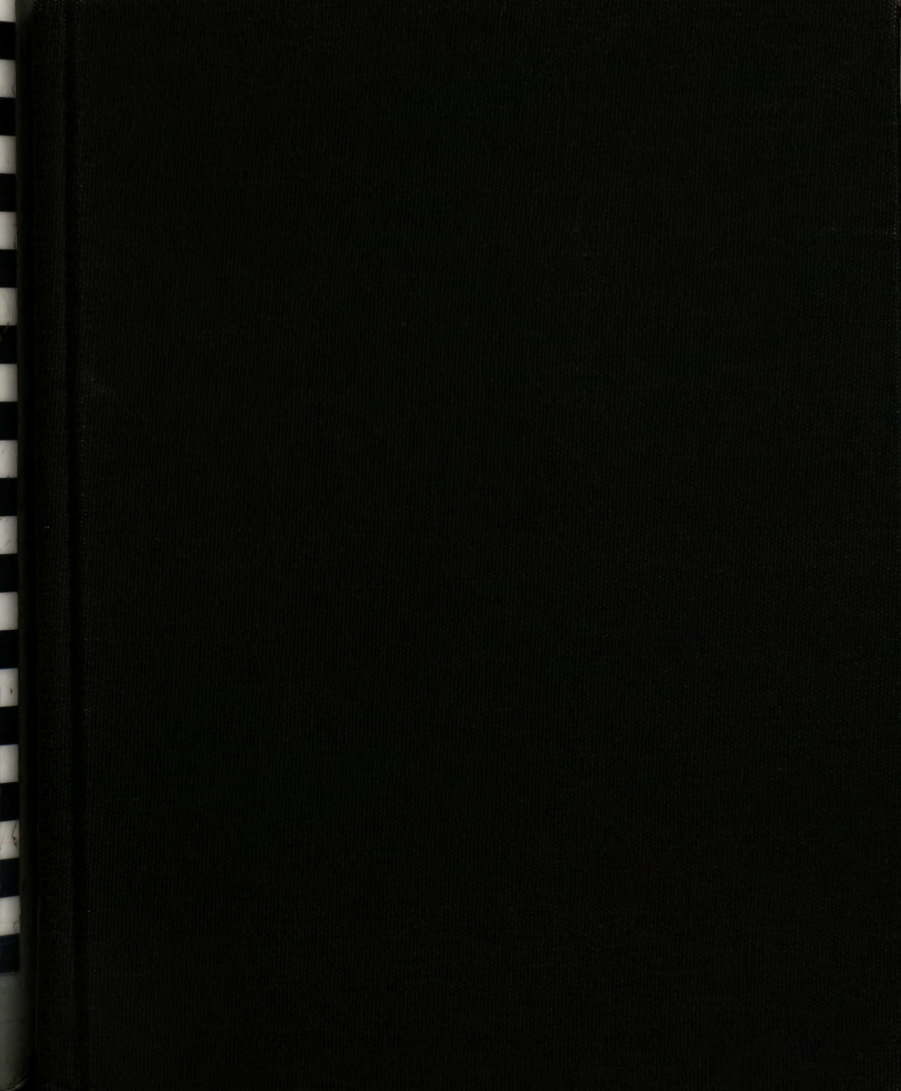






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CONSTITUTIVE MODEL OF TENDON RESPONSES  
TO MULTIPLE CYCLIC DEMANDS

presented by

Keyoung Jin Chun

has been accepted towards fulfillment  
of the requirements for

Ph.D. degree in Mechanics

A handwritten signature in black ink, appearing to read 'David P. Hubbard'. The signature is written over a horizontal line.

Major professor

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CONSTITUTIVE MODEL OF TENDON RESPONSES

TO MULTIPLE CYCLIC DEMANDS

By

Keyoung Jin Chun

A DISSERTATION

Submitted to  
Michigan State University  
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# ABSTRACT

## CONSTITUTIVE MODEL OF TENDON RESPONSES TO MULTIPLE CYCLIC DEMANDS

BY

Keyoung Jin Chun

The purpose of this research has been to measure and to model the responses of tendon to multiple cyclic tests including tests with constant peak strain levels (defined as A-type tests), tests with constant peak strain levels and two rest periods (B-type tests), and tests with different peak strain levels (C-type tests). Cyclic relaxation and recovery phenomena in measured values of peak stress, hysteresis, and slack strain for all three types of cyclic tests have been discussed and compared with predicted results.

The ability of tendon specimens to resist deformation has been studied with sections of long tendons which were divided into the muscle ends, mid-portions, and bone ends. The sections were found to be the stiffest in the bone ends and the least stiff in the mid-portions. Also, mechanical similarity of the anatomically paired tendons has been investigated.

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The surface deformations of tendons have been studied statically in relaxation tests by photographic analysis and dynamically during cyclic extensions in the multiple cyclic tests with the Reticon line scan diode camera. Although there was substantial variability, the study of surface deformations showed that the local surface strains near the gripped ends were generally greater than the local surface strain at the middle segment.

In the modeling work, the hereditary integral form of a quasi-linear viscoelastic law has been employed. Three new theoretical concepts have been employed: 1. a reduced relaxation function with a non-linear exponential function of time, 2. an instant elastic recovery effect during unloading, and 3. negative values of stress (compressive stresses) in theoretical calculations. These concepts have been supported by agreement between measured and predicted responses of soft connective tissue to multiple cyclic extensions. Such agreement has not been attained in the few previous studies.

## ACKNOWLEDGEMENTS

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## I. INTRODUCTION

During the course of common activities, people subject their connective tissues to numerous cycles of load in diverse and complex situations. Many human activities include several thousand mechanical demands on connective tissue. Thus, the response of collagenous tissues to repeated loading and deformation is central to their biomechanical function. Experimental data for cyclic extensions are extremely limited [23,43,56]. Hubbard and his coworkers [23,43] have performed extensive repeated cyclic extension tests on tendons at different strain levels.

Since tendons are predominantly collagen fibers, understanding the mechanical responses of tendons will provide some insights into the responses of other soft connective tissues such as ligaments or fascia whose composition includes collagen. The qualitative responses of collagen to mechanical demands are similar among all collagenous tissues. Their quantitative responses are dependent on the proportions and arrangements of tissue constituents.

Tendon is a collagenous tissue which connects muscle to bone and remains rather inextensible relative to muscle during muscle contraction. Tendon consists primarily of collagen fibers with a small percentage of elastin fibers and a matrix of ground substance. In the study of mammalian tendons, Elliot [10] shows that collagen fibers constitute 70-85% of the dry weight of the tendon while the content of elastin fibers make up only 2% of the dry weight. The

main function of tendon is to transmit force between muscle and bone.

The collagen fibers in tendons are parallel and zigzag crimped rather than sinusoidal [7,8,29,30]. Also, these fibers act mechanically in parallel and lie in the direction of the tendon axis [7,8,29,53]. When the tendon is stretched, the collagen fibers are straightened until all waviness disappears; when the load is released, the waviness reappears [29,41,51,54].

The matrix of ground substance surrounds the fibers in the tendon and aids in metabolism by passively transporting nutrients and waste. The ground substance is a gel and its mechanical role is not clear yet. Yannas [58] ignores the mechanical role of this material. Partington and Wood [39] conclude that the ground substance has significantly less mechanical effect than the elastin fibers. However, Haut [20] indicates that the ground substance may contribute significantly to energy absorption.

Thus, in the study of mechanical properties of tendon, the response of the collagen fibers is predominant in comparison with the responses of the elastin fibers and the matrix of ground substance. However, the elastin fibers and ground substance may contribute in crimping the tissue when the load is released. Also, the ground substance may play a key role in the physiological conditions which are important to tissue behavior.

To better understand the mechanical responses of collagenous tissues, many researchers have developed constitutive models and

compared their predicted results to measured responses from mechanical tests [12,22,28,33,34,45,56]. Fung [14] proposed the use of a quasi-linear viscoelastic theory and showed that mechanical responses of rabbit mesentery data agreed with his theory using an exponential reduced relaxation function with a standard linear solid viscoelastic model.

Haut and Little [22] studied the viscoelastic properties of rat tail tendon. They introduced a logarithmic expression for the reduced relaxation function and a second order stress-strain law. They found that their model was adequate to describe the responses at different strain rates. However, in the case of cyclic extension, the model did not agree well with the experimental data. Similar conclusions were made by Jenkins and Little [28] in the study of the ligamentum nuchae.

Woo, et al. [56] utilized Fung's approach to model the medial collateral ligament. Although agreement between model and experimental data was generally good for a few extension cycles, Woo's model began to predict higher peak and valley stresses than the experimental data within the first ten cycles.

Lanir [33] assumed that the non-linear response of the tissue is due to the waviness of the collagen fibers. He developed a microstructural model which utilized a function of the distribution of fiber slack lengths. He assumed the collagen fibers were linear viscoelastic in the form of the standard linear solid with an exponential reduced relaxation function. His model predicted that

there was less stress relaxation at a lower strain level than at a higher strain level.

An approach similar to Lanir's model was used by Little, et al. [34] to model spinal ligaments from primates. Their model used the same logarithmic reduced relaxation function as Haut and Little [22] and a complex distribution function which includes the effect of fiber orientation and initial waviness. Good agreement was found in single constant strain rate tests. However, they did not attempt to model the cyclic relaxation. None of the currently available models have been shown to adequately predict the responses to the repeated cyclic extensions.

While stretching a tendon, the deformation is not uniform throughout the tendon. Butler, et al. [4] showed that local surface strain near the bone attachment sites of human patellar tendons appeared to be larger than local surface strain in the mid-region during stretching. However, Stouffer, et al. [48] showed that mean values of local strains near the tibia and patella were less than in the center of the fiber bundles. This result conflicts with Butler's result [4].

Previous studies of multiple cyclic extensions with tendons [23,43] used peak strains from 2% to 6%. With 6% strain, there was evidence that there may have been some irreversible changes in tissue responses. Such irreversible changes were not apparent at 4% strain or below. Thus, 4% peak strain is apparently within the range for reversible, viscoelastic responses of tendon. Also, this

4% strain was selected to be below the level for significant fiber damage [42].

In summary, mechanical responses of tendons and other predominantly collagenous tissues have been modeled and measured. Testing has provided an understanding of tendons as nonlinear viscoelastic tissues. The deformations within tendon have been seen to be nonuniform along the length of the tendon. Constitutive modeling has been based on hereditary integral formulation and has successfully predicted some tendon responses. However, constitutive modeling has not as yet predicted the tendon responses to strain histories with continuous repeated extensions, rest periods of zero extension, or variations in peak strain levels.

The fundamental questions addressed in this research are:

1. Can a mathematical model be developed to predict the mechanical responses for multiple cyclic extensions?
2. Can a model describe or predict the responses of tissues to extension histories that contain rest periods?
3. Is the response to a specific level of cyclic extensions affected by the previous extensions at a different level, and if so, how? Can a model predict this phenomenon?

4. How do the surface strains change with repeated cyclic extensions, and does this relate to the changes of load responses with cycles?

## II. EXPERIMENTAL MATERIALS AND METHODS

### II.1. Introduction

Two basic types of empirical studies have been conducted to measure the mechanical responses of tendons:

1. Relaxation tests were conducted in which specimens were extended to either 3% or 4% strain level relative to their initial length and held at that strain level for 22 hours. Specimen extensions, loads, and surface deformations were measured in these relaxation tests. These tests were conducted to provide viscoelastic characteristics for constitutive modeling of tendon responses.
2. Multiple cyclic tests were conducted to better understand the responses of tendons and to compare measured responses with responses which were predicted by the constitutive model. All of the multiple cyclic tests were either continuous cyclic extensions to 3% peak strain, cyclic extensions to 3% peak strain interrupted with rest periods of no extension, or cyclic extensions alternating between 3% and 4% peak strain levels. In addition to the multiple cyclic tests for comparison with predicted results, a limited series of

multiple cyclic tests was conducted to study surface deformations.

## II.2. Specimen Preparation

Tendon specimens were obtained from the hindlimbs of seven canines sacrificed during surgery classes at the MSU College of Veterinary Medicine. All hindlimbs were either dissected within a few hours after death or frozen whole at  $-70^{\circ}\text{C}$  and dissected within two days in the Department of Biomechanics. The tendons were dissected with care to avoid damage by excessive pulling or by nicking with a scalpel. They were cut near the bone insertion and the muscle-tendon interface. Tendons which pass over joints are flared and such tendons were cut transversely in the flared region. Paired tendon specimens at the same anatomical location were chosen from the left and right hindlimb. Each specimen was 45 mm or longer with a near constant cross-sectional area. Thick specimens with major diameters larger than 5 mm were avoided, since it was thought that large cross-sections would not insure uniform pressure between interior and exterior fibers during gripping.

After dissecting, each paired tendon specimen was wrapped in a paper towel dampened with Ringer's lactate solution (see Appendix 1) and sealed in a plastic bag marked with the anatomical site, the section (bone end, mid-portion, and muscle end) and the date of dissection. Thereafter, groups of paired tendons from each canine were put into a large plastic bag, sealed air-tight with tape, and

these bags were put into air-tight containers and stored in a freezer at  $-70^{\circ}\text{C}$ . This packing method prevented tendon dehydration and decay during storage.

Throughout the specimen preparation and test, the specimens were kept either fully moistened or immersed in Ringer's lactate solution at room temperature ( $22^{\circ}\text{C}$ ). Test preparation started by taking a pair of tendon specimens from the freezer and placing them, while still wrapped in the paper towel, into a container which was filled with Ringer's lactate solution. The specimens were soaked in the Ringer's lactate solution for a minimum of 30 minutes during which there was complete thawing and any osmotic processes stabilized. The paper towel was removed and the paired tendons were placed on a plastic dissection tablet. The tendon sheaths were not rigidly connected to the tendon fibers and hence may not follow fiber movement. Therefore, the tendon sheaths were very carefully removed from each tendon. One of the paired tendons was kept for the next test in a refrigerator to prevent decay or returned to the freezer if it would not be tested within one hour.

For a relaxation test, the specimen was marked with a water resistant pen at approximately every 10 mm so that surface deformation and any grip slippage which may have occurred could be measured photographically. For the measurement of surface strain during cyclic extension, targets of self-adhesive, water resistant, stiff, narrow (about 0.5 mm) plastic strips were cut from flexible disk write-protect tabs and were glued with cellulose nitrate [55] at approximately every 10 mm. This cellulose nitrate did not create

local dehydration of the tendon during testing. The Reticon camera scanned these targets and grips for measurement of surface deformation.

### II.3. Testing Equipment

Tests were conducted utilizing an Instron servo-hydraulic materials testing system (Model 1331, Instron Co.), which was controlled by a PDP-11/23 computer. The hydraulic actuator was mounted in the upper crosshead and a submersible load cell was mounted in the saline bath between the lower grip and the lower crosshead. A linear variable displacement transducer (LVDT) mounted in the hydraulic actuator provided an electrical feedback signal proportional to actuator displacement. The 100 lb (444.8 N) load cell (Model SSM-A5-100, Interface Inc.) was fully submersible. A saline bath was used to simulate in vivo tissue fluid environment and to maintain a constant temperature during testing. This saline bath had clear, flat front and rear windows. The front window was a quartz plate for a good camera images. The rear window was a clear plastic plate to allow back lighting for the Reticon line scan camera.

