain energy of bending of a thin plate will have the following form for a unit width.

$$U = \int_0^\theta \frac{M^2 r d\theta}{2D} \quad (3.15)$$

3.3 Thin Wide Ring with Rigid Section

Consider the case of a thin wide ring with a rigid section, submitted to the concentrated force P acting along the vertical diameter (Figure 3.3a). Since the rigid section is symmetric about the vertical diameter, only one half of the ring (Figure 3.3b) need be considered. There are no shearing stresses over the cross section $m-n$ and the force on this cross section is equal to $P/2$. The magnitude of the bending moment M_0 acting on this cross section is statically indeterminate and may be found by the Castigliano theorem (Timoshenko and Young, 1965). The cross section $m-n$ does not rotate during application of the load $P/2$. Hence the displacement due to M_0 (Figure 3.3b) is zero and

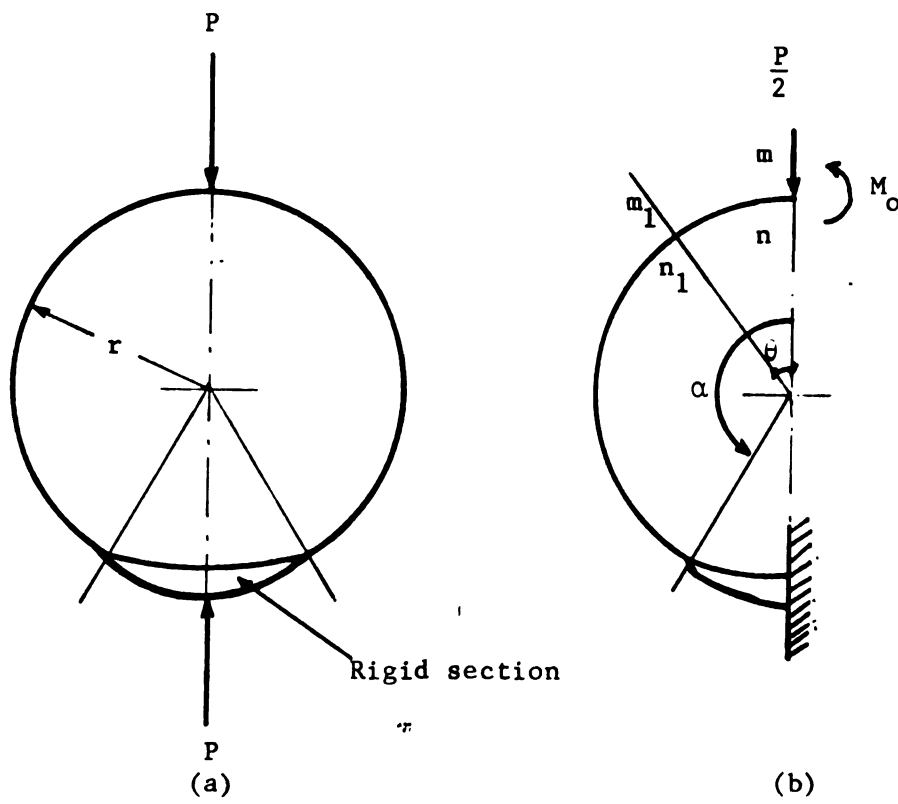


Figure 3.3 Thin wide ring with rigid section.

$$\frac{dU}{dM_o} = 0 \quad (3.16)$$

where U is the strain energy of the ring half. For any cross section m_1-n_1 at an angle θ with the vertical the bending moment M is

$$M = M_o - \frac{Pr}{2} \sin \theta \quad (3.17)$$

and

$$\frac{dM}{dM_o} = 1 \quad (3.18)$$

where moments which tend to decrease the initial curvature of the ring are taken positive. Substituting Equations (3.17) and (3.18) into Equation (3.15) for the potential energy and using Equation (3.16), gives

$$\begin{aligned} 0 &= \frac{dU}{dM_o} = \frac{d}{dM_o} \int_0^{\alpha'} \frac{M^2 r d\theta}{2D} \\ &= \frac{1}{D} \int_0^{\alpha'} M \frac{dM}{dM_o} r d\theta \\ &= \frac{1}{D} \int_0^{\alpha'} (M_o - \frac{Pr}{2} \sin \theta) r d\theta \end{aligned}$$

from which

$$M_o = \frac{Pr}{2\alpha'} (1 - \cos \alpha')$$

For

$$\alpha' = \frac{5}{6} \pi$$

$$M_o = 0.357 Pr \quad (3.19)$$

Substituting Equation (3.19) into Equation (3.17), we obtain

$$M = Pr (0.357 - \frac{1}{2} \sin \theta) \quad (3.20)$$

The decrease in the vertical diameter of the ring may be calculated by the Castigliano theorem. The total strain energy stored in the

ring is

$$\begin{aligned}
 U &= 2 \int_0^{\alpha'} \frac{M^2 r d\theta}{2D} \\
 &= \frac{1}{D} \int_0^{\alpha'} P^2 r^2 (0.357 - \frac{1}{2} \sin \theta)^2 r d\theta \\
 &= \frac{P^2 r^3}{D} \int_0^{\alpha'} (0.12745 - 0.357 \sin \theta + \frac{1}{4} \sin^2 \theta) d\theta \\
 &= \frac{P^2 r^3}{D} \left[0.12745 \theta + 0.357 \cos \theta + \frac{1}{4} \frac{(\theta - \sin \theta \cos \theta)}{2} \right]_0^{\alpha'} \\
 &= \frac{P^2 r^3}{D} [0.25245 \alpha' + 0.357 \cos \alpha' - 0.125 \sin \alpha' \\
 &\quad \cos \alpha' - 0.357]
 \end{aligned}$$

For

$$\alpha' = \frac{5}{6} \pi$$

$$U = 0.0485 P^2 r^3 / D$$

Then the decrease in the vertical diameter is

$$\delta = \frac{dU}{dP} = 0.097 P r^3 / D$$

Therefore,

$$D = 0.097 P r^3 / \delta \quad (3.21)$$

Substituting for D, the equation for a ring of width W is

$$\frac{E W t^3}{12(1 - \nu^2)} = 0.097 \frac{P r^3}{\delta}$$

Then

$$E = 0.097 \frac{12(1 - \nu^2) P r^3}{\delta W t^3} \quad (3.22)$$

3.4 Contact Theory

The theory for two spherical bodies in contact was given by Timoshenko and Goodier (1951) to show that the radius of the contact surface and the approach of the two spheres can be expressed by

$$a = \sqrt[3]{\frac{3\pi}{4} \frac{P (k_1 + k_2) R_1 R_2}{R_1 + R_2}} \quad (3.23)$$

$$\alpha = \sqrt[3]{\frac{9\pi^2}{16} \frac{P^2 (k_1 + k_2)^2 (R_1 + R_2)}{R_1 R_2}} \quad (3.24)$$

where:

a = radius of the contact surface

α = approach of the spheres

R_1 = radius of first sphere

R_2 = radius of second sphere

P = force acting between two spheres

$$k_1 = \frac{1 - \nu_1^2}{\pi E_1}$$

$$k_2 = \frac{1 - \nu_2^2}{\pi E_2}$$

ν_1 = Poisson's ratio of first sphere

ν_2 = Poisson's ratio of second sphere

E_1 = Young's modulus of first sphere

E_2 = Young's modulus of second sphere

For the contact between a sphere with radius R_1 and a flat surface

($R_2 = \infty$)

$$\frac{R_1 R_2}{R_1 + R_2} \quad \frac{R_1}{R_1 / R_2 + 1} = R_1 \quad (3.25)$$

If the flat surface is very rigid compared with the sphere i.e. E_2 is very large, then

$$k_2 = \frac{1 - \nu_1^2}{\pi E_2} = 0 \quad (3.26)$$

Substituting Equations (3.25) and (3.26) into Equations (3.23) and (3.24) gives

$$a = \sqrt[3]{\frac{3 \pi P k_1 R_1}{4}} \quad (3.27)$$

$$\alpha = \sqrt[3]{\frac{9 \pi^2 P^2 k_1^2}{16 R_1}} \quad (3.28)$$

3.5 Assumptions for the Contact Theory

Before applying the contact theory to the bean, the assumptions used for the derivation of the equations must be considered. The assumptions, given by Kosma and Cunningham (1962) are:

1. The material of the contacting bodies is homogeneous.
2. The loads applied are static.
3. Hooke's law holds.
4. Contacting stresses vanish at the opposite end of the body.
5. The radius of curvature of the contacting solid is very large compared with the radius of the contact area.
6. The surface of the contacting bodies are sufficiently smooth so that no tangential forces exist.

3.6 Impact of a Sphere with a Flat Surface

Consider the impact of a sphere and the surface of a semi-infinite body (Figure 3.4). Then, the following equations can be established (Timoshenko and Goodier, 1951).

$$m_1 \frac{d V_1}{dt} = - P, \quad m_2 \frac{d V_2}{dt} = - P \quad (3.29)$$

where:

m_1 = mass of sphere

m_2 = mass of flat surface body

V_1 = velocity of sphere

V_2 = velocity of flat surface body

P = compressive force between the sphere and body

Letting α be the approach between the sphere and body due to local compression, the velocity of approach is

$$\dot{\alpha} = V_1 + V_2$$

From Equation (3.29),

$$\ddot{\alpha} = - P \frac{m_1 + m_2}{m_1 m_2}$$

In the case where $m_2 \gg m_1$ then

$$\frac{m_1 + m_2}{m_1 m_2} = \frac{m_1 / m_2 + 1}{m_1} = \frac{1}{m_1}$$

and

$$\ddot{\alpha} = - \frac{P}{m_1} \quad (3.30)$$

If the time of contact is very long in comparison with the period of lowest mode of vibration of the sphere, then vibration can be neglected and Equation (3.28) which was derived for static conditions,

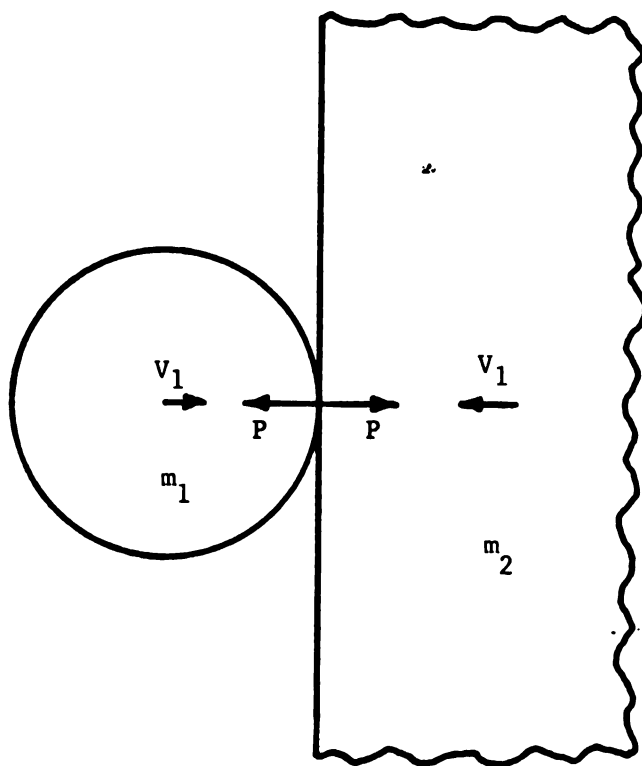


Figure 3.4 Impact of a sphere against a flat surface.

is valid for impact (Timoshenko and Goodier, 1951). According to Mohsenin (1970), the period of impact depends primarily on the deformation occurring at the region of contact. During the deformation process, there is sufficient time for elastic waves to travel to and from several times for dissipation throughout the colliding bodies.

Equation (3.28) may be written as

$$P = n \alpha^{3/2} \quad (3.31)$$

where

$$n = \sqrt{\frac{16 R_1}{9} \left(\frac{E_1}{1 - \nu_1^2} \right)^2} = \frac{4 E_1 \sqrt{R_1}}{3(1 - \nu_1^2)} \quad (3.32)$$

Substituting Equation (3.31) into Equation (3.30)

$$\ddot{\alpha} = - \frac{n \alpha^{3/2}}{m_1} \quad (3.33)$$

Multiplying both sides by $\dot{\alpha}$ and integrating

$$\frac{1}{2} (\dot{\alpha}^2 - v^2) = - \frac{2}{5} \frac{n \alpha^{5/2}}{m_1} \quad (3.34)$$

where v = velocity of approach of the two objects at the beginning of impact.

The maximum value of the approach can be found by putting $\dot{\alpha} = 0$ in Equation (3.34)

$$\alpha_{\max} = \frac{5}{4} \left(\frac{m_1 v^2}{n} \right)^{2/5} \quad (3.35)$$

The maximum compressive force can be calculated by substituting Equations (3.32) and (3.35) into Equation (3.31).

$$P_{\max} = \frac{4}{3} \left[\frac{E_1 \sqrt{R_1}}{(1 - \nu_1^2)} \right]^{2/5} \left(\frac{5}{4} m_1 v^2 \right)^{3/5} \quad (3.36)$$

With this equation we can calculate the value of the maximum compressive force $P_{\max}$ acting on the sphere during impact.

3.7 Maximum Shear Stress of Sphere

The value of the maximum pressure q_0 acting on a contact surface of the sphere can be obtained by equating the sum of the pressure over the contact surface to the compressive force P . Then assuming a hemispherical pressure distribution over the contact surface (Timoshenko and Goodier, 1951 and Shigley, 1963) the following equation results:

$$\frac{q_0}{a} \cdot \frac{2}{3} \pi a^3 = P$$

where a is the radius of contact surface.

Then

$$q_0 = \frac{3P}{2\pi a^2} \quad (3.38)$$

i.e. the maximum pressure is 1.5 times the average pressure on the surface of contact.

As discussed in various references (Timoshenko and Goodier, 1951, Goldsmith, 1960, and Shigley, 1963), the stress for varying depth below the contact surface can be calculated by knowing the radius of the contact surface area and the pressure acting on it. The results of these calculations for points along the vertical axis extended below the center of the contact surface is shown in Figure 3.5. Here, the maximum pressure q_0 at the center of the surface of contact is taken as a unit and the radius of the contact surface is taken as the unit in measuring the distance along the vertical axis.

The fracture of agricultural material is usually caused by the maximum shear stress (Horsfield, et al, 1970). As shown in the figure the maximum shear stress occurs at a depth equal to about a half of the radius of contact surface. Therefore this point can be

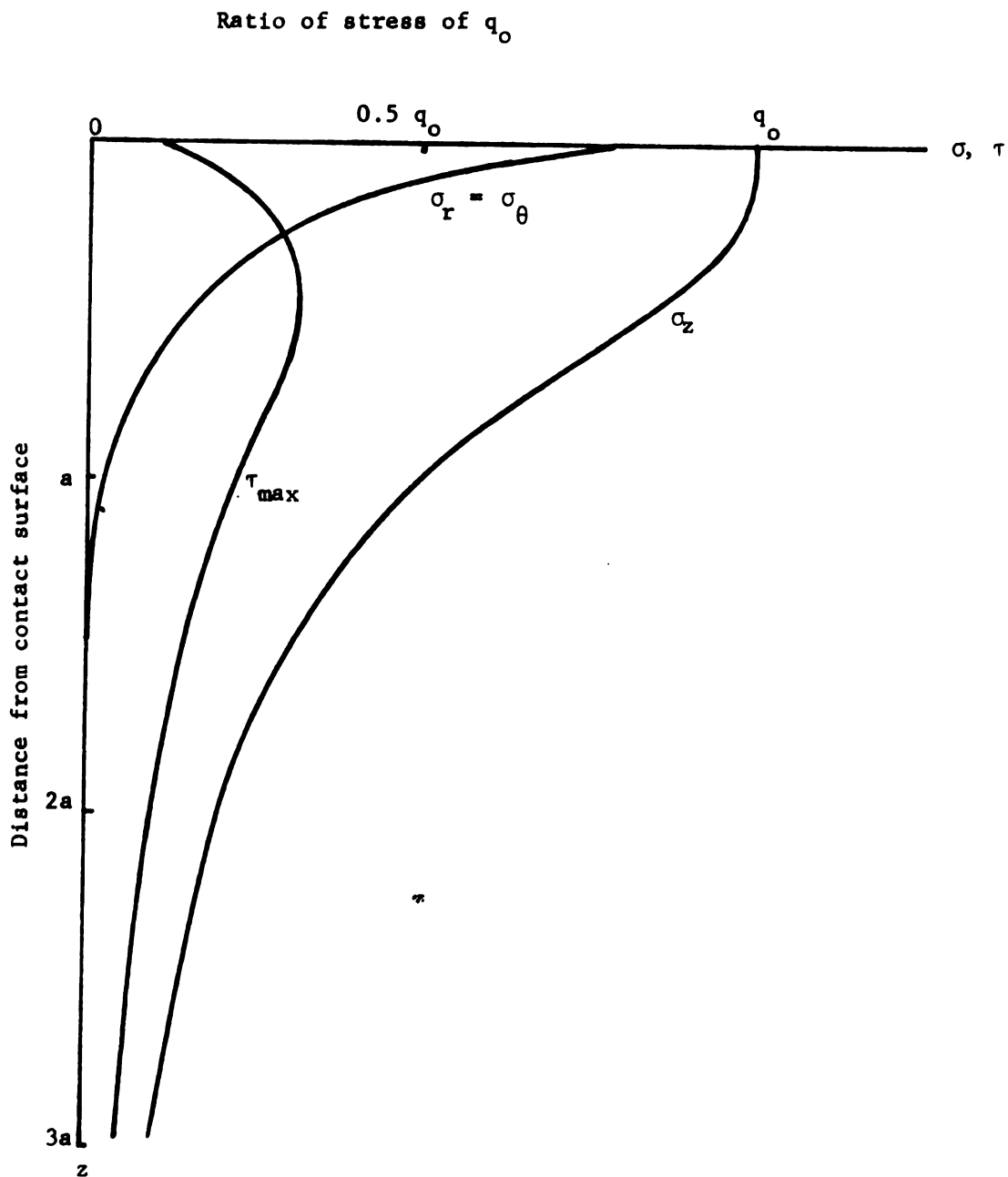


Figure 3.5 Stress components below the surface as a function of the maximum pressure for contacting bodies. (after Timoshenko and Goodier, 1951).

considered as the weakest point. The value of maximum shear stress at this point is about $0.31 q_0$ for the case of $\nu = 0.3$.

The maximum shear stress on the surface was found to occur at the boundary of the circle of contact (Goldsmith, 1960). The maximum value of shear stress is $0.135 q_0$, or one half the difference in the normal stresses given for the surface.

IV. APPARATUS

4.1 Seed Coat Tension Tests

The strength of small seed coat strips was measured using an Instron Universal Testing Machine (Figure 4.1). Paper, 0.003 inches thick, was used as a spacer in the clamps to make the clamp faces nearly parallel when holding the seed coat strip (Figure 4.2). Force-deformation curves for the seed coat strips were recorded on the Instron chart. Moisture and temperature conditions were maintained by enclosing the Instron machine loading frame in a chamber with a plexiglass front. Moisture and temperature controlled air was circulated through this chamber by an Aminco-Aire unit. The humidity in the chamber was monitored with a Hygro-dynamics Model 15-3001 hygrometer indicator.

4.2 Cotyledon Compression Tests

Specimens of cotyledon of rectangular cross section (Figure 4.3) were loaded by the flat surface of a plunger mounted below the cross-head of the Instron machine (Figure 4.4). Other equipment used for the tests was the same as that described in Section 4.1.

4.3 Seed Coat Ring Tests

The seed coat rings (Figure 4.3) cut from whole beans by a Gillings-Hamco thin-sectioning machine (Bromwill Scientific, Division, Will Scientific, Inc.) were compressed with a special loading device. The device for applying very small loads consisted of



Figure 4.1 Instron Universal Testing Machine with the chamber connected to Aminco-Aire unit.

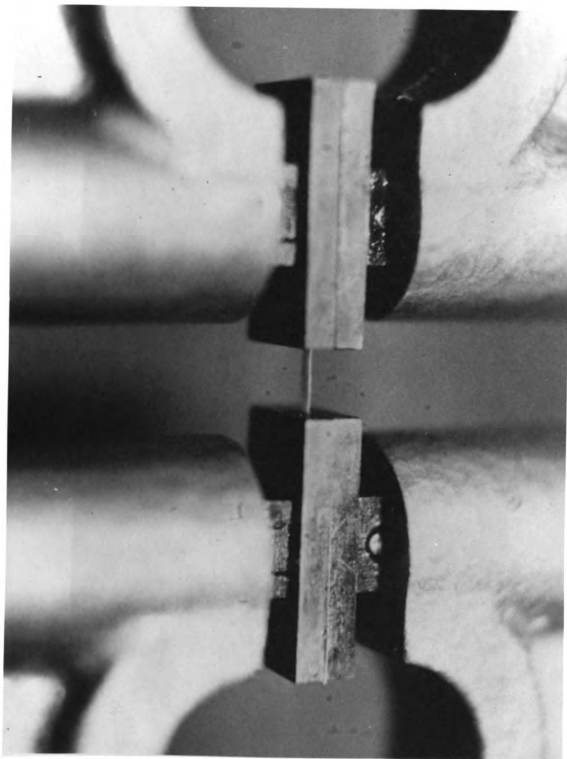


Figure 4.2 Seed coat strip clamped for tension test.



Figure 4.3 Rectangular cotyledon specimen (left) and seed coat ring specimen (right).

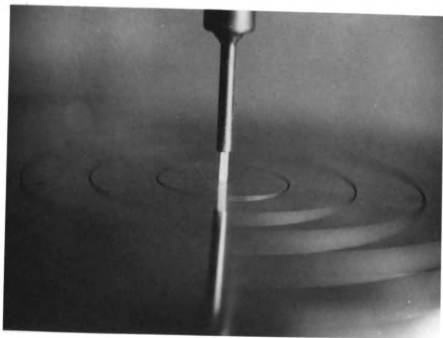


Figure 4.4 Rectangular cotyledon specimen under compression test.

a hand operated screw with a vernier indicating movement of the loading head (Figure 4.5). A 50 gram semiconductor transducer mounted on the loading head and connected to a Daytronic Type 90 strain gage input module was used to measure force. The applied force was read through the Daytronic Model 3000D indicator. The seed coat ring was held on a small hole by vacuum in line with the center of the transducer head (Figure 4.6). Deformation was measured with the vernier and the corresponding forces were read from the Daytronic Model 3000D transducer amplifier-indicator. During the tests the loading system was placed inside the moisture and temperature controlled chamber, which was connected to the Aminco-Aire unit.

4.4 Whole Bean Compression Tests

Whole beans were loaded by the flat surface of the steel plunger mounted on the cross-head of the Instron machine (Figure 4.7). Other equipment was the same as that described in Section 4.1.

4.5 Whole Bean Impact Tests

A laboratory impact tester consisting of a bean holding disk synchronized with an impact disk was used to apply impact loads to beans (Hoki and Pickett, 1971 and 1972). Beans placed by hand in the desired orientation over the holes in the holding disk were held by partial vacuum until impacted by the steel tip at the outer edge of the impact disk (Figure 4.8). The impacted beans were caught by a cloth curtain which dropped the beans into a collector leading to the container at the side of the tester. The speed of the impact disk was sensed by a pulse generator which produces 60 pulses per revolution

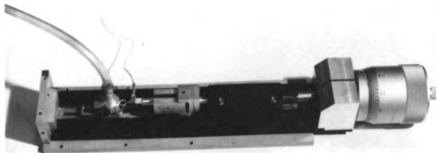


Figure 4.5 Loading device for seed coat ring.

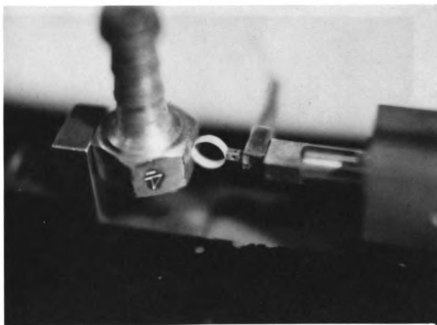


Figure 4.6 Seed coat ring under compression test.

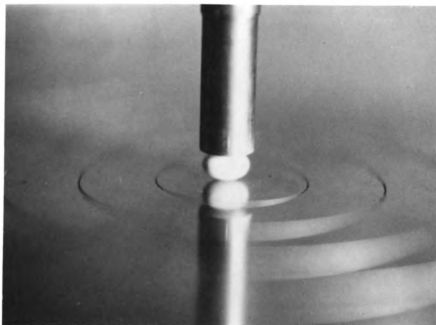


Figure 4.7 Whole bean under compression test (side loading).

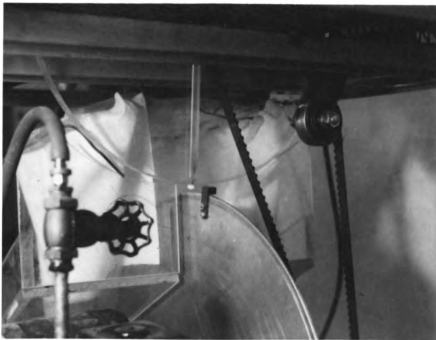


Figure 4.8 Bean holding disk and tip on impact disc.

of the disk. The pulse counter indicates the number of pulses per second giving a direct reading in rpm.

V. METHOD AND PROCEDURE

One problem associated with determining the mechanical properties of agricultural products is the preparation of suitable test specimens. Since the material is soft and relatively high in moisture content, it is difficult to hold the material for cutting into the shape desired for tests. Another problem is finding an effective means of clamping specimens for tensile testing. These difficulties are particularly severe for small products such as navy beans. Special techniques were developed for preparing and holding the specimens for the tests. The strengths of the seed coat and cotyledon were separately measured using different specimen preparation and loading procedures. For determining seed coat strength, tension tests and ring compression tests were conducted and compared. For the cotyledon strength measurement, specimens were cut from whole beans and loaded in compression. Force-deformation relationships were measured for whole beans in compressive loading tests. A loading speed of 0.1 ipm was used for seed coat, cotyledon and whole bean tests performed with the Instron machine. Whole bean impact tests were conducted to determine the relationship between quasi-static properties and impact strength of navy beans. Bean specimens were kept in specific moisture and temperature conditions for 24 hours before the tests. Moisture contents were determined by oven drying at 210 degree F for 48 hours.