For gripping tendon specimens, flat-plate clamp grips were employed with waterproof 100 grit silicon carbide abrasive paper on their inner surfaces. This gripping method provided sufficient friction without either slippage or damage apparent in the specimen. Sacks [43] reported that the fibers within the grips were continuous

and compressed together but neither torn nor fractured with this gripping method.

#### II.4. Computer Equipment

A PDP-11/23 (Digital Equipment Co.) computer which had an RSX-11M+ operating system was used for test control and data acquisition, storage, and analysis. The details of data acquisition and storage are described in Appendix 4. Two RL01 hard disk drives and two RX02 8" floppy disk drives were coupled to this computer. An Instron Machine Interface Unit enabled command and communication between the computer and the testing machine. Data were also monitored and stored on a Nicolet digital oscilloscope (Model 201, Series 2090), which had a 5  $\frac{1}{4}$ " floppy disk drive for data storage. A Nicolet software library [38], designed to implement communication between a PDP-11 computer and a Nicolet digital oscilloscope, transferred the stored data to a PDP-11/23 for analysis. Data were displayed on a Tektronix 4010-1 graphics terminal and a Printronix P-300 high speed line printer. MULPLT [37], a powerful data-file based plotting program, was used as the graphics software.

For modeling calculations, a VAX-11/750 (Digital Equipment Co.) with a VMS operating system was used. Model results were transferred to the PDP-11/23 by Decnet, a file transfer program, for comparison with the measured data.

## II.5. Optical Equipment

For the measurement of the surface strains in the relaxation test, tendon specimens were marked at approximately every 10 mm with dye. Photographs were taken twice (before and just after the extension to the constant strain level) with a WILD MPS 55 microscope camera (Wild Heerburgg Ltd.). Thereafter, 8"x10" prints were developed and the surface deformations were measured with a micrometer.

For the measurement of the surface strains during cyclic extensions, a Reticon camera (Model LC 120 V2048/16), which employs a 2048 element solid state photodiode array to sense the image, was utilized (see Appendix 9 for description). The accuracy of measurement was optically determined by the field-of-view depending on the working distance used. In this study, position differences of 0.7 mils (17.5  $\mu\text{m}$ ) were resolved with about a 35 mm field-of-view. The field-of-view was imaged by the lens onto the photodiode array, which was electronically scanned to provide both analog and digital signal outputs to the RSB6320 camera data formatter and interface unit. This RSB6320 was plug-compatible with a DEC "Q-Bus" and an LSI-11 microcomputer. The digital image data were created in the camera by comparing a user-settable threshold to the camera's analog video. The digital image data from the Reticon camera were accepted and preprocessed by the RSB6320 without a need for a PDP-11/23 CPU control. The formatted camera data were stored in two 254-word RAM memories on-board the RSB6320. These two memories

allowed simultaneous image data storage and computer processing of data. While one memory was getting image scan data, the other was available to the Q-Bus for computer processing of the data. This toggling scheme was used to accommodate the acquisition of camera data at clock rates up to 2 MHz. At this rate, a 2048 pixel scan line would take nominally 2 ms. However, the ultimate limitation on image data rate was generally dependent upon the number of transitions, complexity of the image, and the computer's ability to accept and process image data.

The back lighting system was chosen to make a good uniform light field for the Reticon camera. A 12V-DC fluorescent light was employed as the lighting system to obtain a useful image.

#### II.6. Test Protocol

All tests started with the mounting of the prepared specimen into the upper grip, then lowering it into the lower grip and securing it with care to assure that the specimen was centered and straight. With the specimen slack, the load readout was electronically zeroed and the load cell was calibrated in the 100% (444.8 N) load range. It was then returned to the desired load range (10%, 44.48 N). Thereafter, the specimen was slowly extended until loading was first detected at about 0.3% (0.13 N) of the desired load range. This was the smallest load clearly recordable by the equipment. The length of the specimen at this point was taken to be its initial length, and it was measured as the distance

between the upper and lower grips with a micrometer. Then the front cover, which had a quartz plate window, was mounted and the bath was filled slowly with Ringer's lactate solution to avoid any bubbles around the specimen. The load cell was rezeroed and recalibrated.

#### II.6.a. Relaxation test

The relaxation tests were performed when the specimens were initially stretched at 75%/sec strain rate and the strain levels (3% or 4%) held constant for 22 hours. Load and deformation data were gathered throughout the relaxation test.

#### II.6.b. Multiple cyclic test

The multiple cyclic tests involved three different types of cyclic test sequences (see Fig. 2-1). One sequence (A-type) was cyclic extension with the maximum strain level held constant at 3% throughout the test. Another sequence (B-type) was the same as the first one but with two rest periods during the test. The third sequence (C-type) was cyclic extension with two different maximum strain levels during the test starting with 3% maximum strain and alternating with 4% maximum strain. Maximum strain levels of 3% and 4% were chosen to study strain level sensitivity. These strain levels were selected to be below the level for significant fiber damage [42]. A constant strain rate of 5%/sec was chosen as an intermediate between rapid and slow physiological movement [23,43]. Since a constant strain rate was chosen to eliminate strain rate effects in this study, strain rate sensitivity was not investigated.

Because of the constant strain rate, the frequency and total number of cycles varied between strain levels. The time for one cycle was 1.2 seconds (0.833 Hz) at the 3% strain level and 1.6 seconds (0.625 Hz) at the 4% strain level. For these multiple cyclic tests, all information was supplied to the interactive testing program (see Appendix 5 and 6).

In additional tests for the measurement of surface strains during cyclic extension, the targets and grips on the tendon were scanned by the Reticon camera, and the transitions of the image signal were carefully monitored and checked on the Nicolet digital oscilloscope. All information was supplied to the interactive testing program (see Appendix 7). For these tests, a constant strain rate of 2%/sec was chosen with the maximum strain levels held constant (3%) throughout the test with one rest period (120 sec). The time for one cycle was 3.0 seconds (0.333 Hz) at a 3% maximum strain level. The 2%/sec strain rate was selected for these tests to acquire 34 data samples per cycle at 88 ms per point, the maximum practical scan rate with the Reticon camera and PDP-11/23 computer.

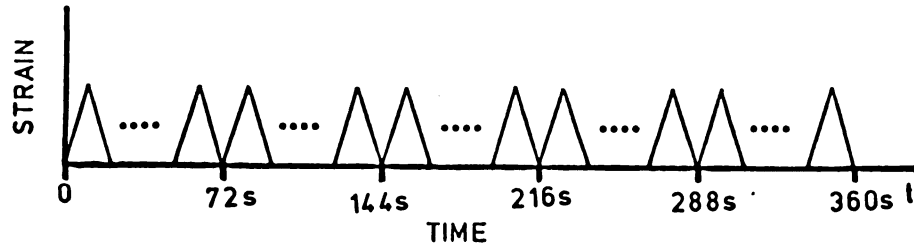
#### II.7. Histology, Cross-Sectional Area Measurement

Upon test completion, the specimen was removed from the grips and placed with specimen identification into a sealed container which was filled with a 2% gluteraldehyde buffer and refrigerated for 3 days at 4°C prior to histological preparation.

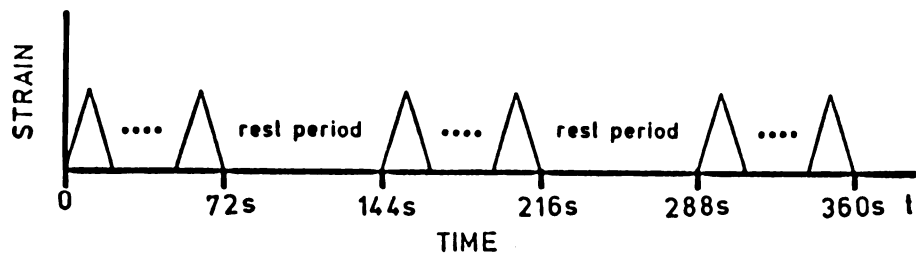
Cross-sections were cut from the middle of the specimen. Slides were prepared according to standard histology procedure (see Appendix 2).

The cross-sectional area was measured to normalize load as stress. Cross-sectional area was determined by using the slide which was picked from the middle section of the specimen. The slide was first placed into a photographic enlarger along with a glass scale (Wild Heerburg Ltd.) and then the photographic paper was developed. The area of the photographic image was measured by a digitizer (Numonic Co.) and multiplied by the appropriate scale factor determined from the image of the glass scale. Considering the combined accuracy of the digitizer and operation, the areas were accurate within  $0.01 \text{ mm}^2$ . Slight size changes that may have occurred during the histological processes were thought to be consistent throughout all specimens.

A. Constant peak strain level test (A-type)



B. Constant peak strain level test with rest periods (B-type)



C. Different peak strain level test (C-type)

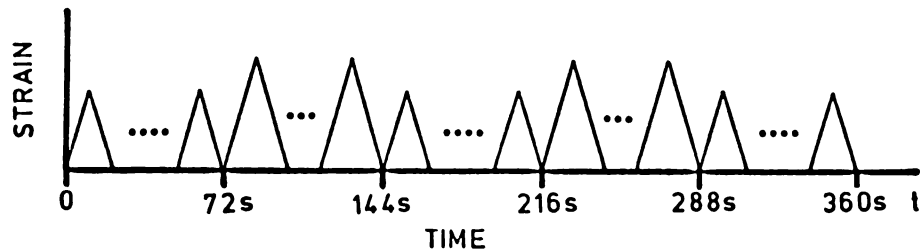


Fig. 2-1 Illustrations of the multiple cyclic test sequences with constant strain rate

### III. EXPERIMENTAL RESULTS

#### III.1. Introduction

As will be developed in Chapter IV, the constitutive model for tendon is based on the hereditary integral formulation proposed by Fung [14]. This constitutive model incorporates information about measured tendon responses in the form of a relaxation function which has been separated into an "elastic" response and a "reduced" relaxation function. The constitutive equation also incorporates some modeling assumptions which are based on an empirical understanding of tendon responses and structure.

The purpose of this chapter is to present empirical results which will be interpreted for use as input to the constitutive model and to present empirical results which will be compared to results from model calculations to assess the predictive capabilities of the model.

This chapter is lengthy, so it is divided into several sections:

1. Introduction.
2. Relaxation Test Results: In this section, relaxation test results are presented and interpreted in the reduced relaxation function for use in the constitutive model.

3. Multiple Cyclic Test Results: In this section, multiple cyclic test results are presented and discussed. These measured results provide insights into tendon responses. The measured data are compared, in Chapter V, with the calculated results from the constitutive model.
4. Sectional and Anatomical Differences in Response: In this section, mechanical responses of the tendon specimens which are sections of single, long tendons (bone end, mid-portion, muscle end) are presented and compared. Also, the similarities of the mechanical responses in the anatomically paired tendons are presented.
5. Measurements of Surface Strains: In this section, measurements of deformations on the surface of tendon specimens during relaxation tests and during multiple cyclic tests are presented and discussed.

### III.2. Constant Strain Relaxation Test Results

The relaxation tests were conducted with anatomically paired tendons from the same animal. As described in Chapter II, data were monitored and stored on a Nicolet digital oscilloscope. The stored data were transferred to the PDP-11/23 computer and translated to a useable file using the Nicolet software library [38]. The files were analyzed graphically with MULPLT [37] and statistically by

calculation of the averages, the standard deviations, and the 95% confidence intervals [35].

In Table 3-1, the anatomical sites, paired status, initial lengths, and areas are shown. Table 3-2 shows the initial and final stresses with a statistical summary. Decrease in load for each test was checked at 21.5 hours after starting and the test was finished at 0.5 hour later for a total test time of 22 hours. There was no decrease in load during the last half hour of any relaxation test.

Figures 3-1(a) through (c) and Figures 3-2(a) through (c) show the stress relaxation results of the paired tendon tests at 3% and 4% strain level, respectively. The stress values have been normalized to a value of 1.0 for the initial stress value for comparison between specimens and interpretation as a reduced relaxation function.

The tendon pair 3-5 and 3-6 in Figure 3-1(c) show similar responses. Almost the same stress relaxation responses are shown in Figure 3-2(a) between the tendon pair 4-1 and 4-2. However, the other tendon pairs, Figures 3-2(b) and (c), show different relaxation responses within the pair. Also, from Table 3-1 and Table 3-2, specimens 3-1, 3-2 and 3-5, 3-6 have similar areas and peak stresses. But their stress relaxation responses are different, as shown in Figure 3-1(a) and Figure 3-1(c). In the case of tests no.4-1 and no.4-2, the areas and peak stresses are different from each other, but the stress relaxation responses are almost the same.

Table 3-1Tendon Specimen Characteristics in Relaxation Test

| Strain Level | Test Number | Anatomical Location       | Pair Status | Initial Length(mm) | Area (mm <sup>2</sup> ) |
|--------------|-------------|---------------------------|-------------|--------------------|-------------------------|
| 3%           | 1           | Extensor digitorum longus | ) pair      | 34.26              | 0.85                    |
|              | 2           | Extensor digitorum longus |             | 33.29              | 0.88                    |
|              | 3           | Peroneus longus           | ) pair      | 33.10              | 1.33                    |
|              | 4           | Peroneus longus           |             | 32.45              | 2.22                    |
|              | 5           | Extensor digitorum longus | ) pair      | 32.04              | 2.06                    |
|              | 6           | Extensor digitorum longus |             | 32.88              | 2.00                    |
| 4%           | 1           | Flexor digitorum longus   | ) pair      | 33.38              | 1.03                    |
|              | 2           | Flexor digitorum longus   |             | 33.43              | 1.21                    |
|              | 3           | Extensor digitorum longus | ) pair      | 35.03              | 1.63                    |
|              | 4           | Extensor digitorum longus |             | 33.40              | 0.68                    |
|              | 5           | Extensor digitorum longus | ) pair      | 33.08              | 2.00                    |
|              | 6           | Extensor digitorum longus |             | 32.75              | 1.33                    |

Table 3-2Initial and Final Stress in Relaxation Tests

| Strain Level | Test Number | Initial Stress (MPa) | Final Stress (MPa) |
|--------------|-------------|----------------------|--------------------|
| 3%           | 1           | 14.18                | 2.43               |
|              | 2           | 13.57                | 4.02               |
|              | 3           | 8.03                 | 2.19               |
|              | 4           | 3.48                 | 0.82               |
|              | 5           | 5.01                 | 1.63               |
|              | 6           | 5.77                 | 1.79               |
| 4%           | 1           | 16.91                | 7.58               |
|              | 2           | 19.57                | 8.69               |
|              | 3           | 13.86                | 2.52               |
|              | 4           | 31.99                | 5.30               |
|              | 5           | 8.70                 | 2.74               |
|              | 6           | 9.63                 | 2.26               |

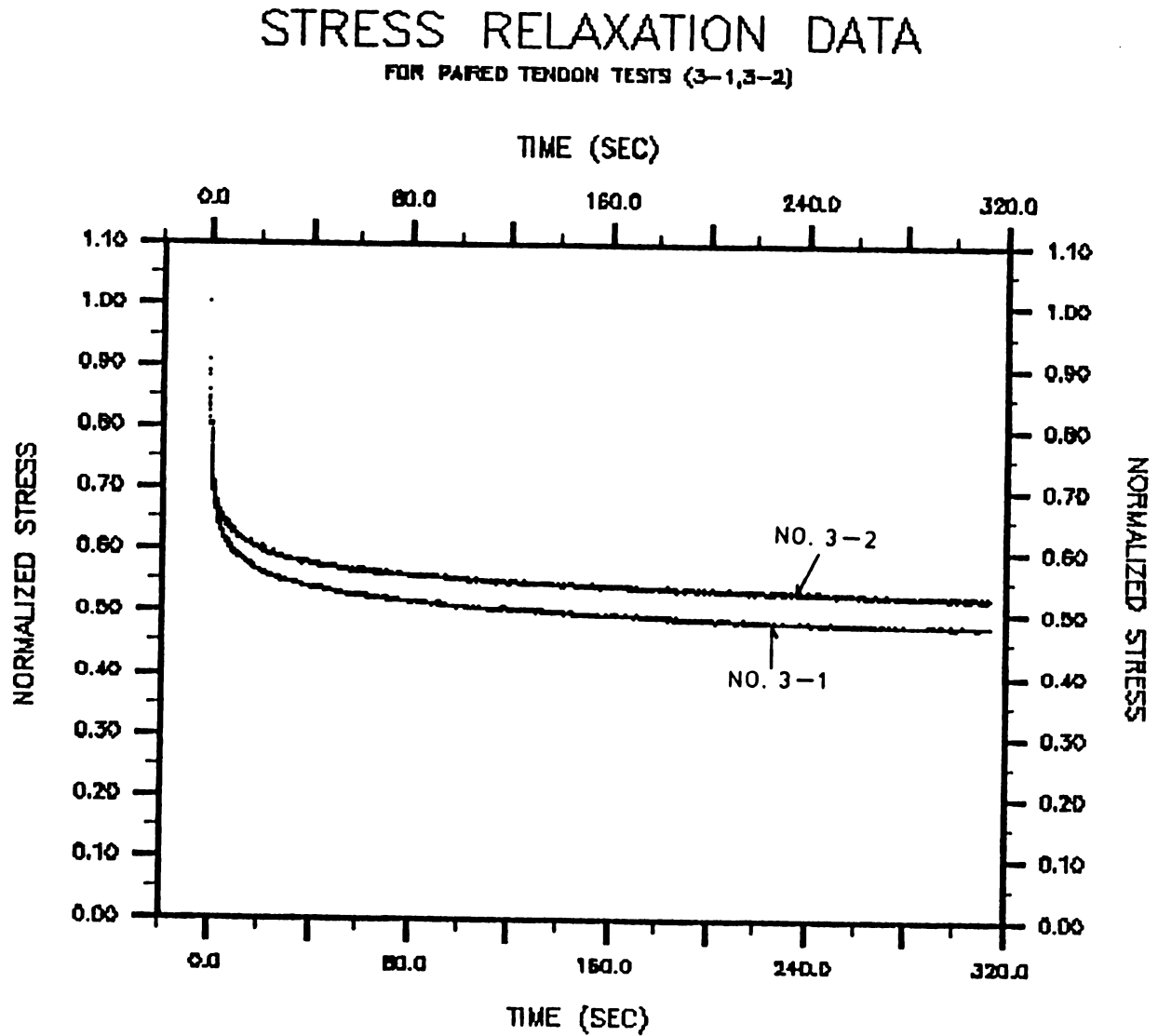


Fig. 3-1(a) Normalized stress relaxation of the paired tendon (test no. 3-1, 3-2) at 3% strain level test

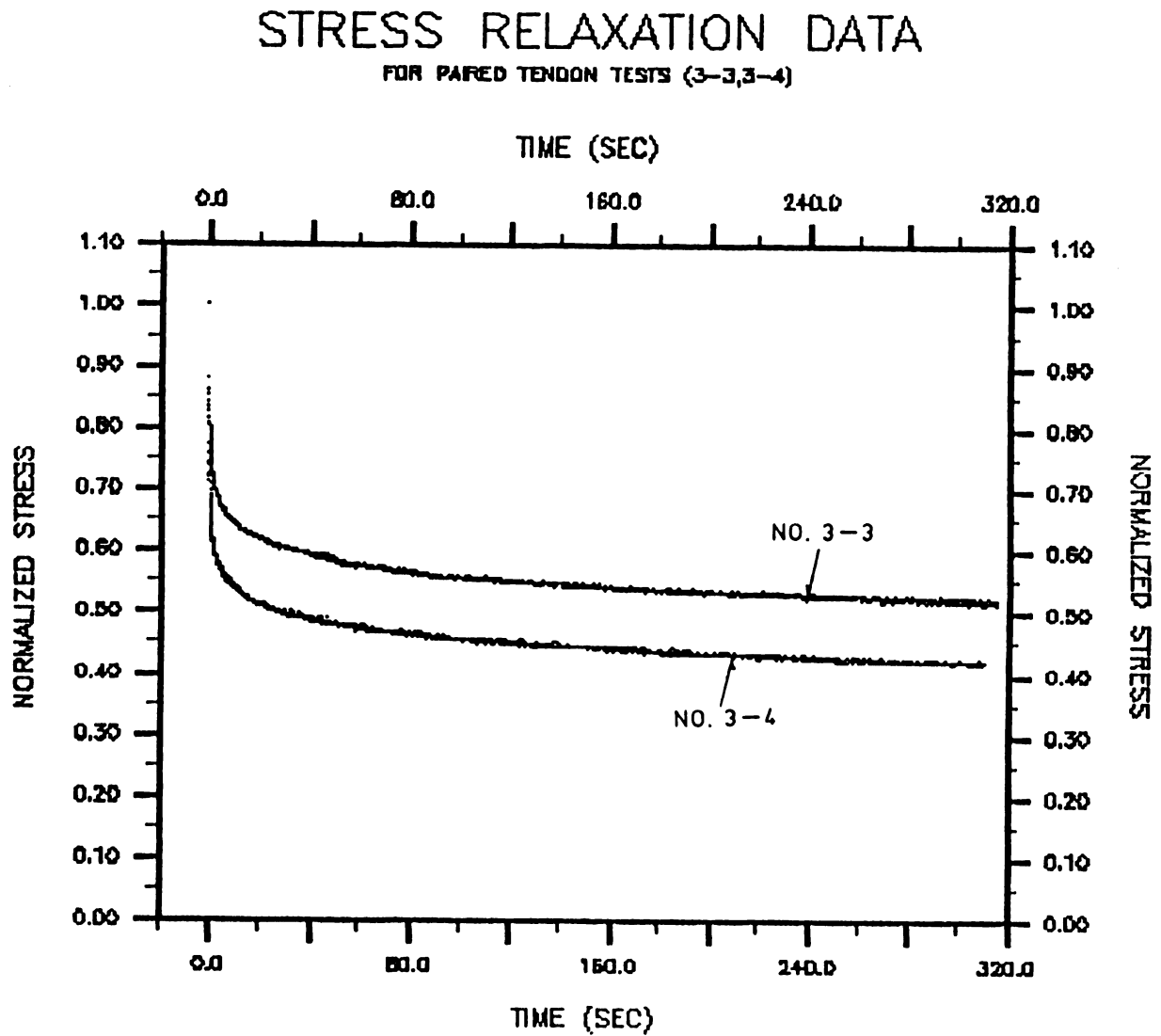


Fig. 3-1(b) Normalized stress relaxation of the paired tendon (test no. 3-3, 3-4) at 3% strain level test

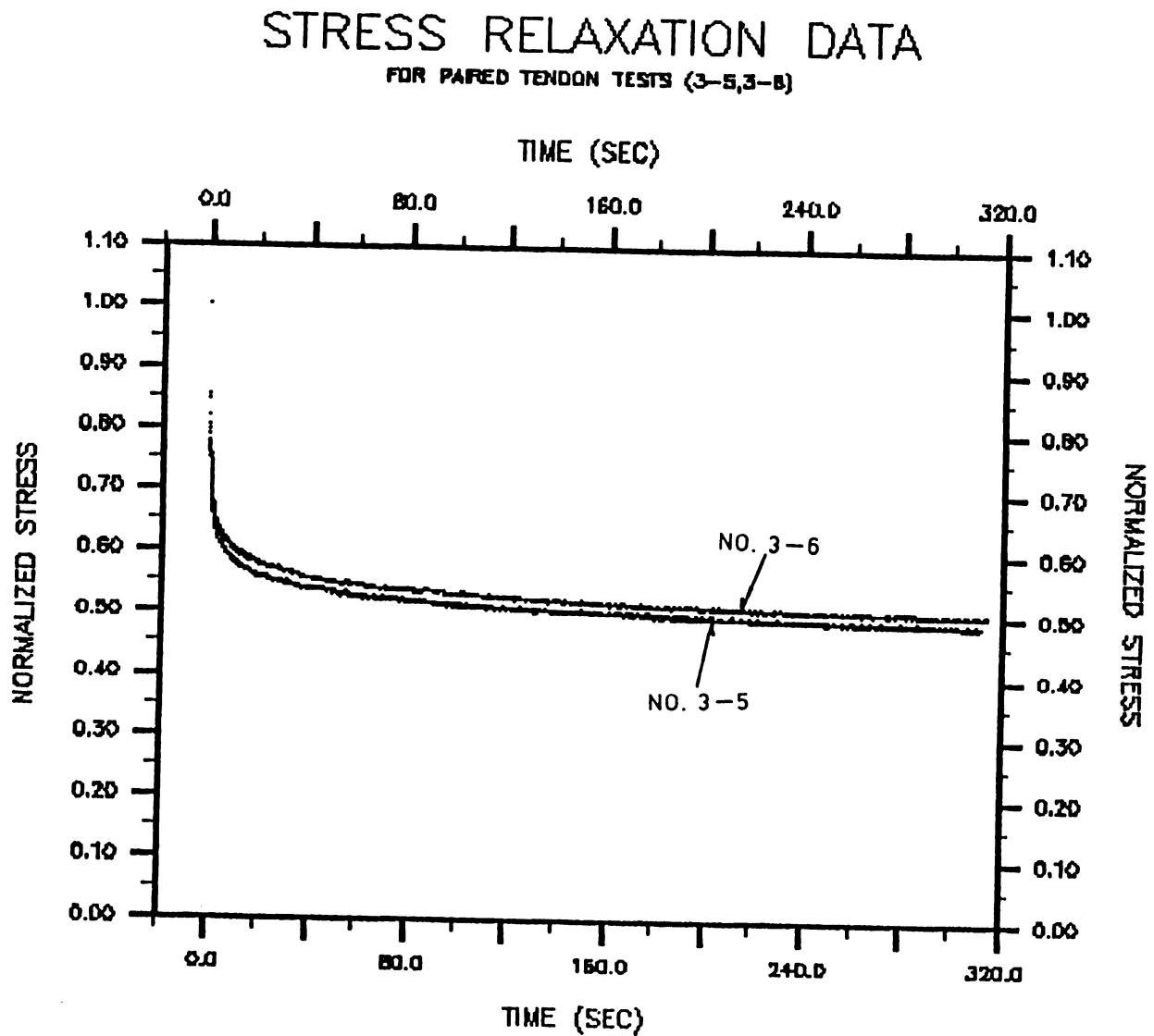


Fig. 3-1(c) Normalized stress relaxation of the paired tendon (test no. 3-5, 3-6) at 3% strain level test

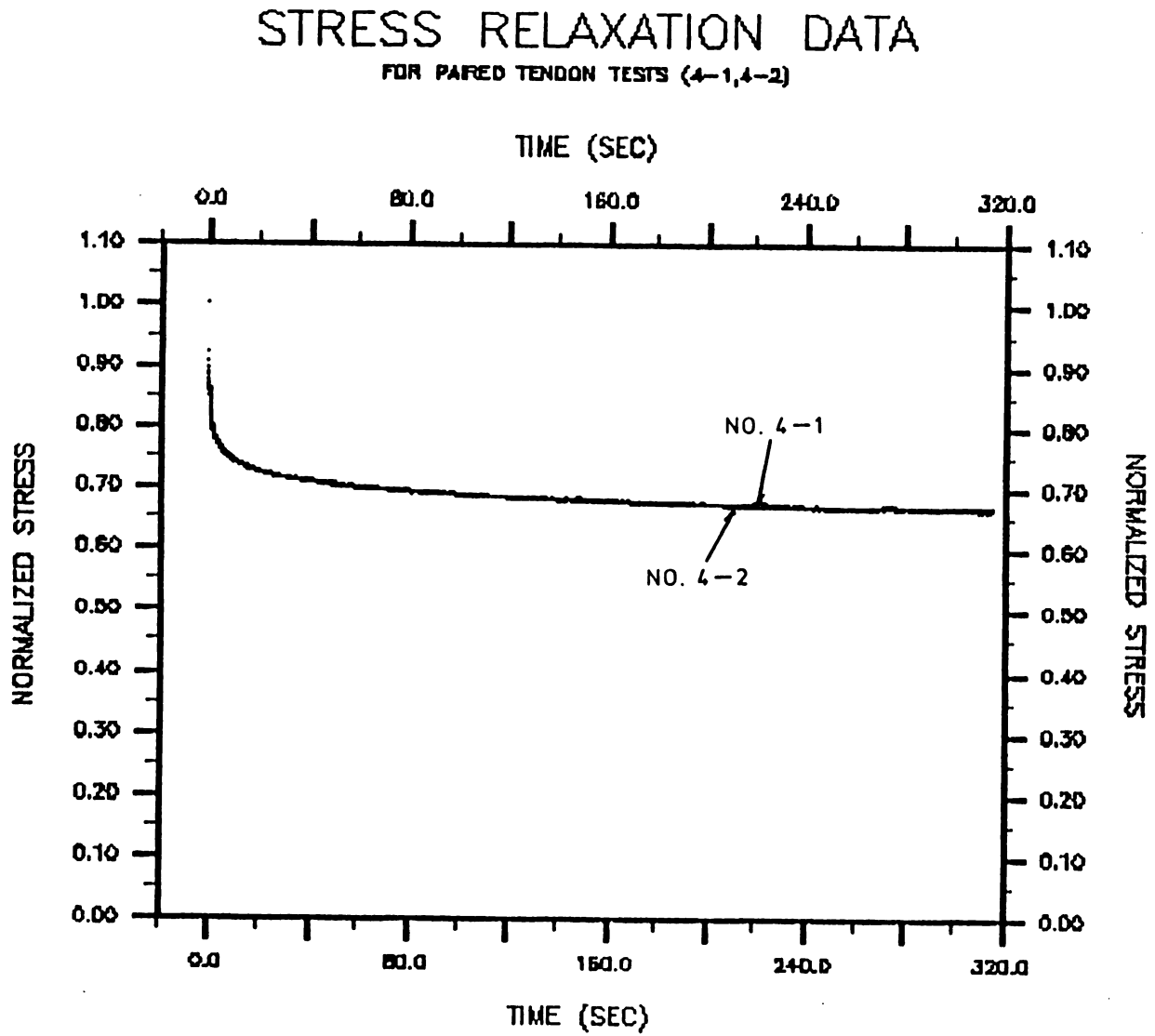


Fig. 3-2(a) Normalized stress relaxation of the paired tendon (test no. 4-1, 4-2) at 4% strain level test