5.1 Sample Preparation

The navy beans used in this study were of the Sanilac variety. The sample beans were harvested by a combine using a cylinder velocity of 1500 fpm. The harvest was conducted in September, 1971. Harvested beans of which moisture content was approximately 18 percent (w.b.) were sealed in air tight containers and stored in a refrigerator at 40 degrees F. Sample preparation procedures were developed to make specimens for the seed coat tests and cotyledon tests. The tests were conducted during the period from May to August in 1972.

5.1.1 Specimens for seed coat tests

The beans of approximately 18 percent moisture content were oriented and imbedded in a plastic material with their major axes parallel to the edge of the plastic (Figure 5.1). Holes, $3/8$ inches in diameter, $1/4$ inches deep, and $1/2$ inches apart were first drilled in a strip of $1/2$ -inch plexiglass plate. Beans were placed in the holes with their major axes parallel to the edge of the strip. Then a liquid mixture of "Quick Mount" (Fulton Metallurgical Products Corporation, 26 Manor Oak Village, 1910 Cochran Road, Pittsburgh, Pa) was poured over the beans in the holes. The mixture became hard plastic after an hour. Two cuts perpendicular to the major axis of the bean, were made 0.079 inches apart near the middle of each bean with the thin section machine. The 0.079 inch plastic plates containing a section of the bean in the center were dried for two days at room temperature. Then the bean disks were taken out of the plastic and the cotyledon sections were removed leaving the seed coat rings (Figure 4.3). The seed coat rings were used for the ring compression tests from which Young's

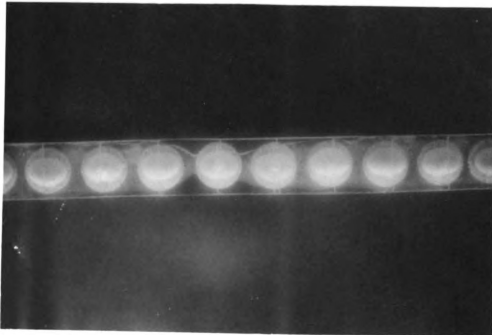


Figure 5.1 Beans imbedded in plastic.



Figure 5.2 Parallel one side blades used for making cotyledon specimens (from left 0.232 inches, 0.074 inches and 0.052 inches apart respectively).

moduli were evaluated. For the seed coat tension tests, the rings were cut to make strips to be held by the clamps (Figure 4.2).

5.1.2 Specimens for cotyledon tests

The beans were first cut by two parallel one-side blades 0.059 inches apart (Figure 5.2) along the major axis and perpendicular to the plane between two cotyledons. Then they were again cut by similar parallel blades 0.079 inches apart to make rectangular cross section bars. These bars were cut to length by using 0.236 inch-apart parallel blades.

5.2 Seed Coat Tension Tests

Seed coat rings were kept in the moisture and temperature controlled chamber for 24 hours before tests were conducted. Immediately before the tests the width of rings was measured by a micrometer and then the rings were opened and the thickness was measured. The strip was held in a vertical position by the Instron clamps. The test length for each specimen (distance between the upper and lower clamps) was adjusted to 0.25 inches. The loads were applied until the specimens were broken. A loading speed of 0.1 ipm was used for the tests. The moisture of specimens was changed between 10-16 percent.

5.3 Cotyledon Specimen Compression Tests

The specimens of cotyledon were kept for 24 hours in the chamber at air conditions selected for the tests. For each test, the specimen was placed upright and the crosshead was adjusted manually to just touch the specimen end. The specimens were loaded until they fractured or

they reached about 10 percent strain. All tests were conducted at a loading speed of 0.1 ipm with bean moisture contents from 10 to 19 percent.

5.4 Seed Coat Ring Tests

The moisture of the seed coat rings was controlled by keeping them in the chamber for 24 hours under specific moisture at 77 degree F. Before each test the diameter and the width of ring were measured with a micrometer. The ring was held in position over a hole by vacuum and loaded by turning the vernier screw by hand. Several measurements were taken within the small deformation range where thin ring theory is applicable. This procedure was repeated three times for each ring specimen and the average values for the measurements were used to plot force-deformation curves. After the tests, each ring was opened for measurement of seed coat thickness with a micrometer. The specimen moisture was changed between 10-16 percent.

5.5 Whole Bean Compression Tests

Whole beans were loaded by the Instron machine at a crosshead speed of 0.1 ipm. The force-deformation curves were obtained to compare with the deformation calculated by using the contact theory and the Young's moduli obtained from simple compression tests of cotyledon specimens.

5.6 Whole Bean Impact Tests

The beans were sorted by using screens with oblong holes $3/4$ inches long. The sample beans were those which passed through holes $15/64$ inches

wide and did not pass through holes 12/64 inches wide. The 40 beans each of 10.6, 15.1 and 17.8 percent moisture content were impacted from the sides at the impact speed varying from 2000 fpm to 3000 fpm. All beans examined were placed into three categories; those with no damage, those with seed coat checks and those with splits.

VI. RESULTS AND DISCUSSION

6.1 Homogeneity and Isotropy

The theory applied to beans in this study was based on the assumption of homogeneity and isotropy of the material. A bean consists of a seed coat enclosing two cotyledons. The thickness of seed coat was found to be 0.003 inches, and therefore was considered to have negligible strength to support external forces during compression or impact loading.

The directional characteristics of the seed coat were examined by testing 10 strips of seed coat cut from two perpendicular directions. One set of 5 strips was cut parallel to the longitudinal axis of the bean and the other set of 5 strips was cut perpendicular to the longitudinal axis. Each set of strips was loaded in tension at a speed of 0.1 ipm. The moisture content of the specimens was 16.2 percent. The average values of Young's moduli for perpendicular and parallel cut were 0.756×10^5 psi and 0.676×10^5 psi respectively. The ultimate stress values for perpendicular and parallel cut were 2260 psi and 2040 psi respectively. For both Young's modulus and ultimate stress, there was no significant difference at the 5 percent level between the two directions. The detailed test results are presented in Table A.1.

Since the test specimen size was large compared to the cell size the specimen can be considered homogeneous. Cross sectional picture of bean cotyledon showed various sizes of polygonal cells of 100 microns maximum (Powrie et al 1960). Since there was no directional characteristics observed in the cells, the cotyledon specimen can be considered to be isotropic.

6.2 Equilibrium Moisture for Seed Coat and Cotyledon

Moisture content of the seed coat and cotyledon were controlled by providing specific equilibrium relative humidities at 77°F through the Aminco-Aire unit. The relative humidities for equilibrium moisture of beans are found in books dealing with processing agricultural products (Hall, 1957). The equilibrium moisture of the cotyledon coincided with the values of the reference book. For higher relative humidity, moisture content of the seed coat was less than the cotyledon by 1 to 2 percent (Figure 6.1).

6.3 Dimension and Weight Change of Beans

Contact radius and deformation of a bean during compressive loading is affected by the radius of surface curvature, as shown by Equations (3.27) and (3.28). The maximum compressive force during impact is also affected by both the radius of curvature and the weight [Equation (3.36)]. Preliminary tests were conducted to examine bean dimensions and weight as affected by moisture content. The medium beans were sorted by using screens with oblong holes $\frac{3}{4}$ inches long. The medium beans were those which passed through holes $\frac{14}{64}$ inches wide and did not pass through holes $\frac{13}{16}$ inches wide. Ten medium size beans (average weight 0.000413 lb) of 18.8 percent moisture content were used for the measurement of length, width, height and weight after 24, 72 and 144 hours of natural drying at room temperature. Measurements were made on each bean by using a micrometer. Percent shrinkage of length, width and height, and percent decrease of weight were computed and are presented in Table A.2. The maximum dimension changes were about 2 percent in length and height and 1 percent in width. Since the maximum compressive force is proportional to the one-fifth power of the radius of curvature, the

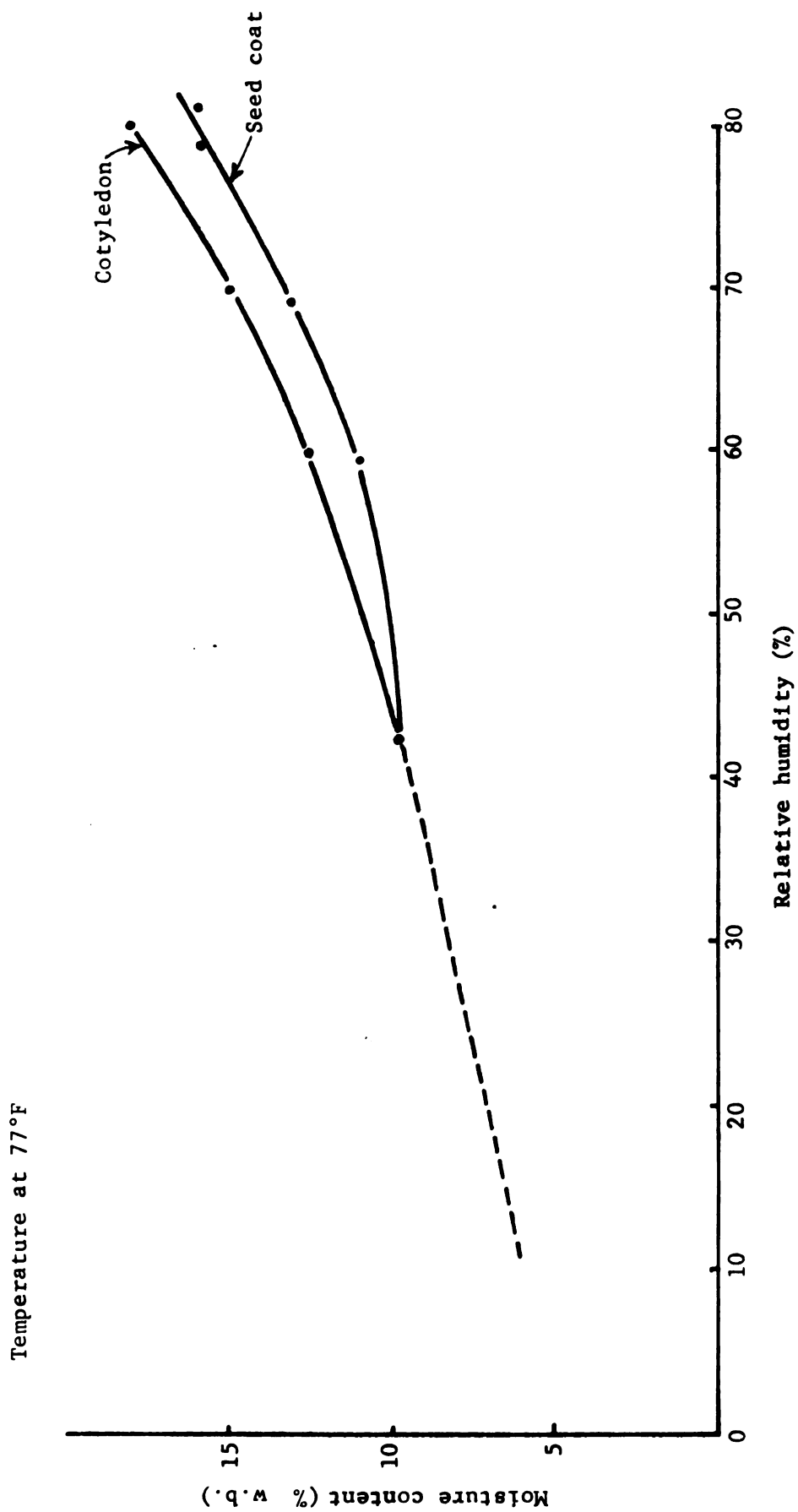


Figure 6.1 Equilibrium moisture content of seed coat and cotyledon.

effect of dimensional change is very small [Equation (3.36)]. Dimensional changes were not large and were therefore considered to have no effect on maximum pressure or stress of the beans. The decrease of bean weight, corresponding to the decrease of moisture from 18.8 percent to 9.1 percent was 10.76 percent. The weight of the bean was adjusted for moisture content for all computations of maximum compressive force and stresses of beans during impact.

Cuts were made through the beans imbedded in the plastic strip (Figure 5.1) for measuring curvature of the side of each bean. The line of intersection of the two perpendicular planes of cut was coincided with the axis of the bean for the width measurement. A 6X Edscorp Pocket Comparator (Edmund Scientific Co., Barrington, New Jersey) was used to measure the major and minor radii of the curvatures of bean surface. The average values of major and minor curvatures were 0.259 inches and 0.126 inches respectively. The moisture content of the beans was 18.8 percent. Details of measurement results are given in Table A.3.