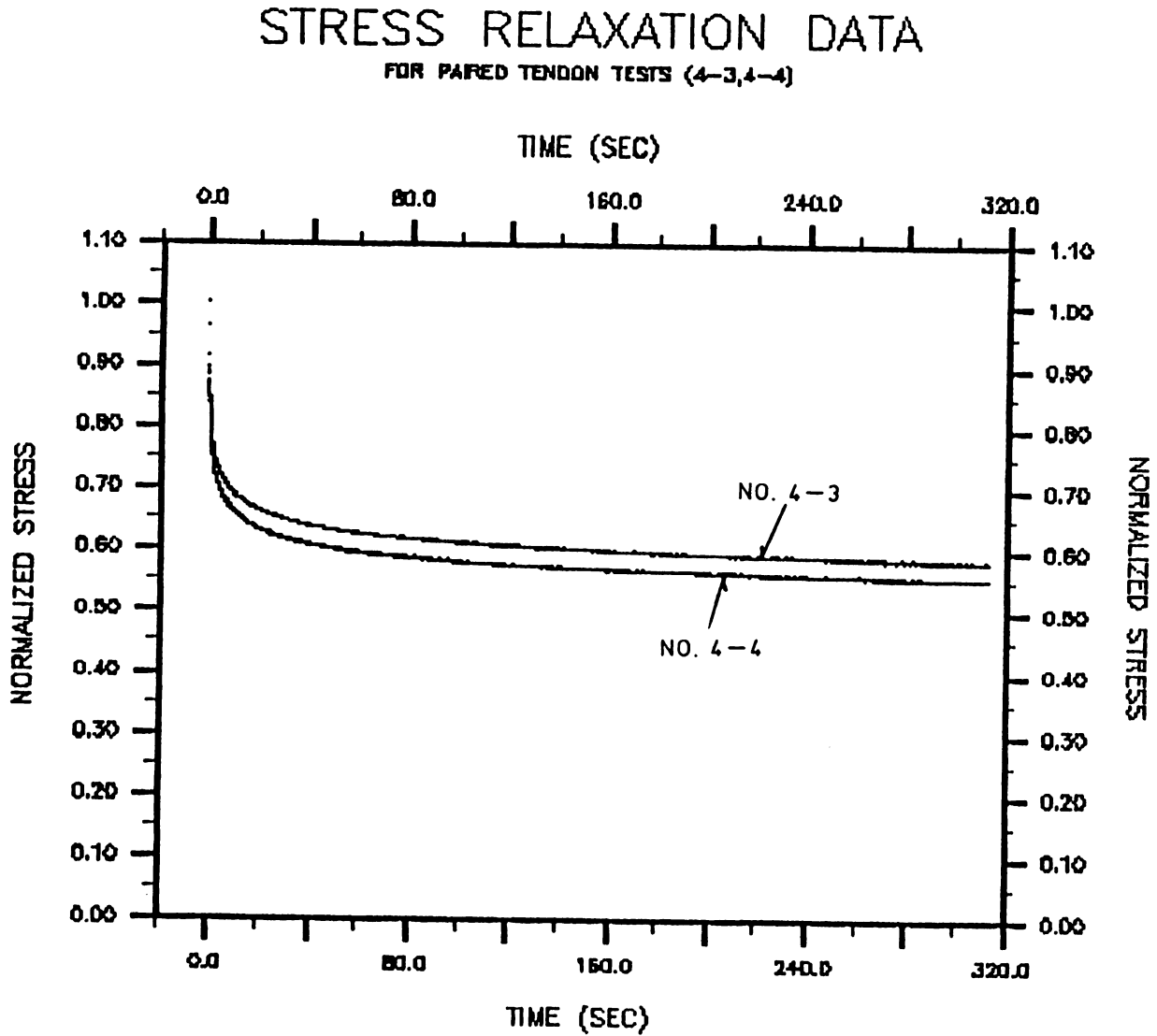


Fig. 3-2(b) Normalized stress relaxation of the paired tendon (test no. 4-3, 4-4) at 4% strain level test

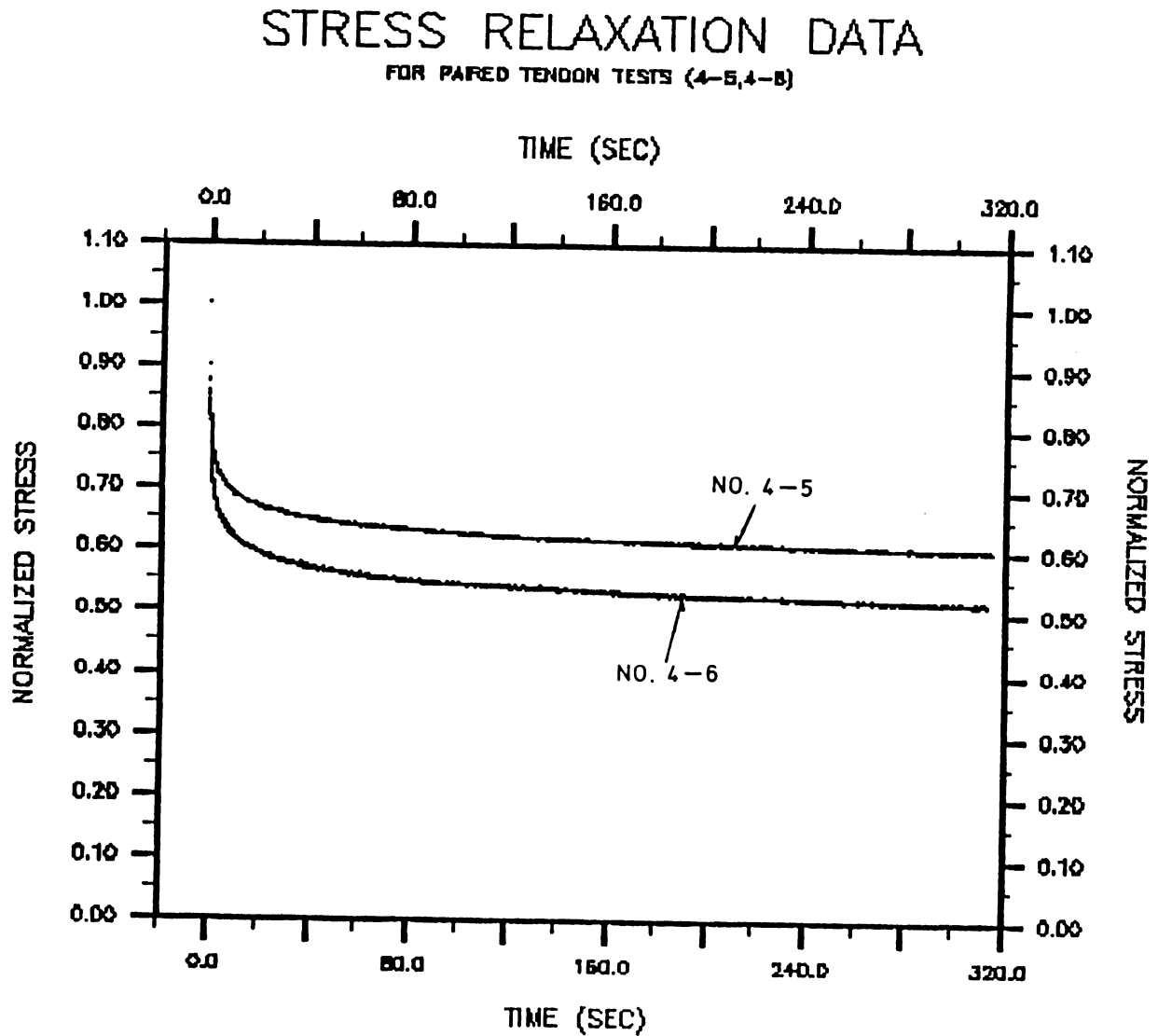


Fig. 3-2(c) Normalized stress relaxation of the paired tendon (test no. 4-5, 4-6) at 4% strain level test

For the reduced relaxation function, an exponential expression for a standard linear solid viscoelastic model,  $G(t) = a + be^{-ut}$ , where  $a$ ,  $b$ , and  $u$  are positive constants [14,33,45,56], and a logarithmic expression,  $G(t) = g - h \ln t$ , where  $g$  and  $h$  are positive constants [22,28,34], have been used thus far. However, the above expressions have not described well the viscoelastic nature of biological tissues. The logarithmic equation [22,28,34] yields negative values with large time and is not appropriate for modeling long term responses of soft tissues. The above exponential equation [14,33,45,56] does not fit both short and long term responses.

From the analysis of the relaxation tests, a new reduced relaxation function for soft tissues is proposed in the form:

$$G(t) = \alpha + \beta e^{-\mu t^q} \quad (3-1)$$

and called the standard non-linear solid reduced relaxation function, where  $\alpha$ ,  $\beta$ ,  $\mu$ , and  $q$  are positive constant values.

Since  $G(t)$  for  $t = 0$  is defined to have a value of 1.0, we obtain:

$$G(0) = \alpha + \beta = 1.0. \quad (3-2)$$

As  $t \rightarrow \infty$ , equation (3-1) tends to  $\alpha$  (positive value). Since the soft connective tissues do not behave like fluid but rather solid viscoelastic materials, then:

$$\lim_{t \rightarrow \infty} G(t) \rightarrow \alpha > 0. \quad (3-3)$$

This is shown for tendon above in this section by no further relaxation after 21.5 hours.

Differentiation of equation (3-1) yields:

$$\begin{aligned} \frac{dG(t)}{dt} &= \beta e^{-\mu t^q} \frac{d(-\mu t^q)}{dt} \\ &= -\beta \mu q t^{q-1} e^{-\mu t^q} < 0 \end{aligned} \quad (3-4)$$

where  $\frac{dG(t)}{dt}$  is the slope of the reduced relaxation function.

Since  $\beta$ ,  $\mu$ , and  $q$  are always positive, the slope of  $G(t)$  is negative. Thus, this reduced relaxation function is a continuously decreasing function of time. The tissue behavior satisfies the fading memory principle [5,40] with increasing time. This fading memory principle is reasonable since the tissue behavior would be physically unrealistic with a growing memory for the more distant action. In fact, all relaxation tests for tendons in this study have satisfied this principle.

The coefficients of the reduced relaxation function were determined by a least square error method [35] and are listed in Table 3-3. This table presents the data from 3% and 4% nominal strain level tests in the averages, standard deviations, and 95%

confidence intervals from a t-test. For the 3% strain level, the value of  $\alpha$  is lower and the values of  $\beta$ ,  $\mu$ , and  $q$  are higher than for the 4% strain level, and all values are positive and less than 1. Also, this table shows that the coefficients of the anatomically paired tendons are similar to each other with few exceptions.

The residual for a data point is the difference between the actual data value and its estimated value from an equation. The sum of squares of the residuals, the residual sum, estimates the quality of fit of the data to the linear regression equation. When the data are exactly linear, the residual sum is zero. The small individual value of residual sum (in Table 3-3) with the least-square technique shows a high quality of fit with about 2000 data to each linear regression equation.

From these results, evaluation of the reduced relaxation function,  $G(t)$ , indicates that there is more stress relaxation at a lower strain level than at a higher strain level. This character of the reduced relaxation function is shown for the mean values in Figure 3-3. Figures 3-4 and 3-5 show the normalized stress relaxation as measured and calculated from equation (3-1) in typical 3% and 4% strain level tests. The agreement is excellent.

Table 3-4 is the statistical summary of all the possible values of the coefficients in the reduced relaxation function for 3% and 4% strain levels. This means that any constants between maximum and minimum values in this table can be chosen for  $\alpha$ ,  $\beta$ ,  $\mu$ , and  $q$  with 95% confidence. Figure 3-6 shows relaxation responses

calculated with extreme coefficient values for 3% and 4% strain. These responses overlap by more than half their ranges.

In Table 3-5, the significance for the statistical data is shown by comparing two (3% and 4%) population means at 95% confidence interval with t-test table [35]. Here, the critical t-value is  $\pm 2.228$ . This comparison shows that a significant difference occurs only for  $\mu$ , and the other coefficients of the reduced relaxation function are not statistically different.

Table 3-3

Summary of the Coefficients in the Reduced Relaxation  
Function for Paired Tendons

$$G(t) = \alpha + \beta e^{-\mu t^q}$$

| Strain<br>Level | Test<br>Number | $\alpha$ | $\beta$ | $\mu$ | p    | q(-1/p) | Residual<br>sum |
|-----------------|----------------|----------|---------|-------|------|---------|-----------------|
| 3%              | 1              | 0.17     | 0.83    | 0.49  | 7.67 | 0.130   | 0.99            |
|                 | 2              | 0.30     | 0.70    | 0.56  | 7.91 | 0.126   | 0.98            |
|                 | 3              | 0.27     | 0.73    | 0.48  | 6.93 | 0.144   | 0.34            |
|                 | 4              | 0.24     | 0.76    | 0.68  | 7.73 | 0.129   | 0.40            |
|                 | 5              | 0.33     | 0.67    | 0.71  | 8.05 | 0.124   | 0.94            |
|                 | 6              | 0.31     | 0.69    | 0.64  | 8.18 | 0.122   | 0.61            |
|                 | Ave.           | 0.27     | 0.73    | 0.59  | 7.75 | 0.129   | 0.71            |
|                 | S.D.           | 0.06     | 0.06    | 0.09  | 0.44 | 0.008   | 0.30            |
|                 | 95%CI          | 0.06     | 0.06    | 0.09  | 0.46 | 0.008   | 0.32            |
|                 |                |          |         |       |      |         |                 |
| 4%              | 1              | 0.45     | 0.55    | 0.46  | 7.81 | 0.128   | 0.59            |
|                 | 2              | 0.45     | 0.55    | 0.47  | 8.24 | 0.121   | 0.27            |
|                 | 3              | 0.18     | 0.82    | 0.35  | 7.63 | 0.131   | 0.57            |
|                 | 4              | 0.17     | 0.83    | 0.38  | 7.87 | 0.127   | 0.86            |
|                 | 5              | 0.31     | 0.69    | 0.46  | 8.65 | 0.116   | 0.42            |
|                 | 6              | 0.23     | 0.77    | 0.50  | 8.12 | 0.123   | 1.07            |
|                 | Ave.           | 0.30     | 0.70    | 0.44  | 8.05 | 0.124   | 0.63            |
|                 | S.D.           | 0.13     | 0.13    | 0.06  | 0.37 | 0.005   | 0.29            |
|                 | 95%CI          | 0.14     | 0.14    | 0.06  | 0.39 | 0.005   | 0.30            |
|                 |                |          |         |       |      |         |                 |

Table 3-4

All Possible Status of the Coefficients  
in the Reduced Relaxation Function for 3% and 4%  
Strain Levels at 95% C.I. with t-test table

| Strain Level | Status | $\alpha$ | $\beta$ | $\mu$ | p    | q     |
|--------------|--------|----------|---------|-------|------|-------|
| 3%           | MIN    | 0.21     | 0.79    | 0.68  | 7.29 | 0.137 |
|              | AVE    | 0.27     | 0.73    | 0.59  | 7.75 | 0.129 |
|              | MAX    | 0.33     | 0.67    | 0.50  | 8.21 | 0.121 |
| 4%           | MIN    | 0.16     | 0.84    | 0.50  | 7.66 | 0.129 |
|              | AVE    | 0.30     | 0.70    | 0.44  | 8.05 | 0.124 |
|              | MAX    | 0.44     | 0.56    | 0.38  | 8.44 | 0.119 |

Table 3-5

Comparison of Two (3% and 4%) Population Means for the Values  
of Coefficients at 95% C.I. with t-test table

| $\alpha$ | $\beta$ | $\mu$  | p      | q     |
|----------|---------|--------|--------|-------|
| -0.513   | 0.513   | 3.397* | -1.278 | 1.298 |

The Critical Value:  $\pm 2.228$

\*: the value which is over the critical value

# REDUCED RELAXATION FUNCTION

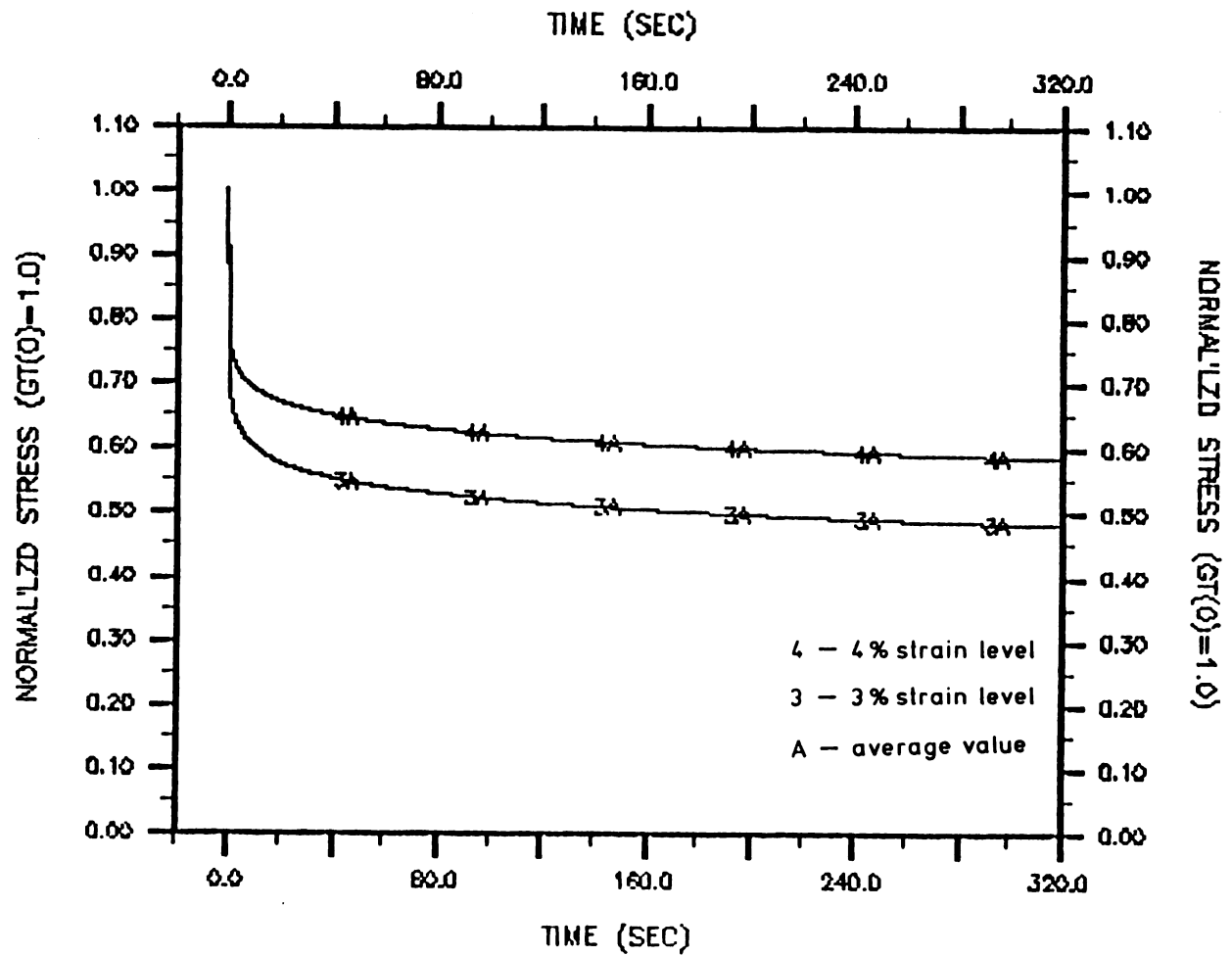


Fig. 3-3 Normalized stress relaxation for the mean values at 3% and 4% strain levels

## REDUCED RELAXATION FUNCTION

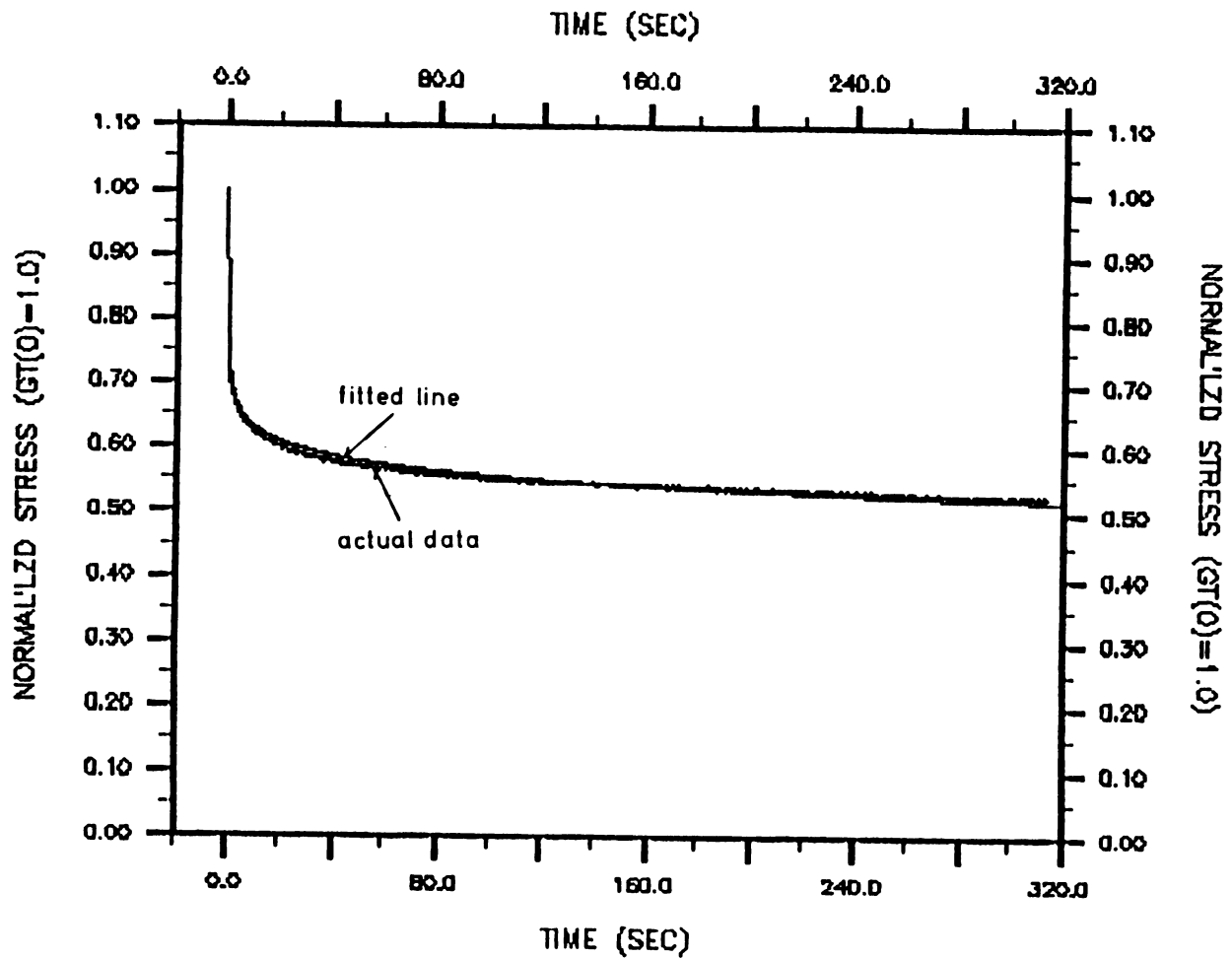


Fig. 3-4 Typical normalized stress relaxation at 3% strain level as measured and calculated with standard non-linear solid reduced relaxation function (test no. 3-3)

# REDUCED RELAXATION FUNCTION

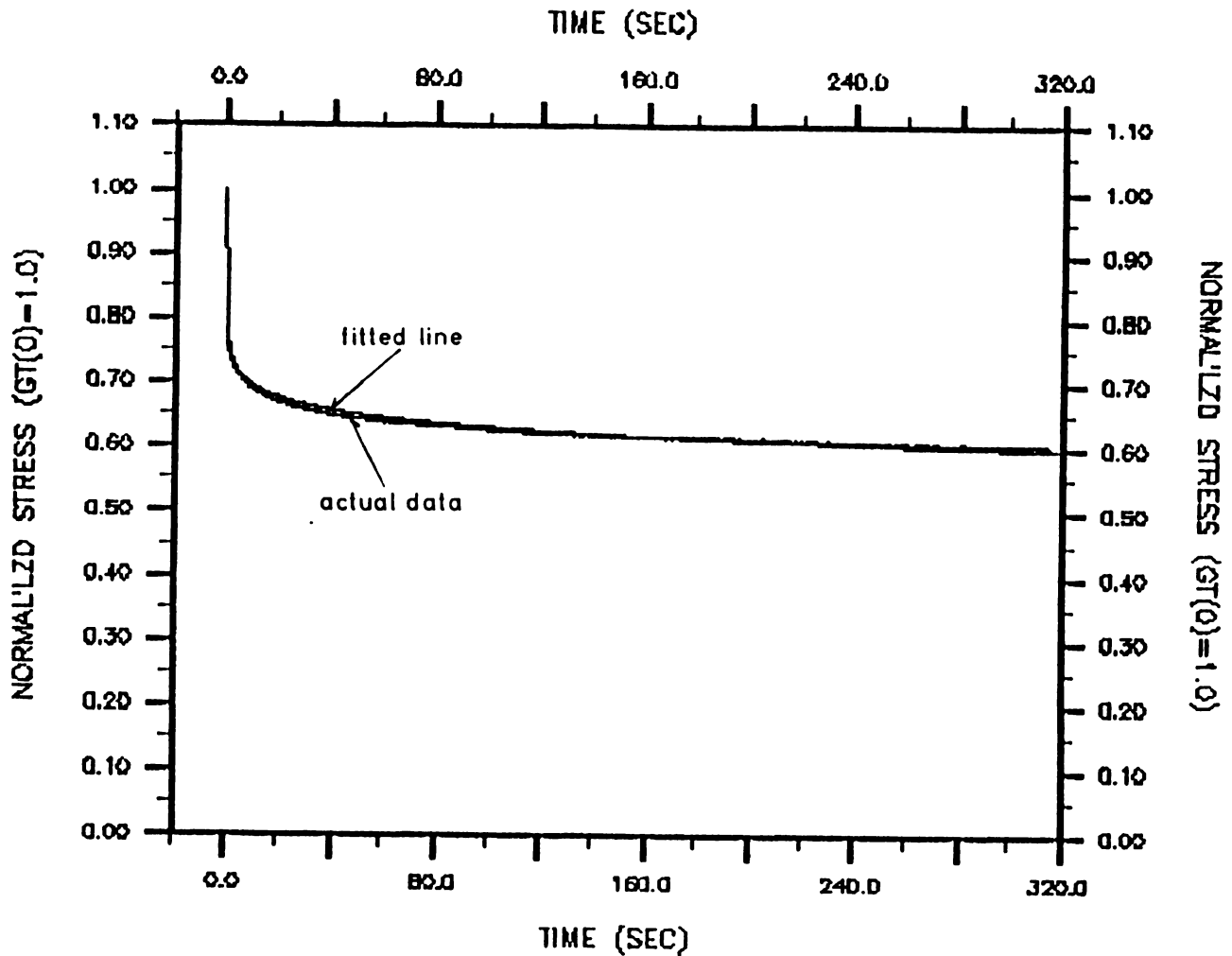


Fig. 3-5 Typical normalized stress relaxation at 4% strain level as measured and calculated with standard non-linear solid reduced relaxation function (test no. 4-5)

## REDUCED RELAXATION FUNCTION

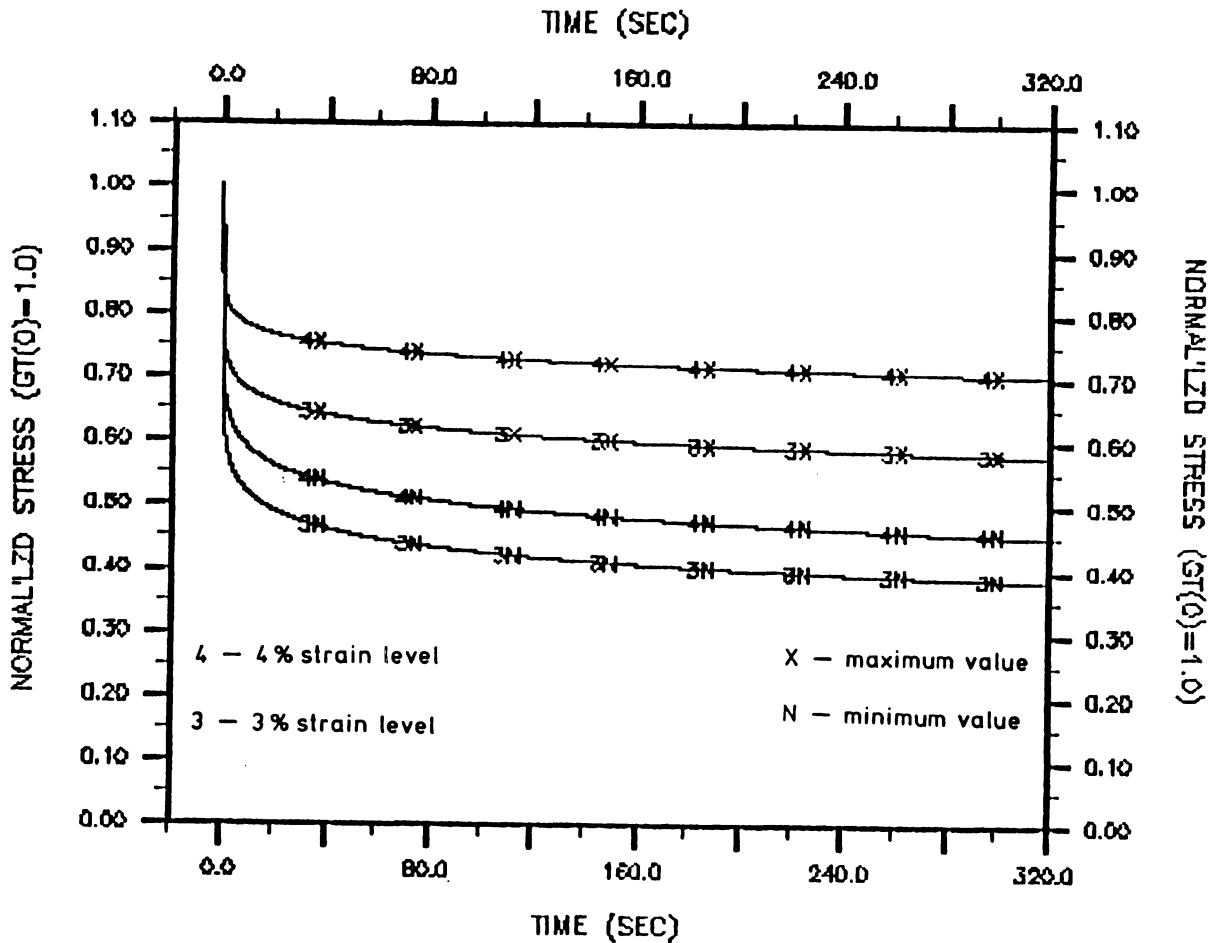


Fig. 3-6 Normalized stress relaxation of the possible values with 95% confidence at 3% and 4% strain levels

### III.3. Multiple Cyclic Test Results

Multiple cyclic tests were conducted to obtain an empirical understanding of tendon responses and to obtain measured data for comparison with responses predicted from the constitutive model. These tests were conducted with anatomically paired tendons from the same animal with sections of long tendons (bone end, mid-portion, and muscle end) which are called the "same tendon", and with tendons from different anatomical sites. It has been possible to study, in a limited way, the similarity and difference of mechanical responses for each group of tendons. As described in Chapter II, the multiple cyclic tests involved three different types of cyclic test sequences (see Figure 2-1). The data were obtained by programs TEN360 (see Appendix 5) and SUB360 (see Appendix 6) on a PDP-11/23 computer, displayed graphically by using MULPLT [37], and analyzed statistically by calculation of the averages, the standard deviations, and the 95% confidence intervals [35].