6.4 Bean Seed Coat Strength

Young's modulus was computed by using the measured section area and the maximum slope of the force-deformation curve. The maximum strength was computed by dividing the maximum measured force by the section area of the specimen. Young's modulus increases with decreasing moisture content, Figure 6.2. However the rate of change in Young's modulus with change in moisture content was relatively small for the high moisture contents. Young's modulus at 10 percent moisture content was 2.7×10^5 psi which is almost four times greater than the value of 0.7×10^5 psi at 16.2 percent moisture. As indicated by the rapid increase of Young's modulus with decreasing moisture content particularly

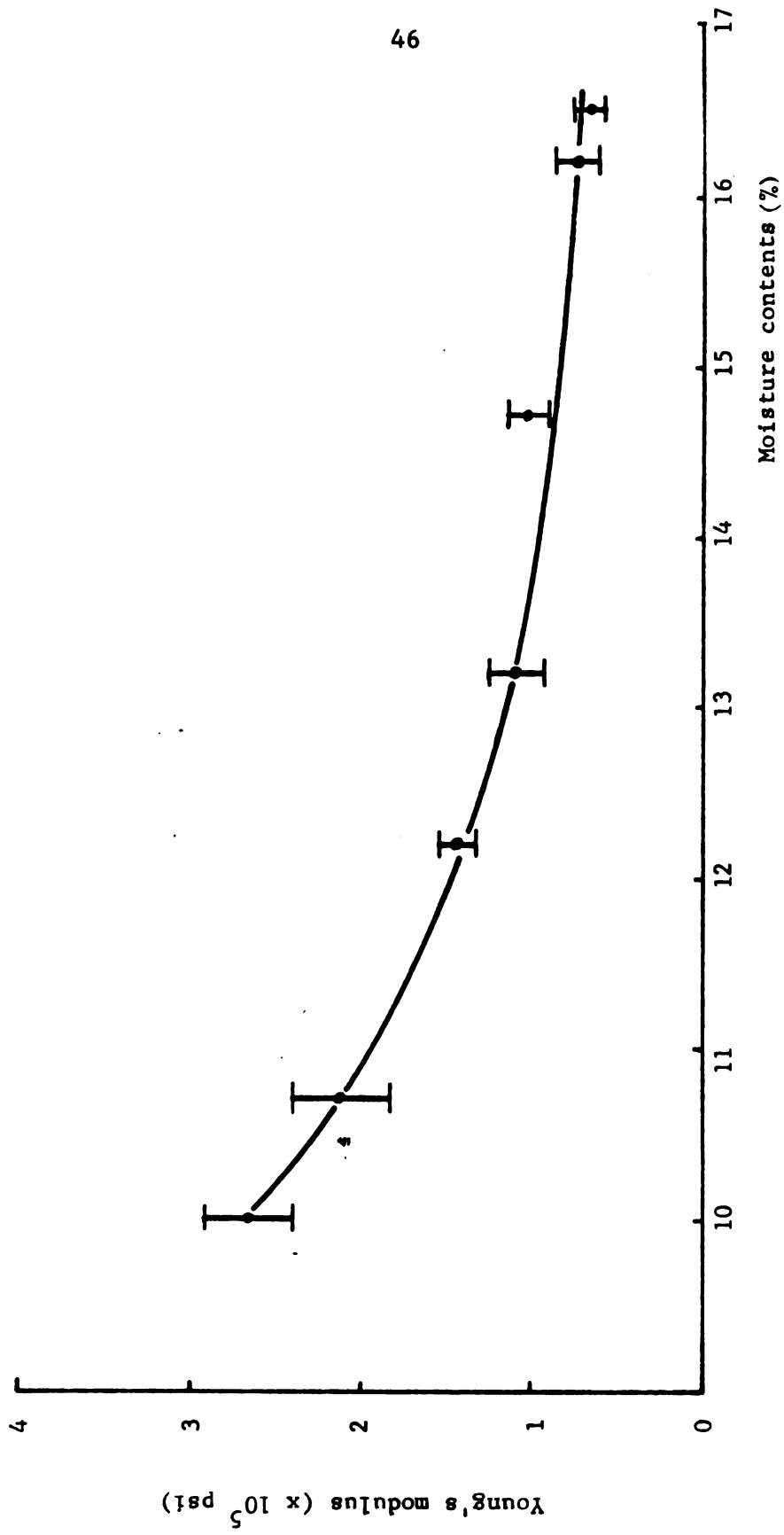


Figure 6.2 Effect of moisture content on the Young's modulus of seed coat.

below 12 percent, the bean seed coat becomes more rigid. The increased rigidity does not permit the seed coat to deform as easily resulting in higher stress particularly for impact loading. Data for the seed coat tension test results are given in Table A.4.

The effect of moisture content on the maximum strength is shown in Figure 6.3. The maximum strength increases slowly with decreasing moisture content in the range of 16.2 to 12.0 percent moisture and abruptly in the moisture range below 12 percent. The maximum strength of 5×10^3 psi reached at 10 percent moisture content is 2.5 times greater than the strength of 2.0×10^3 psi at 16.2 percent moisture.

6.5 Seed Coat Ring Compression Tests

Young's modulus was calculated by using Equation (3.22), the measured force-deformation relation, and dimensions of a ring subjected to a compressive force at the top (Figure 3.3a). The results of seed coat ring compression tests for various moisture contents are given in Table A.6. Young's modulus was computed assuming Poisson's ratio, $\nu = 0.3$. Figure 6.4 shows Young's modulus of the seed coat at various moisture contents calculated from the thin ring theory. Young's modulus increases with decreasing moisture content. The increase of Young's modulus with decreasing moisture content was not large for moisture contents higher than 12 percent. However the value of Young's modulus increased rapidly when the moisture content became lower than 12 percent. These results are very similar to the results obtained by simple tension tests (Figure 6.2). The value of Young's modulus at 10 percent moisture content calculated by the thin ring theory was 3.1×10^5 psi which was little larger than 2.7×10^5 psi obtained from

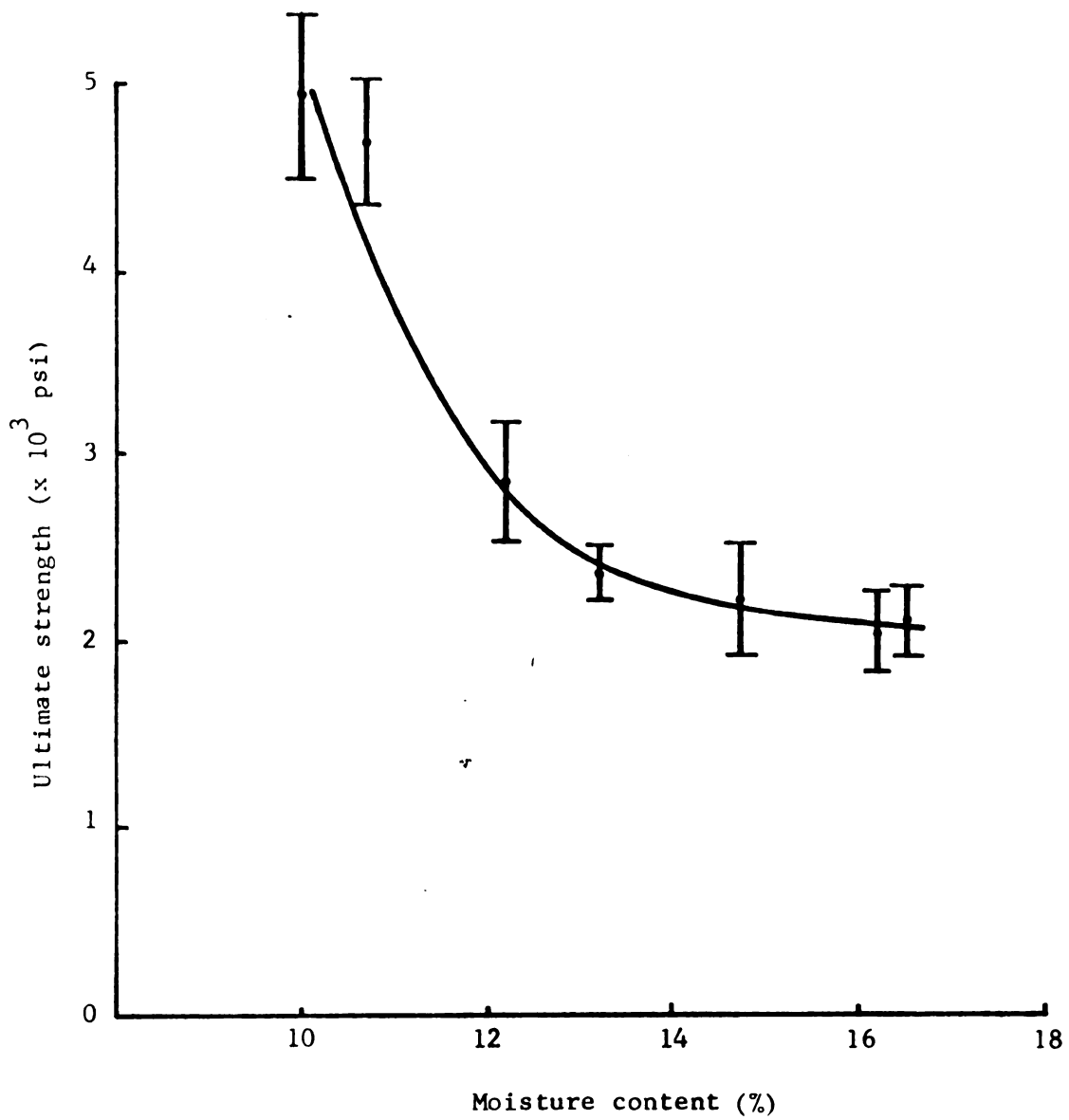


Figure 6.3 Effect of moisture content on the ultimate strength of seed coat.

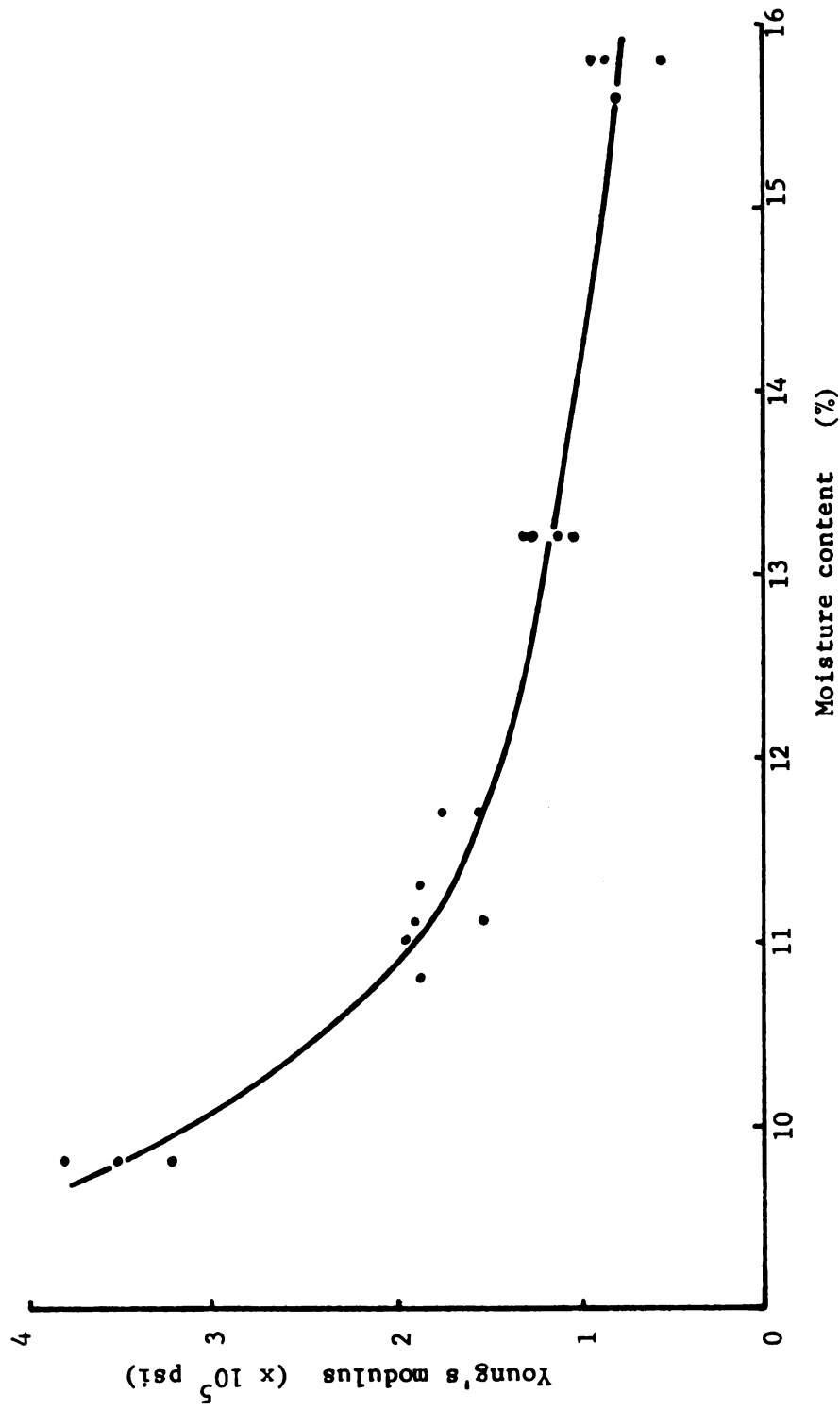


Figure 6.4 Young's modulus of seed coat calculated by using thin ring theory.