Table 3-6 shows the tendon specimen characteristics with the anatomical locations, tendon status (pair, same, different), initial lengths, areas, and peak loads for the first extension cycle to 3% peak strain.

## III.3.a. Cyclic relaxation and recovery

A typical load-time response of a tendon in an A-type cyclic extension test (see Figure 2-1) is shown in Figure 3-7. In this figure, the peak loads of cycles throughout the test are shown as normalized so that the peak of the first cycle has a value of 1.0. This normalization facilitates comparison and summary of results from different specimens. The peak normalized loads rapidly decrease for the first few cycles of testing then continue to decrease to a lesser degree. Figure 3-8 shows the corresponding stress-strain plots with loading and unloading curves at the first, 60th (72 sec), and 300th (360 sec) cycles. In this figure, the initial extension (upper curve at the first cycle) starts at zero strain (no slack strain) and proceeds with an increasing slope between stress and strain to a peak stress at 3% strain. As the strain decreases after the peak of the first cycle, the unloading curve is below the loading curve and the slope of this unloading curve is greater than the slope of the loading curve. Also, the slack strain of this unloading curve is about 0.6%. In the 60th cycle, the specimen must be extended to a strain of about 0.8% before it bears load (loading slack strain) and the unloading slack strain is 0.9%. In the 300th cycle, the loading slack strain is about 0.9% and the unloading slack strain is over 1.0%. Hysteresis decreases from cycle to cycle in this figure.

Table 3-7 shows the statistical summary of normalized cyclic load relaxation for 3% constant peak strain level tests (A-type, see Fig. 2-1). The average peak normalized load decreases 20.5% for 300 cycles. However, the average peak normalized load for 60 cycles decreases 14.1%. These results show that the peak normalized loads decrease more rapidly for the first few cycles of testing then continue to decrease to a less degree as shown in Figure 3-7.

The typical normalized peak load-time response of a tendon in a B-type cyclic extension test (see Figure 2-1) is shown in Figure 3-9. The relaxation in the first cyclic block (0 to 72 sec) is similar to an A-type test. At the beginning of cyclic testing periods after the rest periods (at 144 sec, 61st cycle and at 288 sec, 121st cycle), the peak loads recover (increase) from the peak load values just before the rest period, then they relax quickly for a few cycles and continue to relax throughout the cyclic test period.

In Figure 3-10, stress-strain plots are shown for a typical test of cyclic extension with rest periods (B-type test). The initial extension (upper curve) starts at zero strain (no loading slack strain) and proceeds with an increasing slope to a peak stress at 3% strain. In the second cycle, the specimen is extended to a strain of about 0.5% before it bears load (loading slack strain). The second extension results in a stress-strain response which lies below the first extension, a more abrupt increase in slope, and greater slope at the maximum strain (3%). The last extensions of

each cyclic block of extensions (solid lines at 72 , 216 , and 360 sec) and the first extension after the rest periods (dotted lines at 144 and 288 sec) are also shown in this figure. As shown in Figure 3-9, recovery is evident by comparing the responses before and after the two rest periods from 72 to 144 sec and from 216 to 288 sec. In Figure 3-10, the paths of unloading are not shown so that subsequent loading paths will be clear.

Table 3-8 shows the statistical summary of normalized cyclic load relaxation for 3% constant maximum strain level test with two rest periods (B<sub>2</sub>-type test, see Figure 2-1). Individual recovery, defined as the percent difference between the last peak load before the rest period and the first peak load after the rest period, is shown to be nonzero. Load recovery after the first rest period is generally greater than that after the second rest period. The average value of recovery with a 72 sec rest period is 2.9% after the first rest period and 2.5% after the second rest period. Hubbard and Chun [24] showed that the average value of recovery with an 1800 sec rest period was 3.9% after the first rest period and 3.3% after the second rest period at a 3% maximum strain level. These results show that there is more recovery of peak load with a longer rest period, but most of the recovery occurs in the beginning of the rest period. The peak normalized load of each cycle in the B-type test is not statistically different from that of corresponding cycle in the A-type test via a t-test at  $p = 0.05$ .

The typical load-time response of a tendon in a C-type cyclic extension test (see Figure 2-1) is shown in Figure 3-11. In this figure, the loads from cycles throughout the test are normalized so that the peak load of the first cycle has a value of 1.0. The peak normalized load relaxation at the first cyclic block (0 to 72 sec) is similar to that of A and B-type tests. In the second cyclic block (72 to 144 sec), the maximum strain level is 4% and the loads are much greater than the loads of the first cyclic block (3% maximum strain level). The peak normalized loads rapidly decrease for the first few cycles then continue to decrease to a lesser degree as in the first cyclic block. In the third cyclic block (144 to 216 sec), the peak loads did not relax, but rather they increased (recovered) a little with successive cycles. In the fourth block (216 to 288 sec, 4% maximum strain level), the responses are like those of the second cyclic block. Also, in the fifth cyclic block (288 to 360 sec, 3% maximum strain level), the responses are similar to those of the third cyclic block.

The recovery (increase in the peak normalized load) with initial cycles at the lower maximum strain level (3%) after the higher maximum strain level (4%) seems to be natural phenomena in tissue behavior. Thus, tendons recover during initial periods of lower extensions after higher extensions.

Figure 3-12 shows the stress-strain plots of the first loading curve in each cyclic block from a C-type test (see Figure 2-1). The initial extension (upper curve) starts at zero strain (no loading

slack strain) and proceeds with an increasing slope to a peak stress at 3% strain. The 60th cycle (the last cycle in the first cyclic block) is not shown in this figure but the stress is lower than that of the first cycle and nearly the same as the 61st cycle up to 3% strain.

In the 61st cycle (the first cycle in the second cyclic block), the specimen was extended up to the 4% strain level and the peak stress is much greater than that of the first cyclic block. The 105th cycle (the last cycle in the second cyclic block) is not shown in this figure; but the specimen was extended up to the 4% strain level, and the stress is a little lower than that of the 61st cycle.

In the 106th cycle (the first cycle in the third cyclic block), the maximum strain level returned to 3% and the stress is less than that of the 60th cycle (the last cycle in the first cyclic block). During the third cyclic block, the stresses are increased (recovered) with cycles until the 165th cycle (the last cycle in the third cyclic block).

In the 166th cycle (the first cycle in the fourth cyclic block), the maximum strain level is changed to 4%. The stress is lower than that of the 61st cycle but higher than that of 105th cycle at the end of the second cyclic block. Thus, the tendon specimen recovered with cycles during the third cyclic block. Then, the stresses decreased until the 210th cycle (the last cycle in the fourth cyclic block).

In the 211th cycle (the first cycle in the fifth cyclic block), the maximum strain level returned to 3% and the stress is lower than that of the 165th cycle (the last cycle in the third cyclic block). The stress increased with cycles in this last cyclic block.

Table 3-9 presents the statistical summary of cyclic load relaxation in 3-4% different maximum strain level tests (C-type test, see Figure 2-1). The average value of relaxation in normalized load is 26.9% in the second cyclic block and the relaxation in normalized load is 10.4% in the fourth cyclic block. The average value of recovery is 2.0% in the third cyclic block and is 1.9% in the fifth cyclic block. The peak normalized load from the first to 60th cycle is not statistically different from that of its corresponding cycle in the A and B-type tests via a t-test at  $p = 0.05$ .

Table 3-6Tendon Specimen Characteristics in Cyclic Tests

| Strain Level | Test No. | Anatomical Location           | Tendon Status | Initial Length(mm) | Area (mm <sup>2</sup> ) | Peak Load(N) |
|--------------|----------|-------------------------------|---------------|--------------------|-------------------------|--------------|
| 3-3%         | 1        | Peroneus longus               | } pair        | 32.54              | 0.58                    | 18.23        |
|              | 2        | Peroneus longus*(b.s.)        |               | 32.42              | 0.63                    | 18.47        |
|              | 3        | Flexor digitorum brevis       | } pair        | 33.10              | 1.47                    | 16.90        |
|              | 4        | Flexor digitorum brevis       |               | 33.76              | 1.62                    | 14.97        |
|              | 5        | Extensor digitorum longus     |               | 35.93              | 1.02                    | 18.65        |
|              | 6        | Extensor digitorum longus     |               | 33.04              | 1.33                    | 14.25        |
| 3-0%         | 1        | Peroneus longus*(m)           | } same        | 32.61              | 0.61                    | 12.50        |
|              | 2        | Peroneus longus*(msl.s.)      |               | 31.47              | 0.68                    | 16.05        |
|              | 3        | Extensor digitorum longus     |               | 33.70              | 1.07                    | 15.23        |
|              | 4        | Extensor digitorum longus     | } same        | 32.56              | 0.92                    | 17.38        |
|              | 5        | Flexor digitorum longus(m)    |               | 32.29              | 1.05                    | 3.66         |
|              | 6        | Flexor digitorum longus(b.s.) |               | 31.28              | 1.34                    | 17.95        |
| 3-4%         | 1        | Peroneus longus               | } pair        | 34.28              | 0.90                    | 10.02        |
|              | 2        | Extensor digitorum longus     |               | 33.35              | 0.55                    | 7.17         |
|              | 3        | Peroneus longus               |               | 30.86              | 1.00                    | 11.94        |
|              | 4        | Peroneus longus               | } same        | 34.21              | 1.21                    | 12.09        |
|              | 5        | Flexor digitorum longus(m)    |               | 33.67              | 1.10                    | 2.11         |
|              | 6        | Flexor digitorum longus(b.s.) |               | 31.89              | 1.63                    | 7.21         |

\* : The same tendon

b.s. : bone end section,      msl.s. : muscle end section,      m : mid-portion

# CYCLIC LOAD RELAXATION DATA

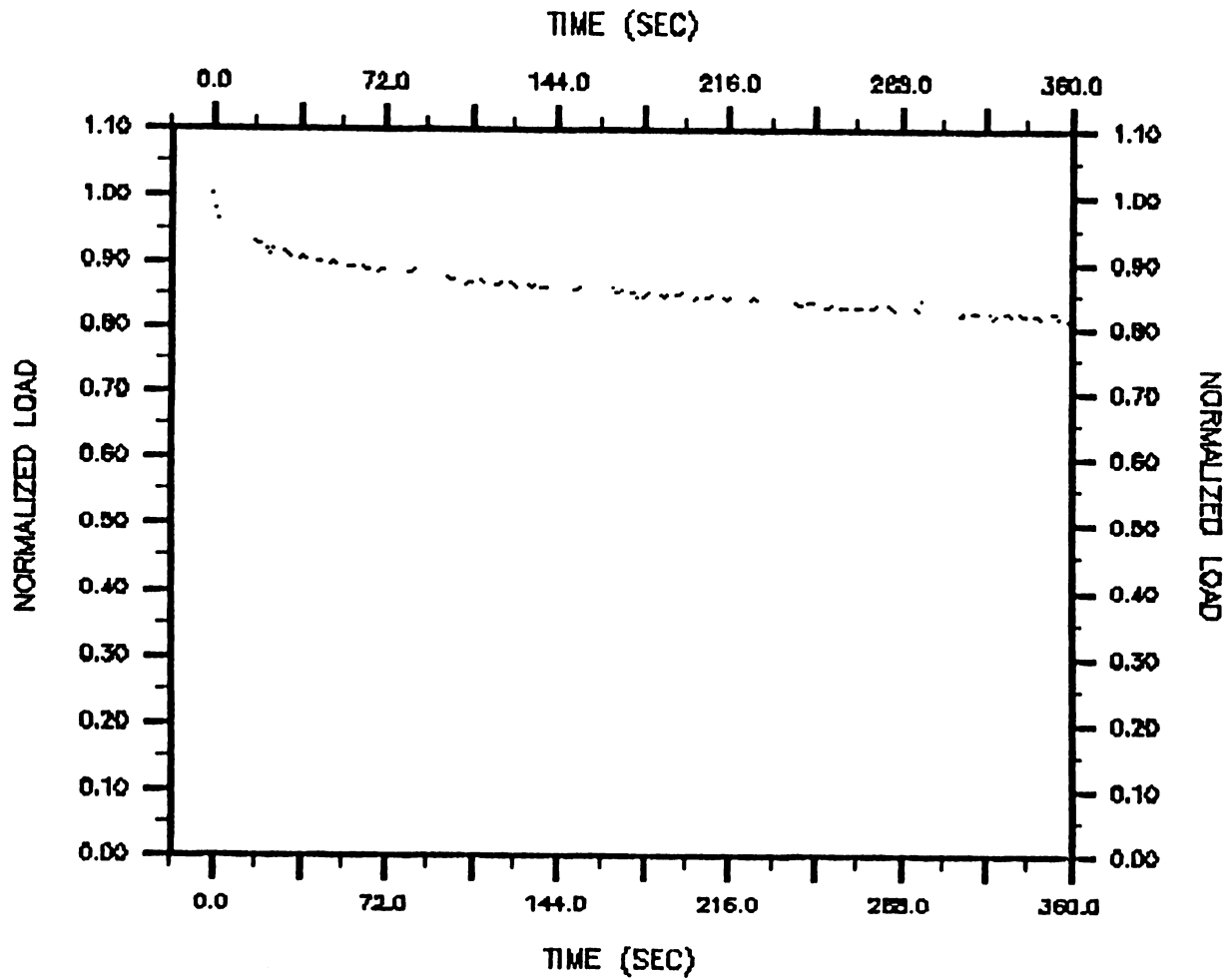


Fig. 3-7 Normalized cyclic load relaxation for 3% constant peak strain level test (A-type test, see Fig. 2-1)