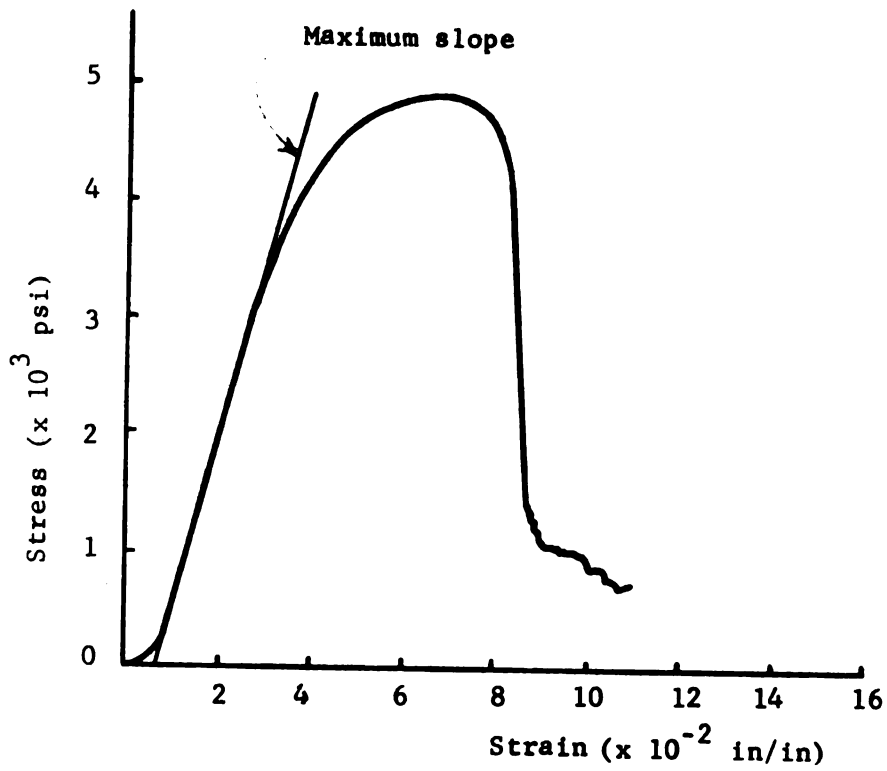
the simple tension test under the same moisture content. This 14 percent difference could be due to a small measurement error in the thin ring tests. The Young's moduli for the 11 to 16 moisture content range were almost coincidental, supporting the applicability of the thin ring theory to the bean seed coat.

6.6 Bean Cotyledon Compressive Strength

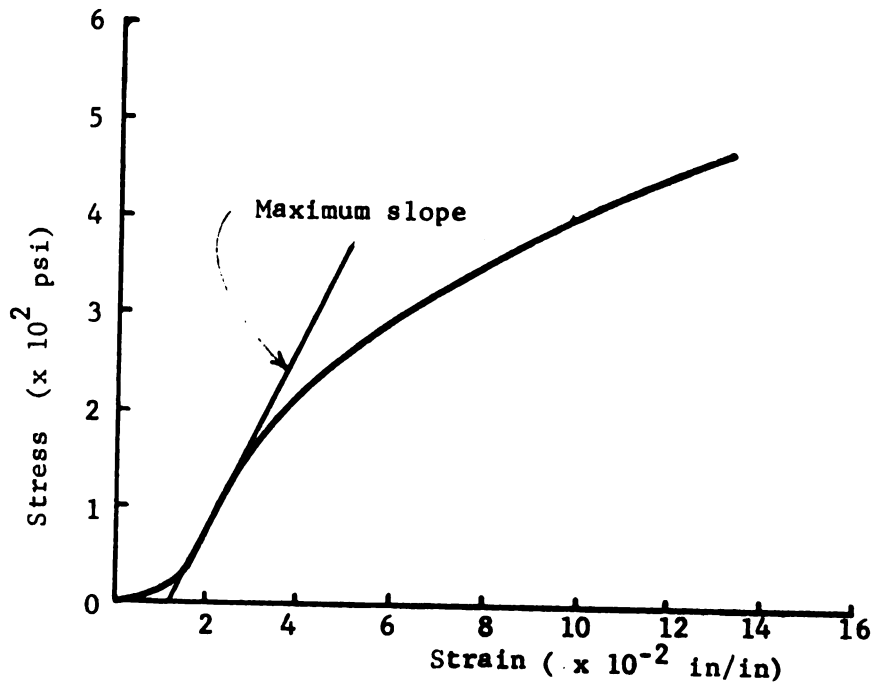
Typical stress-strain curves for low and high moisture contents obtained from the cotyledon compression tests are shown in Figure 6.5. Young's modulus of the bean cotyledon was calculated by using the maximum slope of the stress-strain curve. The maximum strength was determined by dividing the recorded maximum force by the section area of specimen.

Young's modulus of the bean cotyledon increases with decreasing moisture content (Figure 6.6). The modulus of 1.45×10^5 psi at 10 percent moisture content is 24 times greater than the value of 0.06×10^5 psi at 19.5 percent moisture. Rapid increase of Young's modulus as moisture content was decreased below 12 percent was a distinct phenomenon. The Young's modulus of the seed coat was only about 2 times greater than that of the cotyledon at 10 percent moisture content while it was 4 times greater at 16 percent moisture. Data for the cotyledon compression tests for various moisture contents are given in Table A.5.

Figure 6.7 shows the effect of moisture content on the ultimate cotyledon strength. For moisture contents below 12 percent, the ultimate stress was calculated by dividing the ultimate force by the section area of the specimen. The cotyledon specimen at 10 percent moisture content showed a definite point of ultimate strength at about 2 percent strain.



(a) Low moisture content (10%)



(b) High moisture content (18%)

Figure 6.5 Typical stress-strain curves for cotyledon.

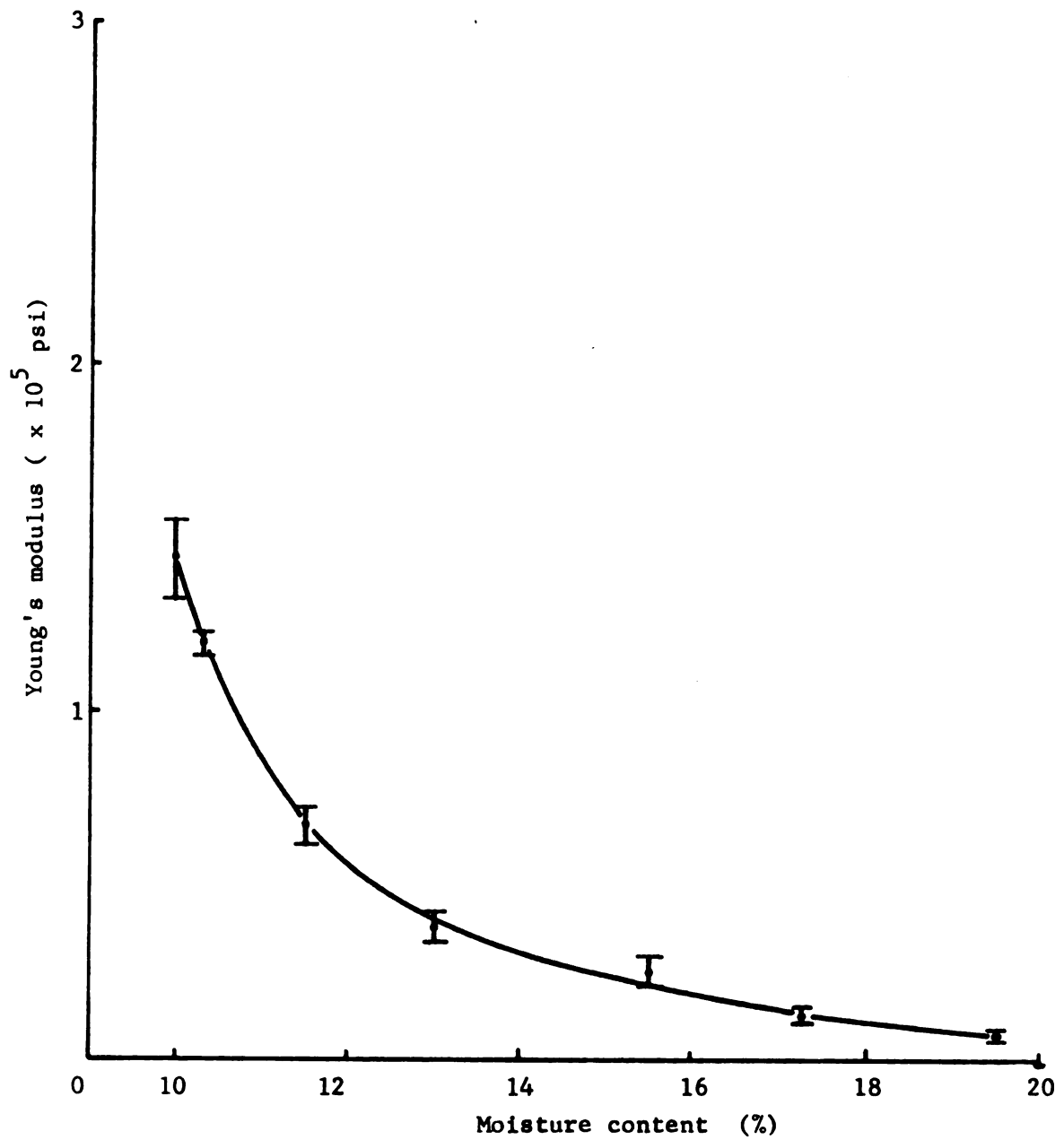


Figure 6.6 Effect of moisture content on the Young's modulus of cotyledon.

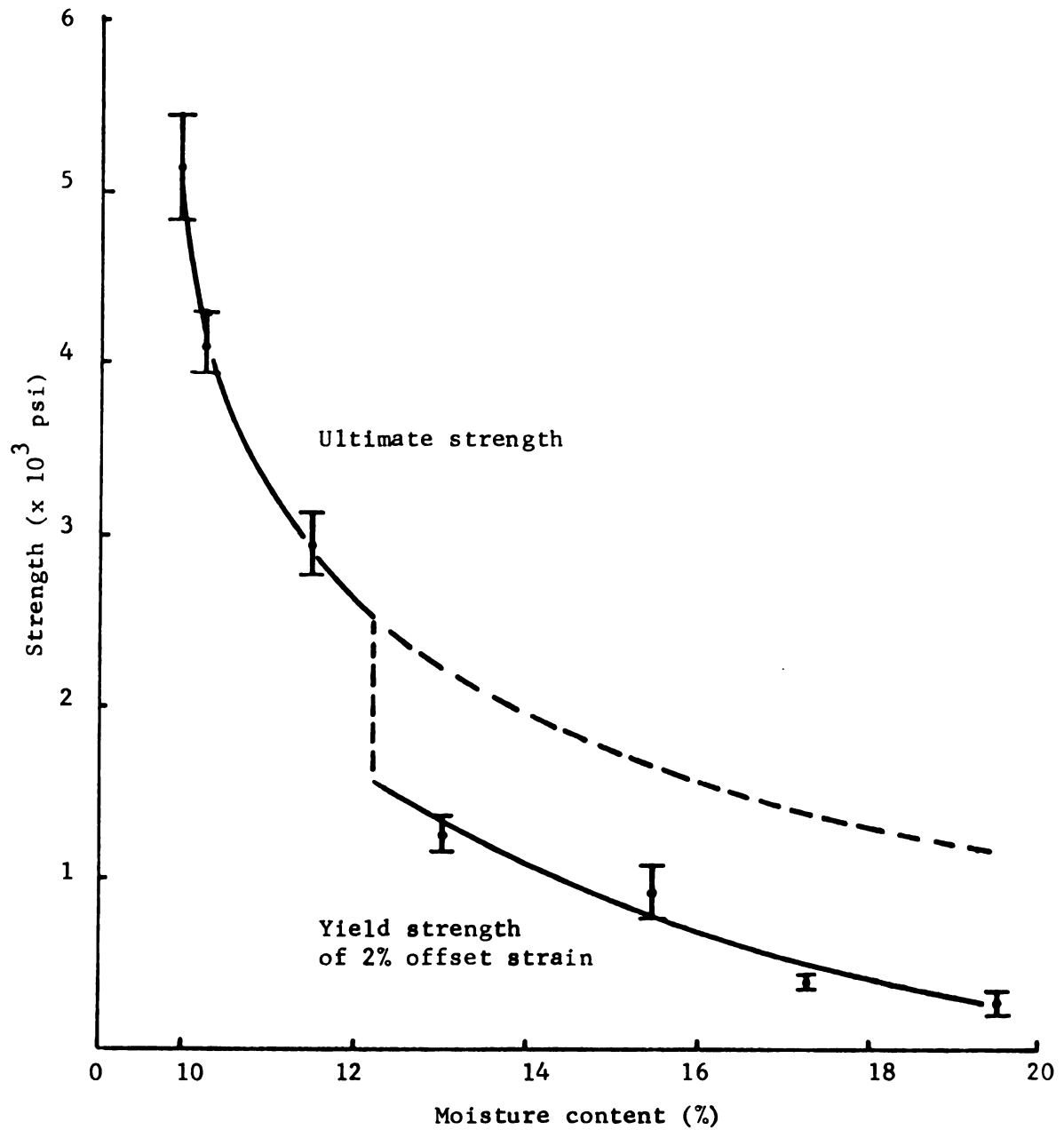


Figure 6.7 Effect of moisture content on the ultimate strength of cotyledon.