# STRESS VS. STRAIN

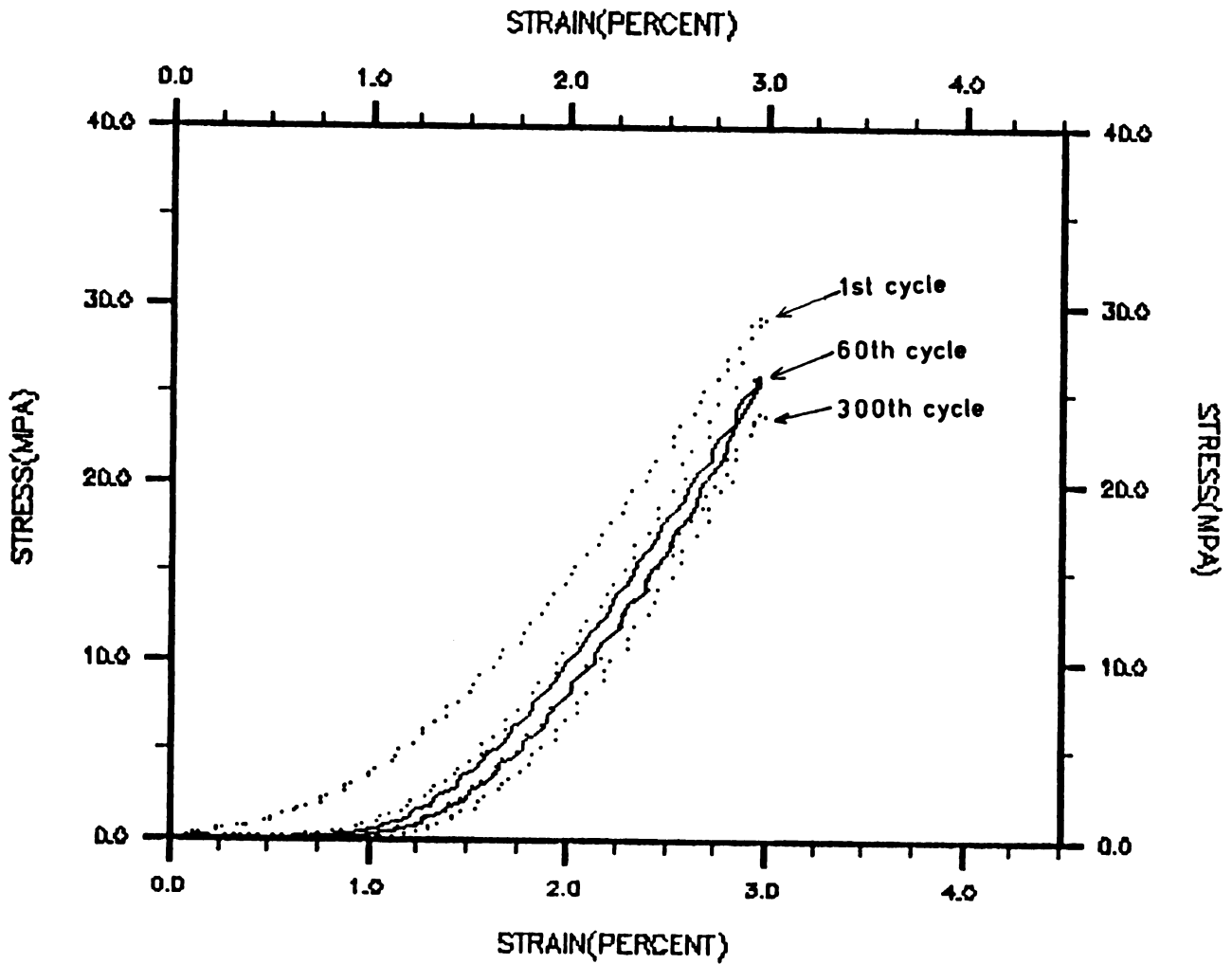


Fig. 3-8 Stress-strain responses with cycles for 3% constant peak strain level test (A-type test, see Fig. 2-1)

Table 3-7

Summary of Normalized Cyclic Load Relaxation (%) for 3% Constant  
Peak Strain Level Test (A-type test, see Fig. 2-1)

| Cycle No.<br>Time | 1     | 2    | 3    | 60<br>72s | 120<br>144s | 180<br>216s | 240<br>288s | 300<br>360s |
|-------------------|-------|------|------|-----------|-------------|-------------|-------------|-------------|
| 33-1              | 100.0 | 96.3 | 95.5 | 85.8      | 81.6        | 79.6        | 77.4        | 76.3        |
| 33-2              | 100.0 | 97.9 | 96.5 | 88.6      | 86.0        | 84.4        | 82.3        | 81.0        |
| 33-3              | 100.0 | 97.4 | 95.4 | 85.7      | 84.3        | 84.0        | 82.1        | 80.9        |
| 33-4              | 100.0 | 96.5 | 94.5 | 85.4      | 82.4        | 81.8        | 81.1        | 80.2        |
| 33-5              | 100.0 | 96.5 | 95.1 | 86.7      | 84.7        | 83.3        | 82.0        | 80.3        |
| 33-6              | 100.0 | 95.3 | 94.1 | 83.3      | 80.9        | 78.6        | 78.3        | 78.0        |
| Ave.              | 100.0 | 96.7 | 95.2 | 85.9      | 83.3        | 82.0        | 80.5        | 79.5        |
| S.D.              | 0.0   | 0.9  | 0.8  | 1.7       | 2.0         | 2.4         | 2.1         | 1.9         |
| 95% C.I.          | 0.0   | 0.9  | 0.8  | 1.8       | 2.1         | 2.5         | 2.2         | 2.0         |

# CYCLIC LOAD RELAXATION DATA

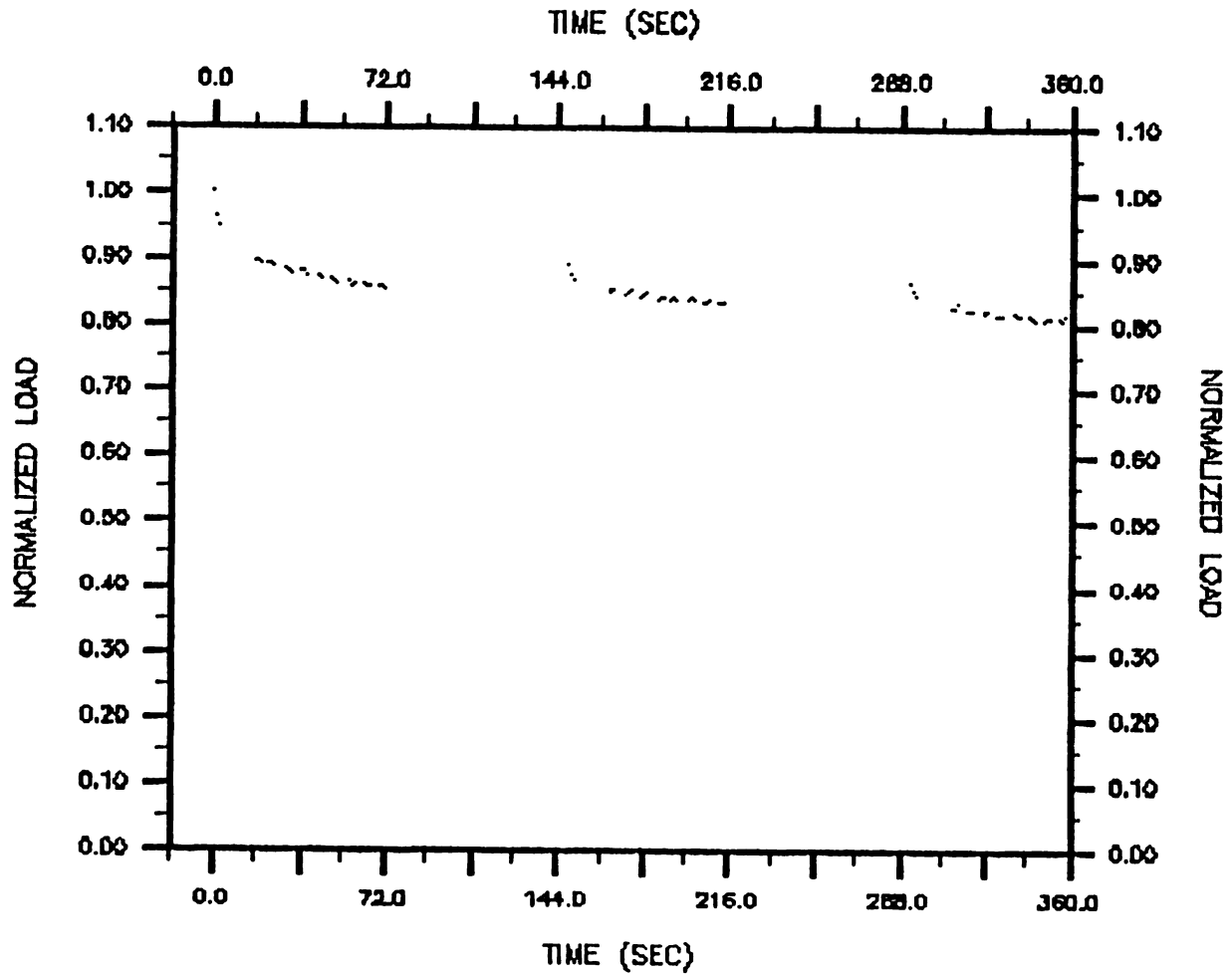


Fig. 3-9 Normalized cyclic load relaxation for 3% constant peak strain level test with rest periods (B-type test, see Fig. 2-1)

## STRESS VS. STRAIN

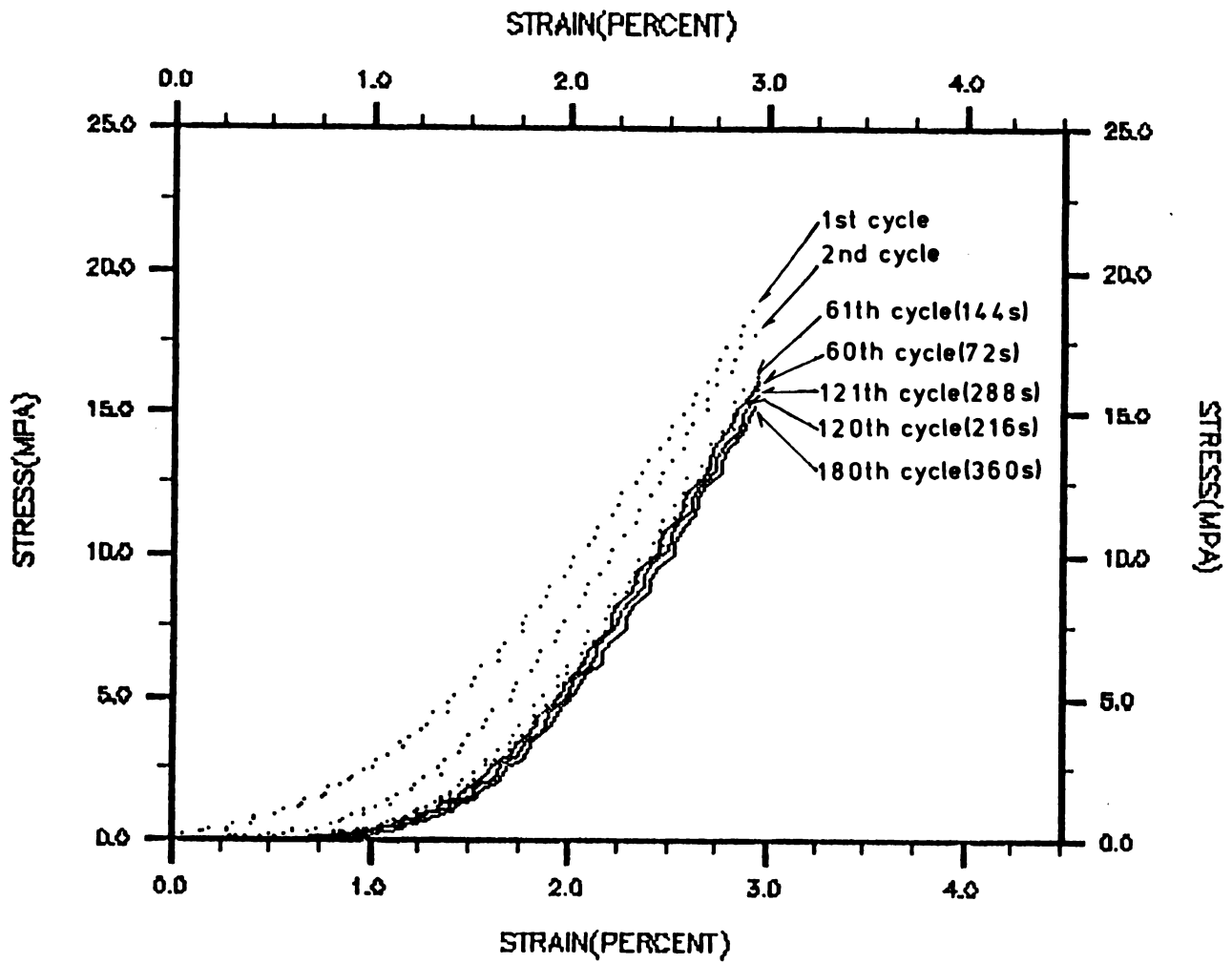


Fig. 3-10 Stress-strain responses with cycles for 3% constant peak strain level test with rest periods (B-type test, see Fig. 2-1)

Table 3-8

Summary of Normalized Cyclic Load Relaxation (%) for 3% Constant  
Peak Strain Level Test with Rest Periods  
(B-type test, See Fig. 2-1)

| Cycle No.<br>Time | 1     | 2    | 3    | 60<br>72s | 61<br>144s | 120<br>216s | 121<br>288s | 180<br>360s |
|-------------------|-------|------|------|-----------|------------|-------------|-------------|-------------|
| 30-1              | 100.0 | 97.6 | 96.2 | 86.9      | 89.2       | 83.8        | 86.8        | 81.7        |
| 30-2              | 100.0 | 96.5 | 95.4 | 85.1      | 87.4       | 83.6        | 85.5        | 81.2        |
| 30-3              | 100.0 | 96.3 | 95.4 | 85.1      | 89.3       | 84.5        | 86.7        | 82.8        |
| 30-4              | 100.0 | 96.2 | 94.9 | 85.3      | 89.1       | 83.3        | 86.5        | 81.5        |
| 30-5              | 100.0 | 93.5 | 87.5 | 69.0      | 71.4       | 63.7        | 66.1        | 60.7        |
| 30-6              | 100.0 | 96.8 | 95.6 | 87.9      | 90.3       | 86.5        | 88.6        | 85.8        |
| Ave.              | 100.0 | 96.2 | 94.2 | 83.2      | 86.1       | 80.9        | 83.4        | 79.0        |
| S.D.              | 0.0   | 1.4  | 3.3  | 7.1       | 7.3        | 8.5         | 8.5         | 9.1         |
| 95% C.I.          | 0.0   | 1.5  | 3.5  | 7.5       | 7.7        | 8.9         | 8.9         | 9.6         |