The fracture of the specimen occurred by the shearing of the material in a plane about 45 degrees from the normal axis. For a moisture content near 12 percent there was generally no specific point of fracture. For moisture contents above 12 percent the specimen continued deforming and started buckling even after having 10 percent strain. Since no fracture was observed for high moisture cotyledon tests, offset yield strength was obtained instead of ultimate strength (Table A.5). The offset yield strength is the stress at which the strain exceeds by a specified amount (the offset) an extension of the initial proportion of the stress-strain curve (American Society for Testing and Materials, 1970). A 2 percent offset strain was used to obtain the yield strength of the cotyledon specimens with moisture contents higher than 12 percent. The solid line in Figure 6.7 shows the ultimate strengths and the 2 percent offset yield strength. The curve had a definite point of discontinuity at 12 percent moisture content where the transition was made between the measured ultimate strength and the offset yield strength. Since ultimate strength of the cotyledon is greater than the yield strength for moistures above 12 percent, the measured ultimate strength curve was extended parallel to the yield strength curve to represent the expected ultimate strength for the higher moisture beans. The extension is shown as a dotted line in Figure 6.7. Cotyledon compressive strength and seed coat tensile strength were both about 5×10^3 psi for a 10 percent moisture content. Seed coat strength decreased more slowly as the moisture content was increased than did the strength of the cotyledon. Consequently seed coat strength was greater than cotyledon strength for higher moisture contents.

6.7 Evaluation of the Assumptions for Contact Theory

The assumptions used for the derivation of contact theory (Section 3.5) must be evaluated before the application to the bean under various loading conditions. The assumptions are presented with the discussion about the applicability and limitation of the theory.

1. The material of the contacting bodies is homogeneous. --
A bean seed consists of two cotyledons and seed coat. As discussed in the Section 2.4, the thickness of the seed coat was about 0.003 inches which was very small compared with the cotyledon. The Young's modulus of the seed coat was only 2 to 4 times that of cotyledon. Therefore, the seed coat did not appear to support a significant amount of force when the bean was loaded from the side. It was assumed that all forces were supported by the cotyledon. Homogeneity of each cotyledon was assumed since the cells forming cotyledon tissues were randomly and undirectionally arranged, and therefore the mechanical behavior was considered as being equivalent to that of a homogeneous and isotropic body. Assuming isotropy for the seed coat was justified by the test results (Section 6.1).
2. The loads applied are static. -- The loading speed used for measurement of mechanical behavior of whole beans was very slow, that is quasi-static.
3. Hooke's law holds. -- As shown in Figure 6.5, beans with low moisture content were nearly elastic but high moisture beans showed viscoelastic behavior, which might result in some disparity between elastic theory and experimental results.

4. Contacting stresses vanish at the opposite end of the body. -- For quasi-static side loading of an individual bean the region farthest from the load point was in the plane between the bean cotyledons. Since the area of this region was 5 to 20 times of the contact area, the stress for the region was relatively low and assumed as negligible.
5. The radius of curvature of the contacting solid is very large compared with the radius of the contact area. -- For beans with low moisture content the radius of curvature of the contacting surface was 6 times larger than the radius of the contact area. For beans with high moisture content the radius of curvature of the contacting surface was 3 times of the radius of the contact area. Though an exact solution could not be obtained particularly for high moisture beans, the use of contact theory for an approximate solution was possible and justified from a practical point of view. According to Mohsenin (1970), the relative simplicity of elastic solutions, and the fact that the contact theory had shown good correlation with experimental results have been the main reasons for extensive use of this approach despite its inconsistencies.
6. The surface of the contacting bodies are sufficiently smooth so that no tangential forces exist. -- Since the surface of a navy bean and the surface of finished steel were very smooth, negligible tangential forces were assumed between them.

6.8 Whole Bean Compression

With Equation (3.28) the deformation of a sphere under compression can be calculated by knowing the sphere size, the elastic constants and the applied force. Application of the contact theory to loading the sides of the bean by flat surfaces requires approximation of the curvature of the bean surface. The approximate spherical radius may be obtained from the relation (Fridley et al., 1970)

$$R_1 = \frac{2 R_a R_b}{R_a + R_b}$$

where subscripts a and b respectively refer to the major and minor radii of curvature of the side of the bean at the point of load. The major and minor radii of curvature of the medium beans (Section 6.3 and Table A.3) are 0.259 inches and 0.126 inches respectively. These values were substituted into the above equation to get the spherical radius R_1 . The value of R_1 was found to be 0.170 inches. Poisson's ratio, ν , was assumed to be 0.3 and the strength of the seed coat was assumed as negligible for the calculation of theoretical deformations. The values of k_1 for 11.6 percent and 18.8 percent moisture were calculated using Young's moduli measured in the cotyledon compression tests. By substituting the values of k_1 and R_1 into Equation (3.28) and giving specific values of P_1 , the theoretical deformations for the values given for P_1 were calculated to draw theoretical force-deformation curves. The theoretical force-deformation curves were compared with the force-deformation curves obtained in the whole bean compression tests (Section 4.4).

Figures 6.8 and 6.9 show the theoretical and experimental force-deformation curves for moisture contents of 11.6 percent and 18.8 percent respectively. The theoretical curves nearly coincide with the

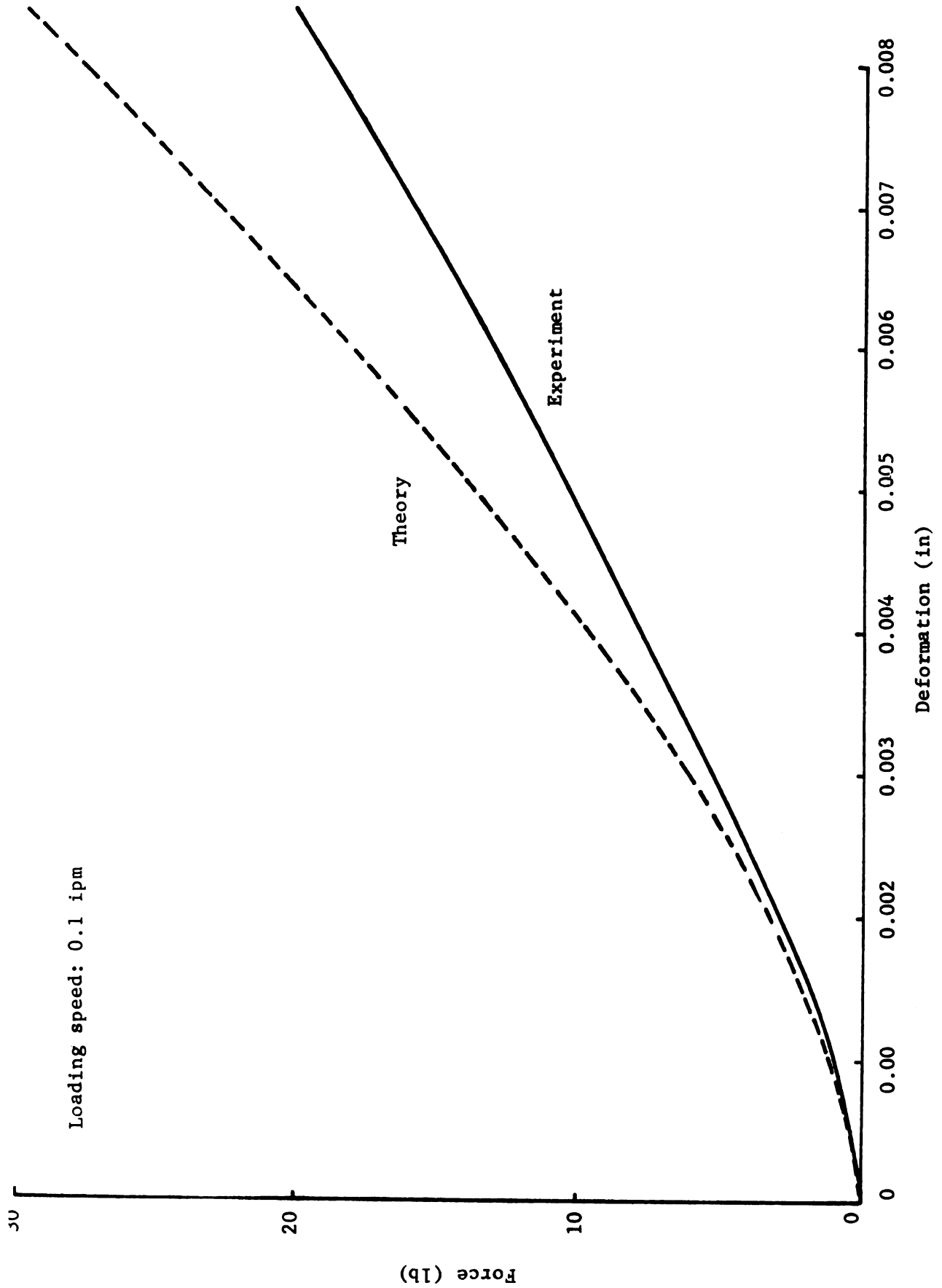


Figure 6.8 Force-deformation curve for the whole bean at low moisture content(11.6%).

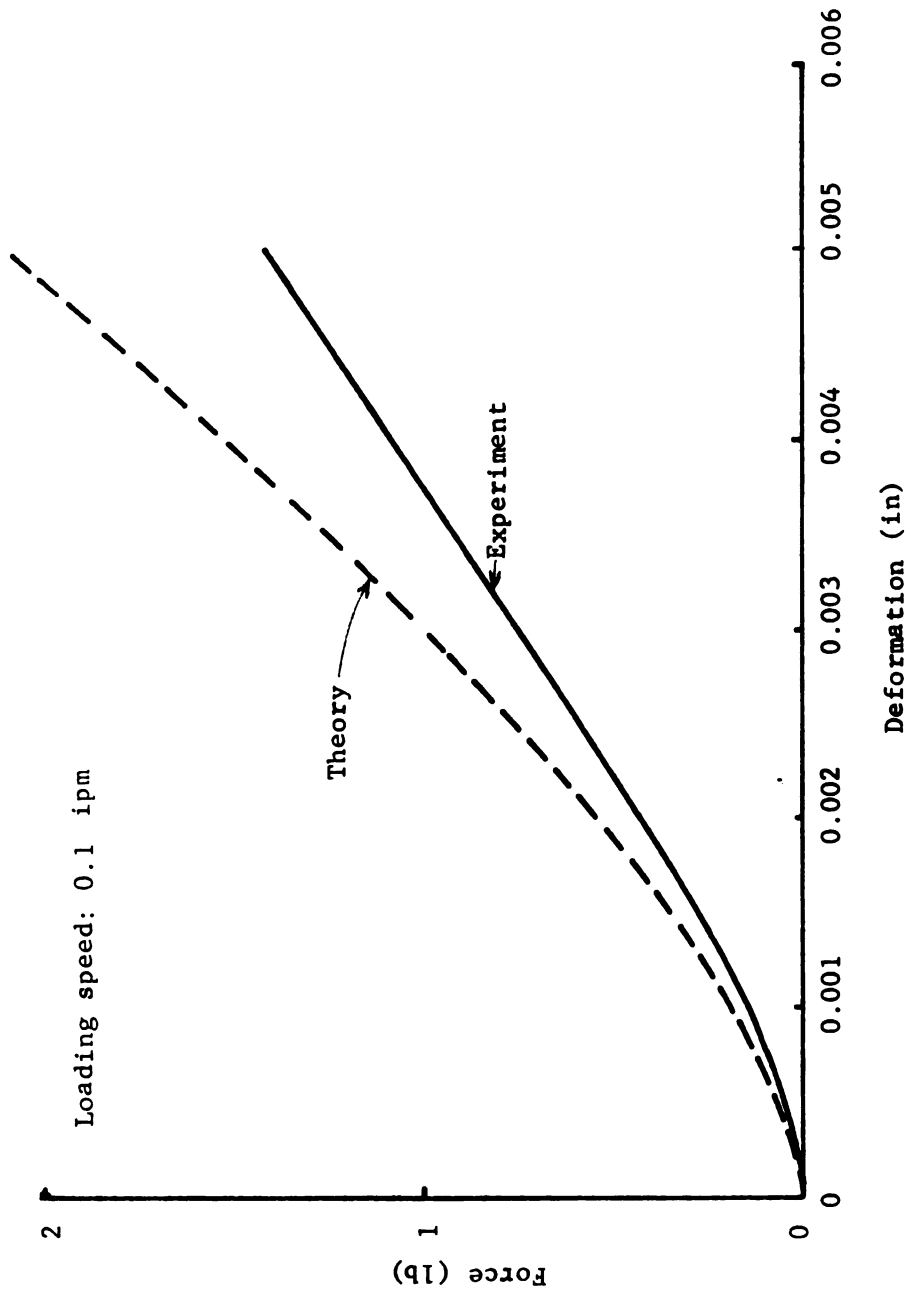


Figure 6.9 Force-deformation curve for the whole bean at high moisture content (18.8%).

experimental results for both low and high moisture contents. However some departure was observed for large deformations, which probably resulted from the viscoelastic properties of the beans. These results indicate that assumptions made for the calculations were valid for relatively small deformations. Since the material behavior during impact loading would likely be more nearly elastic, the departure may become considerably smaller even for large deformation.

6.9 Whole Bean Damage Analysis During Impact

To determine whether beans were expected to be damaged during side impact loading, the internal maximum shear stress of the cotyledon and maximum shear stress on the seed coat were assumed as suitable criteria. Equations discussed in Section 3.7 were utilized for calculating the cotyledon and seed coat stresses. Seed coat strength was assumed to be negligible for the analysis of maximum shear stress in the cotyledon. The shear strain on the seed coat was assumed to have the same magnitude as the maximum shearing strain on the contact surface of the cotyledon. The maximum compressive force $P_{\max}$ was calculated by substituting the measured Young's modulus E_1 , the value of 0.3 for Poisson's ratio ν_1 , the value of 1.70 for the radius of curvature R_1 , and specific values of m_1 and V (Tables A.7 and A.8) into Equation (3.36). The contact area a and approach α were calculated by substituting the values of $P_{\max}$, R_1 and k_1 into Equations (3.27) and (3.28) respectively. The maximum pressures on the surface of contact were calculated by substituting the values of $P_{\max}$ and the corresponding radius a of the contact area into Equation (3.38). As discussed in Section 3.7, the maximum internal shear stresses and the maximum shear stresses on the

contact surface of the cotyledon were then calculated from the maximum pressures on the surface of contact. Stresses were calculated for impact velocities of 2000 fpm and 3000 fpm (Tables A.7 and A.8).

The shear moduli for the cotyledons were calculated from the Young's moduli obtained from the specimen for deformation measurement and an estimated Poisson's ratio of 0.3. Then the maximum shear strain on the contact surface of the cotyledon was calculated by using calculated shear moduli and maximum shear stresses at the boundary of the circle of contact of the cotyledon for impact velocities of 2000 fpm and 3000 fpm. Shear moduli of the seed coat were calculated from the Young's moduli determined from the seed coat strip force-deformation measurements and a Poisson's ratio of 0.3. Since the maximum shear strain on the seed coat was assumed to have the same value as the maximum strain on the surface of the cotyledon, the value of maximum shear strain on the cotyledon were multiplied by the shear moduli of the seed coat to obtain the maximum shear stresses on the seed coat (Table A.9). Maximum shear stress is presented in Figures 6.10 and 6.11, together with the percent damage when impacting beans and the quasi-static shear strength determined from the tensile and compressive tests.

As shown in Figure 6.10, maximum shear stress on the seed coat during impact increases rapidly with decrease of moisture content lower than 14 percent. The shear strength was greatly exceeded by the calculated maximum shear stress which implies that a majority of the beans should have seed coat checks. However as shown in the impact test results the percent of checks was far less than expected from the calculated stress particularly for the impact velocity of 2000 fpm. One possible reason for this discrepancy is that the shear strength value may be considerably lower than the actual strength during impact. Under dynamic loading most

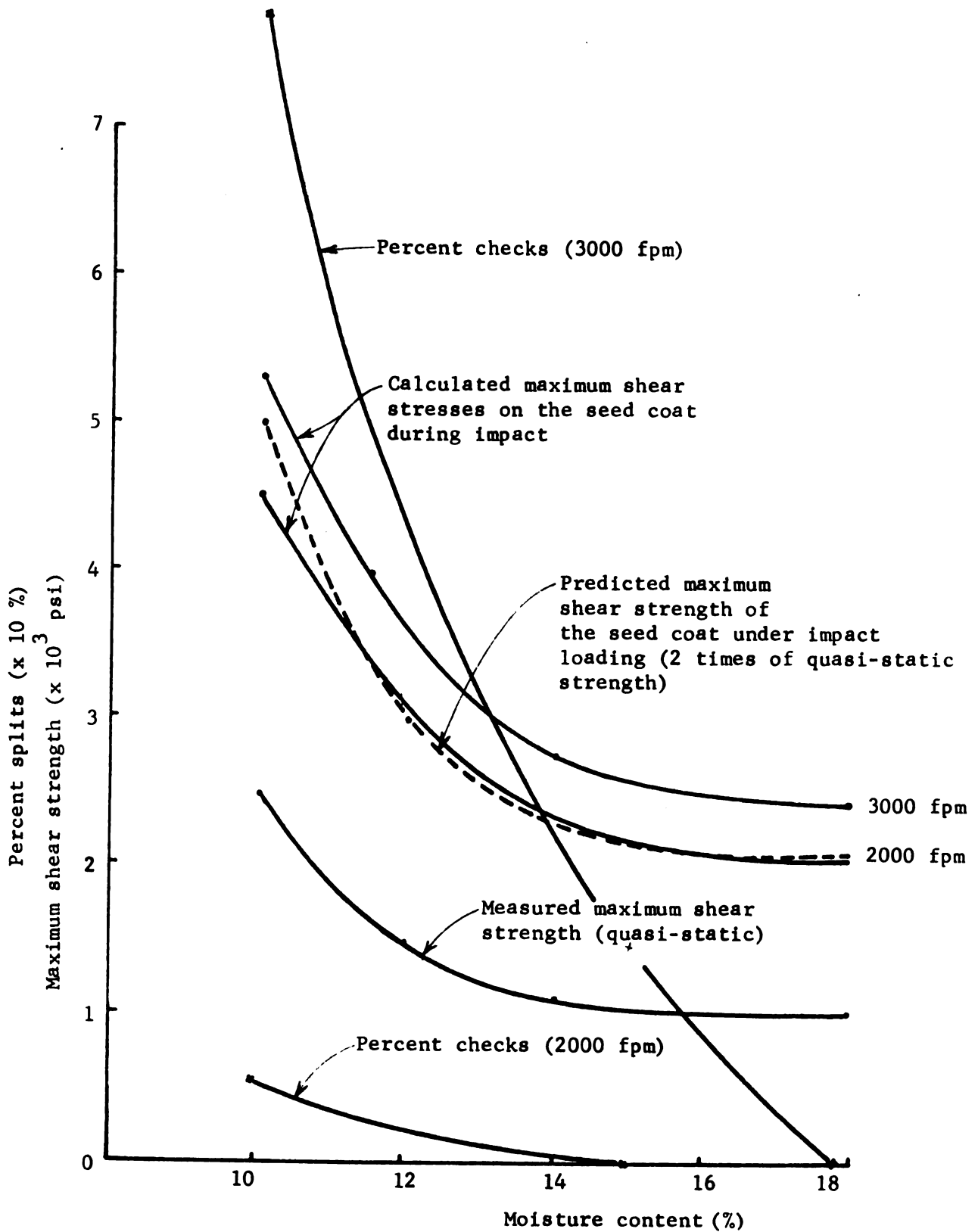


Figure 6.10 Seed coat shear strength and damage for impact loading.

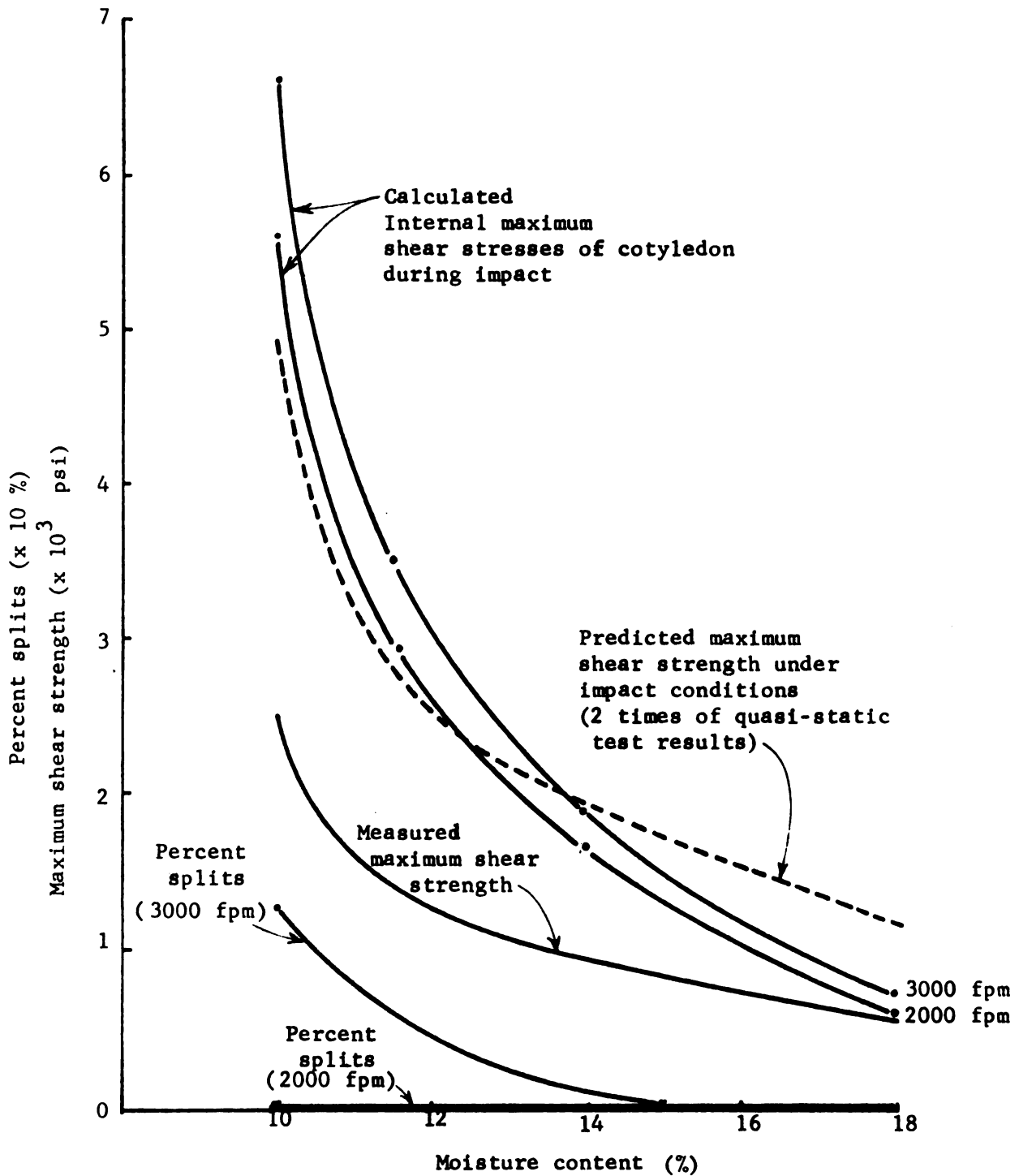


Figure 6.11 Cotyledon shear strength and damage for impact loading.

metallic materials show an increased strength which may reach 1.2 to 1.5 times the quasi-static strength (Goldsmith, 1960). This phenomena may also occur with the bean seed coat material. If dynamic strength of the seed coat is assumed as two times the quasi-static strength, then the dotted curve shown in Figure 6.10 represents the seed coat strength. The dotted curve almost coincides with the calculated maximum shear stress on the seed coat during impact at 2000 fpm. This agrees with the fact that very few checks appeared in the impact tests at 2000 fpm. The curve of shear strength is always below the maximum shear stress curve at 3000 fpm. This generally agrees with the impact test results at 3000 fpm, showing the checks increasing rapidly with decreasing moisture. The test result of no checks at 18 percent moisture content is one discrepancy from the expected results. The reason for this is unknown but may be due to viscoelastic behavior of the seed coat at high moisture, which results in stress relaxation leading to lower actual stress than calculated.

Figure 6.11 shows the calculated maximum internal shear stress and the shear strength of the cotyledon, together with the percent splits for 2000 fpm and 3000 fpm impact velocities. The shear strength was greatly exceeded by the calculated internal maximum shear stress which implies that a majority of the beans should have failed. However as shown in the impact test results the percent of splits, beans with at least one of the cotyledons splits into two or more pieces, was far less than expected from the calculated stress. If the dynamic strength of the cotyledon were assumed to be two times the quasi-static strength then the dotted curve shown in Figure 6.11 represents the cotyledon strength. This curve intersects the curves of the calculated internal maximum

shear stress for 3000 fpm at a moisture content of 14 percent. This agrees better with the impact test results at 3000 fpm, showing the splits starting at about 14 percent moisture content. The predicted maximum shear strength curve is about the calculated internal maximum stress curve for 2000 fpm until the moisture content is decreased to about 12 percent. After that, the curve is almost superposed upon the internal maximum shear stress curve. This agrees with the fact no splits appeared in the impact tests at 2000 fpm. If dynamic shear strength of the seed coat and cotyledon were known more accurate prediction would be possible.

6.10 Summary of Results

The principal findings in this study were as follows:

1. Young's moduli and ultimate stresses increased with decreasing moisture content for both the seed coat and cotyledon. The abrupt increase in Young's modulus and ultimate stress as moisture content decreased below 12 percent was a common phenomenon for the seed coat and the cotyledon.
2. Young's modulus for the seed coat was 2.7×10^5 psi at 10 percent moisture and 0.7×10^5 psi at 16 percent moisture.
3. Ultimate tensile strength of the seed coat material was 5.0×10^3 psi at 10 percent moisture and 2×10^3 psi at 16 percent moisture.
4. Young's modulus for the cotyledon was 1.4×10^5 psi at 10 percent moisture and 0.17×10^5 psi at 16 percent moisture.
5. Ultimate compressive strength for the cotyledon was 5×10^3 psi at 10 percent moisture, but no ultimate

strength was obtained at moisture contents higher than 12 percent because the stress-strain curve for these tests always had a positive slope even for high strain.

6. The Young's modulus of the seed coat calculated from the seed coat ring compression tests agreed with the results from the tension tests.
7. The deformation of the whole bean predicted by the contact theory generally agreed with deformation measured for the whole bean under quasi-static loading. However the predicted deformation was usually somewhat lower than the measured value and the difference tended to be greater for the higher moisture contents.
8. The contact theory incorporated with the impact theory was used to predict the seed coat checks and splits of navy beans during impact. The predicted occurrence of seed coat checks and splits was higher than for impact test results. If the ultimate strength of the seed coat and the cotyledon for impact loading are taken as 2 times the values measured for quasi-static loading, the impact test results agree well with the predictions.

VII. CONCLUSIONS AND RECOMMENDATIONS

The conclusions derived from this study are as follows:

1. The analysis and prediction of mechanical damage to navy beans by using the contact theory shows promise. By knowing the physical properties of beans and loading conditions it is possible to predict when impact damage will occur.
2. In order not to have seed coat checks of more than 1.5 percent at the impact velocity of 3000 fpm, the moisture content of beans should be higher than 14.5 percent. For a velocity of 2000 fpm the seed coat check will be less than 0.5 percent for the moisture content greater than 10 percent
3. For impact loading, elasticity theory should hold better than for quasi-static loading because the bean material under impact is expected to have more nearly elastic behavior.
4. The ultimate strength of navy beans under impact loading appears to be almost 2 times that measured under quasi-static loading.
5. If dynamic ultimate strength of the bean seed coat and cotyledon material were known, damage to beans could be more accurately predicted for impact loading.
6. The application of ring theory to the bean seed coat strength measurement is reasonable. The same application

would be possible for other products with a structure similar to navy beans.

7. Application of the contact theory for predicting bean deformation under static loading is appropriate for beans with low moisture content. Beans with high moisture content appear to be more viscoelastic resulting in larger error.
8. The contact theory and information on the physical properties of beans can be applied to design improved harvesting and handling system of beans.

Further studies should be made to determine the dynamic ultimate strength of navy beans. Similar studies would be useful for other agricultural products where damage due to impact loads is encountered. Future studies on navy beans or other products should include determination of Poisson's ratio to permit more accurate stress analysis. Also studies on the coefficient of restitution for navy beans and other grains will be useful. Evaluating the effect of shear impact may be more complicated but of great interest.

Application of the contact theory offers great potential in dealing with the mechanical damage of agricultural products. Mechanical damage occurs during harvesting and handling only if material contact is made. The degree and extent of damage depend upon the physical properties of the material and the loading conditions. The physical properties needed for mechanical damage analysis include size, shape, weight, surface coefficient of friction, radius of curvature of the surface, elastic or viscoelastic constants and ultimate strength of the material. If these properties were known, approximate solutions may

be obtained for many problems involving fracture, deformation, or crushing of agricultural products through application and expansion of the contact theory. Reasonable accuracy will be obtained with relative simplicity, if tabulated physical property data are available for use in the calculations.

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APPENDIX

TABLE A.1--Young's modulus and ultimate strength of seed coat for two different cuts under the moisture content of 16.2 percent.

	Test No.	Young's Modulus ($\times 10^5$ psi)	Ultimate Strength (psi)
Perpendicular cut	1	0.7414	2111
	2	0.5925	2098
	3	0.7490	2115
	4	0.9153	2704
	5	0.7830	2291
	Average	0.7562	2264
	S.D.	0.1152	259
Parallel cut	1	0.6765	1838
	2	0.8281	2890
	3	0.5641	1824
	4	0.7746	2164
	5	0.5367	1508
	Average	0.6760	2045
	S.D.	0.1273	526

Note: No significant difference at 5% level between the two different cuts for both Young's modulus and ultimate stress values.

Loading speed : 0.1 ipm

TABLE A.2--Relative change of bean dimensions and weight for medium beans with hours of natural drying under room temperature.*

Hours of drying	0		24		72		144	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Shrinkage of length (%)	0	0	2.17**	0.41	2.16	0.32	2.16	0.29
Shrinkage of width (%)	0	0	1.12	0.23	1.14	0.30	1.18	0.26
Shrinkage of height (%)	0	0	2.06	0.36	2.16	0.55	2.30	0.78
Decrease of weight (%)	0	0	7.74	0.38	10.76	0.51	11.76	0.57
Moisture content (%)	18.8	1.3	12.0	0.2	9.1	0.2	8.1	0.1

*Values are based on the measurement of 10 beans.

**The reason for this value slightly exceeding the values after more hours may be due to the measurement error.

TABLE A.3--Radii of curvatures of the two sides of medium beans

Bean No.	Minor radius (m m)		Major radius (m m)	
	Side 1	Side 2	Side 1	Side 2
1	3.0	3.3	5.9	7.1
2	3.1	3.2	6.6	7.7
3	3.7	3.2	6.6	5.8
4	3.4	3.2	6.4	6.8
5	2.9	3.0	6.3	6.6
6	2.9	3.0	6.5	8.0
7	3.2	3.2	7.1	5.9
8	3.0	3.4	6.4	6.1
9	3.1	3.8	6.3	6.4
10	3.5	2.9	6.1	7.1
Average including Sides 1 and 2	3.200 (0.1260 in.)		6.585 (0.2593 in.)	
S. D.	0.255 (0.0100 in.)		0.580 (0.0228 in.)	

Note: Moisture content: 18.8%

TABLE A.4--Mechanical strength of bean seed coat at various moisture contents

Moisture Content (% w.b.)	Number of specimen tested	Young's Modulus ($\times 10^5$ psi)	S. D. ($\times 10^5$ psi)	Ultimate Strength (psi)	S. D. (psi)	Ultimate shear strength (psi)	S. D. (psi)
10.0	8	2.66	0.26	4976	440	2448	220
10.7	5	2.12	0.28	4669	332	2335	166
12.2	4	1.43	0.10	2879	328	1439	164
13.2	4	1.09	0.16	2390	132	1195	66
14.7	4	1.05	0.11	2230	301	1115	150
16.2	5	0.76	0.12	2064	216	1032	108
16.5	9	0.68	0.08	2146	197	1073	99

Note: Maximum shear strength was taken as a half of the ultimate strength.

Loading speed: 0.1 ipm.

TABLE A.5--Mechanical strength of bean cotyledon at various moisture contents.

Moisture content (% w.b.)	Number of specimen tested	Young's modulus ($\times 10^5$ psi)	S.D. ($\times 10^5$ psi)	Ultimate strength (psi)	S.D. (psi)	Ultimate shear strength (psi)	S.D. (psi)	Remarks
10.0	10	14.5	1.1	5164	303	2582	152	
10.3	5	12.0	0.3	4092	179	2046	90	
11.5	11	6.7	0.5	2929	176	1465	88	
13.0	12	3.7	0.4	1252	111	626	55	2% offset strain
15.5	9	2.5	0.3	916	160	408	80	2% offset strain
17.3	11	1.1	0.2	398	34	199	17	2% offset strain
19.5	10	0.6	0.1	326	61	163	30	2% offset strain

Note: Maximum shear strength was taken as a half of the ultimate strength.

Loading speed: 0.1 ipm.

TABLE A.6--Young's modulus of bean seed coat calculated from thin ring theory.

Test No.	Moisture content (%)	D Diameter (in)	W Width (in)	t Thickness (in)	P/ δ (lb/in)	E ($\times 10^5$ psi)
1	9.8	0.2198	0.0639	0.0034	0.576	3.22
2	9.8	0.2242	0.0625	0.0033	0.532	3.53
3	9.8	0.2211	0.0632	0.0031	0.500	3.81
4	10.8	0.2105	0.0642	0.0034	0.385	1.88
5	11.0	0.2087	0.0636	0.0033	0.379	2.00
6	11.1	0.2151	0.0651	0.0037	0.375	1.51
7	11.1	0.2084	0.0655	0.0034	0.412	1.92
8	11.3	0.2057	0.0656	0.0032	0.350	1.88
9	11.7	0.1960	0.0640	0.0037	0.578	1.78
10	11.7	0.1890	0.0645	0.0035	0.483	1.56
11	13.2	0.2106	0.0652	0.0032	0.197	1.14
12	13.2	0.2118	0.0657	0.0038	0.299	1.04
13	13.2	0.2026	0.0670	0.0033	0.278	1.28
14	13.2	0.2170	0.0640	0.0032	0.200	1.29
15	15.6	0.2198	0.0650	0.0034	0.148	0.81
16	15.8	0.2298	0.0640	0.0032	0.078	0.60
17	15.8	0.2208	0.0659	0.0033	0.150	0.90
18	15.8	0.2120	0.0638	0.0036	0.216	0.92
19	15.8	0.2154	0.0649	0.0035	0.188	0.94

Note: $\nu = 0.3$

TABLE A.7--Calculations of internal maximum shear stress of the cotyledon and maximum shear stress on the seed coat at 2000 fpm.

Moisture content (%)	Young's modulus ($\times 10^5$ psi) E	$k = \frac{1-\nu^2}{\pi E}$ ($\times 10^{-5}$)	Bean mass ($\times 10^{-6}$ sec ² -lb/in) m	Maximum approach (in) α	Maximum compression force (lb) P _{max}	Radius of contact area (in) a	Maximum pressure (psi) q _o	Internal* maximum shear stress (psi) $\tau_{\max}$	Maximum** shear stress on the contact surface of cotyledon (psi) $\tau_{\text{coty max.}}$
10.0	1.45	0.1997	0.983	0.0055	35.74	0.0306	18224	5649	2460
11.5	0.65	0.4456	0.999	0.0076	26.18	0.0360	9645	2990	1302
14.0	0.31	0.9344	1.024	0.0103	19.76	0.0420	5348	1658	722
18.0	0.10	2.8966	1.069	0.0166	12.90	0.0531	2184	677	295

Note: Radius R = 0.170 inches

* $\tau_{\max} = 0.31 q_o$

Poisson's ratio $\nu = 0.3$

** $\tau_{\text{coty max}} = 0.135 q_o$

TABLE A.8--Calculations of internal maximum shear stress of cotyledon and maximum shear stress on the seed coat at 3000 fpm

Moisture content (%)	Young's modulus (x10 ⁵ psi) E	$k = \frac{1-\nu^2}{\pi E}$ (x10 ⁻⁵)	Bean mass (x10 ⁻⁶ sec ² - lb/in) m	Maximum approach (in) a	Maximum compression force (lb) P _{max}	Radius of contact area (in) a	Maximum pressure (psi) q _o	Internal* maximum shear stress (psi) τ _{max}	Maximum** shear stress on the contact surface of cotyledon (psi) τ _{coty max.}
10.0	1.45	0.1997	0.983	0.0076	58.14	0.0360	21420	6640	2892
11.5	0.65	0.4456	0.999	0.0106	42.59	0.0424	11311	3507	1527
14.0	0.31	0.9344	1.024	0.0143	32.14	0.0494	6288	1949	849
18.0	0.10	2.8966	1.069	0.0229	20.98	0.0624	2576	798	348

Note: Radius R = 0.170 inches

Poisson's ratio ν = 0.3

$$* \tau_{\max} = 0.31 q_o$$

$$** \tau_{\text{coty max}} = 0.135 q_o$$

TABLE A.9--Calculations of maximum shear stresses on the bean seed coat.

Moisture content (%)	Young's modulus of cotyledon E_{coty} ($\times 10^5$ psi)	Shear modulus of cotyledon $G_{coty} = \frac{E_{coty}}{2(1+\nu)}$ ($\times 10^5$ psi)	Maximum shear strain on the contact surface of cotyledon		Young's modulus of seed coat E_{coat} ($\times 10^5$ psi)	Shear modulus of seed coat $G_{coat} = \frac{E_{coat}}{2(1+\nu)}$ ($\times 10^5$ psi)	Maximum shear stress on the seed coat $\tau_{coat max} = G_{coat} \gamma_{coat max}$ (psi)	
			$\gamma_{coty max} = \frac{\tau_{coty max}}{G_{coty}}$ ($\times 10^{-2}$)	$\tau_{coty max}$ G_{coty} ($\times 10^{-2}$)			2000 fpm	3000 fpm
10.0	1.45	0.558	4.409	5.183	2.66	1.023	4510	5302
11.5	0.65	0.250	5.208	6.108	1.70	0.654	3406	3995
14.0	0.31	0.119	6.067	7.134	1.00	0.385	2335	2747
18.0	0.10	0.038	7.063	9.158	0.70	0.269	2088	2464

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