# CYCLIC LOAD RELAXATION DATA

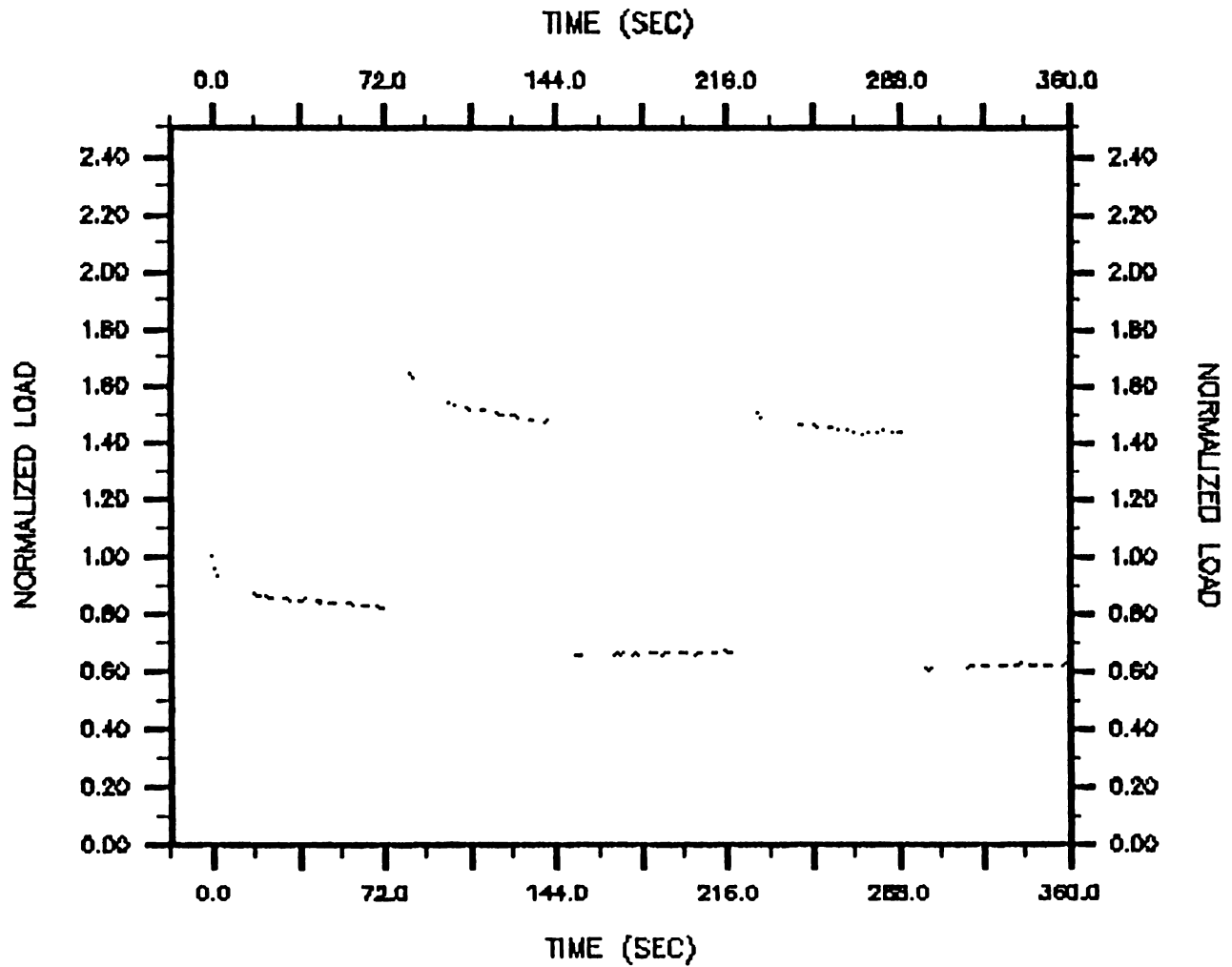


Fig. 3-11 Normalized cyclic load relaxation for 3-4% different peak strain level test (C-type test, see Fig. 2-1)

# STRESS VS. STRAIN

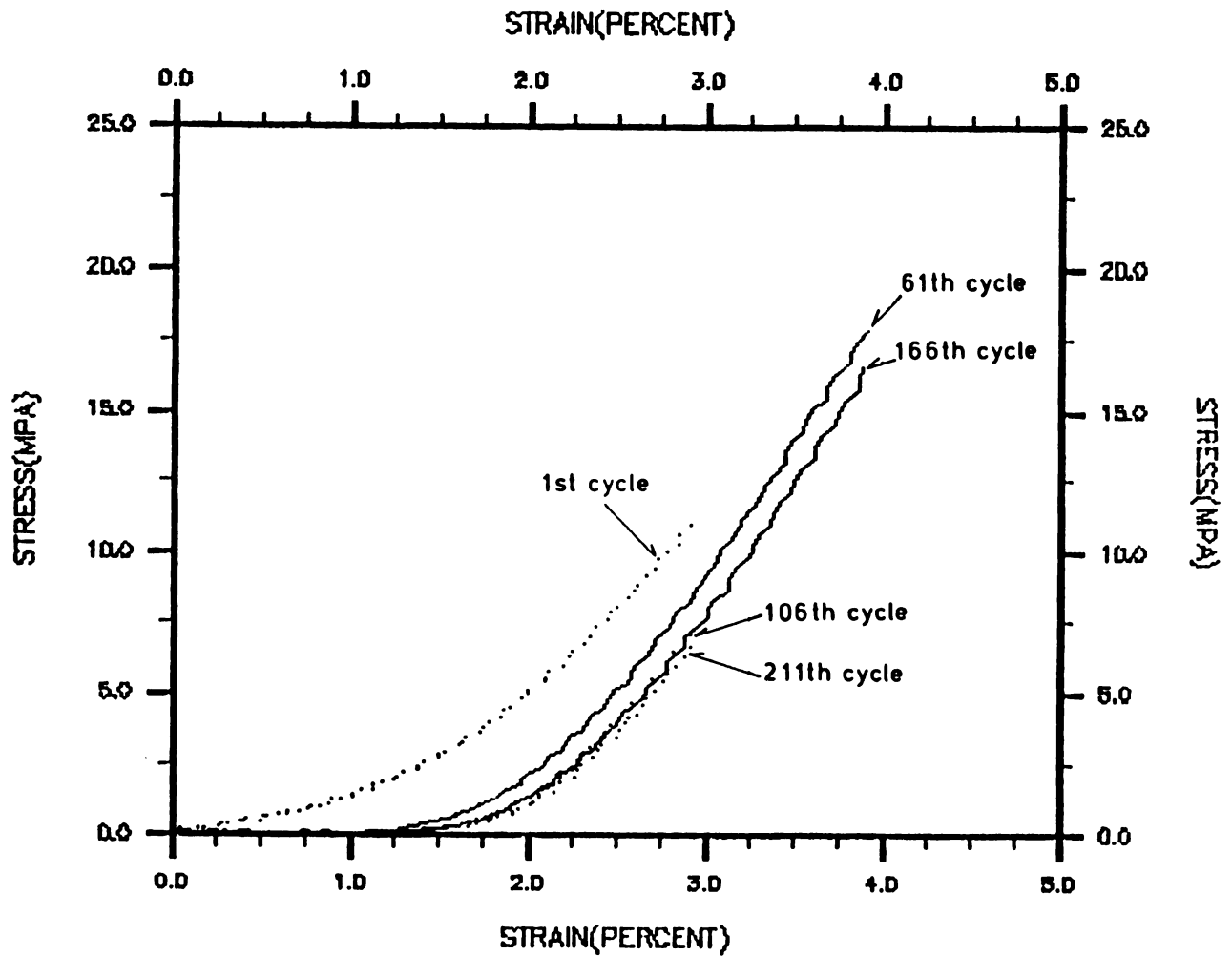


Fig. 3-12 Stress-strain responses with cycles for 3-4% different peak strain level test (C-type test, see Fig. 2-1)

Table 3-9

Summary of Normalized Cyclic Load Relaxation (%) for 3-4%  
Different Peak Strain Level Test (C-type test, see Fig. 2-1)

| Cyc No.<br>time<br>PKSL | 1<br>3 | 2<br>3 | 3<br>3 | 60<br>72s<br>3 | 61<br>4 | 105<br>144s<br>4 | 106<br>3 | 165<br>216s<br>3 | 166<br>4 | 210<br>288s<br>4 | 211<br>3 | 270<br>360s<br>3 |
|-------------------------|--------|--------|--------|----------------|---------|------------------|----------|------------------|----------|------------------|----------|------------------|
| 34-1                    | 100.0  | 96.2   | 93.5   | 82.0           | 164.4   | 147.8            | 65.2     | 66.3             | 150.2    | 143.3            | 60.9     | 62.6             |
| 34-2                    | 100.0  | 95.1   | 92.7   | 77.2           | 190.3   | 164.8            | 54.7     | 56.5             | 169.6    | 156.8            | 49.8     | 50.8             |
| 34-3                    | 100.0  | 95.4   | 93.4   | 81.6           | 166.6   | 146.4            | 61.7     | 64.2             | 151.5    | 143.1            | 57.7     | 58.9             |
| 34-4                    | 100.0  | 96.4   | 94.6   | 83.8           | 172.1   | 155.7            | 65.6     | 68.1             | 158.2    | 151.2            | 61.6     | 63.4             |
| 34-5                    | 100.0  | 89.7   | 84.5   | 60.8           | 217.6   | 162.9            | 25.7     | 28.8             | 165.0    | 152.6            | 19.5     | 22.6             |
| 34-6                    | 100.0  | 94.0   | 91.5   | 78.2           | 223.3   | 195.8            | 55.9     | 56.8             | 201.2    | 191.6            | 50.4     | 53.2             |
| Ave.                    | 100.0  | 94.5   | 91.7   | 77.3           | 189.1   | 162.2            | 54.8     | 56.8             | 166.0    | 156.4            | 50.0     | 51.9             |
| S.D.                    | 0.0    | 2.5    | 3.7    | 8.4            | 26.0    | 18.1             | 15.0     | 14.5             | 18.8     | 18.1             | 15.8     | 15.2             |
| 95% CI                  | 0.0    | 2.6    | 3.9    | 8.8            | 27.3    | 19.0             | 15.7     | 15.2             | 19.7     | 19.0             | 16.6     | 16.0             |

Cyc No.: Cycle Number

PKSL: Peak Strain Level (%)

## III.3.b. Hysteresis

The hysteresis is defined by the following equation:

$$\text{Hysteresis (\%)} = \frac{\text{Energy loading} - \text{Energy unloading}}{\text{Energy loading}} \times 100 \%$$

Figure 3-13 shows the average hysteresis versus time in 3% constant peak strain level tests (A-type test, see Figure 2-1). The statistical summary of hysteresis is listed in Table 3-10.

Hysteresis rapidly decreases for the first few cycles of testing then continues to decrease to a lesser degree as in the case of the normalized cyclic peak load. The average value of hysteresis decreases during 300 cycles from an initial value of 31.7% to a final value of 13.7%.

Figure 3-14 shows the average hysteresis versus time in 3% constant peak strain level tests with two rest periods (B-type test, see Figure 2-1). The statistical summary of hysteresis is listed in Table 3-11. Hysteresis for each cycle decreases within each cyclic block, and some recovery occurs after each rest period as in the case of the normalized cyclic peak load. The average value of recovery in hysteresis with a 72 sec rest period is 2.0% for the first rest period and 1.9% for the second rest period. Hubbard and Chun [23] showed that the average value of recovery with an 1800 sec rest period was 2.8% for the first rest period and 2.0% for the

second rest period at a 3% peak strain level. These results show that there is more recovery with longer rest period as in the case of the normalized cyclic peak load. Hysteresis of each cycle in the B-type tests is not statistically different from that of its corresponding cycle in the A-type test via a t-test at  $p = 0.05$ .

Figure 3-15 shows the average hysteresis versus time in 3-4% different peak strain level tests (C-type test, see Figure 2-1). The statistical summary of hysteresis is listed in Table 3-12. Hysteresis within each cyclic block decreases as in the A and B-type tests. However, there are increases after transitions to both 3% and 4% maximum strain levels.

The decreases of hysteresis between the first and second cycle are more than half of the overall decreases. For all the test types, the range of the average hysteresis values is 32% to 40% for the first cycle, 20% to 25% for the second cycle and 14% to 17% for the last cycle. The hysteresis values for the first cycle in the present study are comparable to canine [23] values of 34% to 37% and human [26] values of 15% to 45%. The values (14% to 17%) of hysteresis at 360 sec in the present study are comparable to other studies of canine tendons: 16% to 20% hysteresis [23] at 9000 sec with two rest periods (each 1800 sec) and 17% to 22% hysteresis [43] at 9000 sec with no rest period.

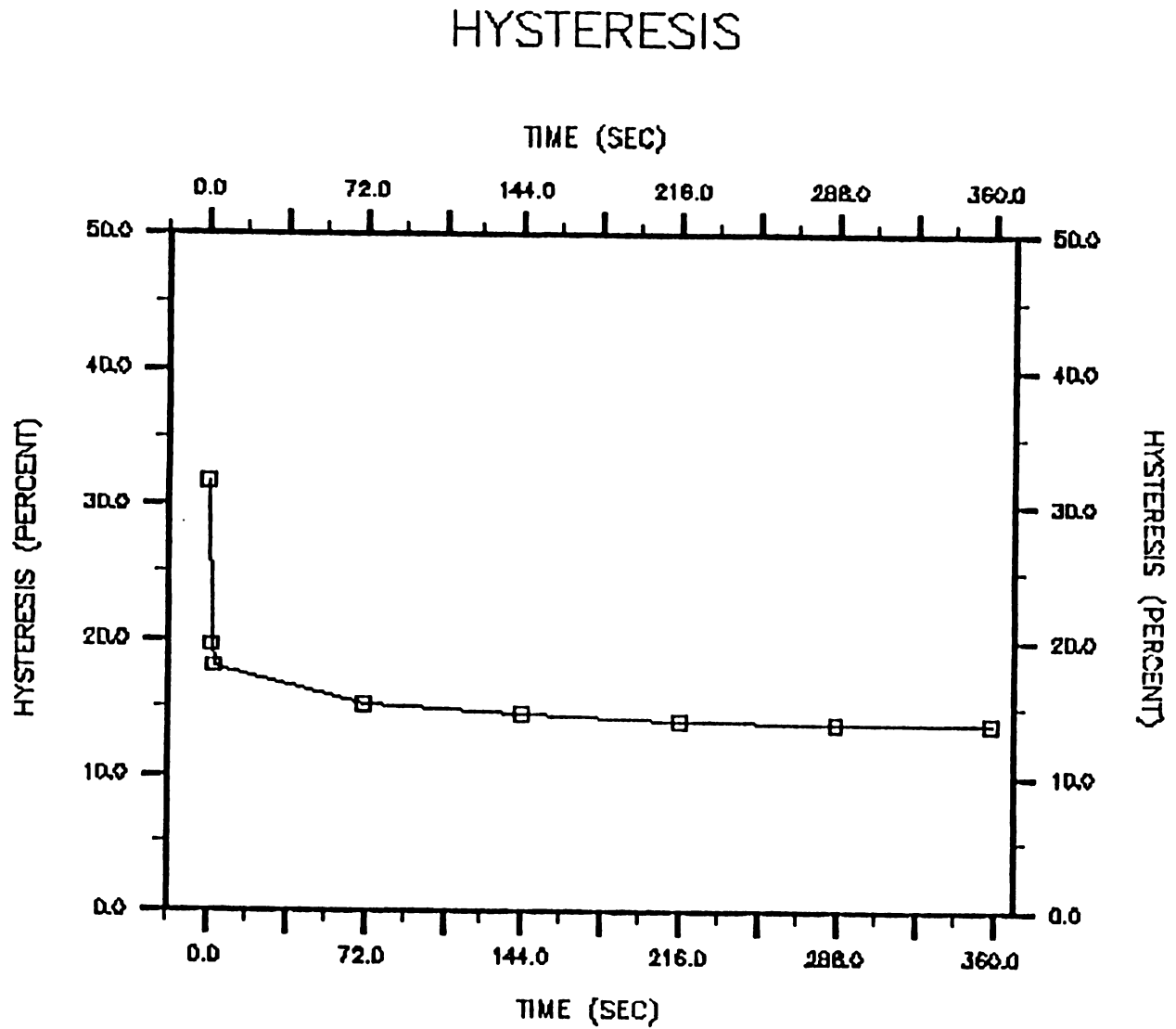


Fig. 3-13 Average hysteresis (%) in 3% constant peak strain level tests (A-type test, see Fig. 2-1)

Table 3-10

Summary of Hysteresis (%) in 3% Constant Peak Strain Level Tests  
(A-type test. See Fig. 2-1)

| Cycle No.<br>Time | 1    | 2    | 3    | 60<br>72s | 120<br>144s | 180<br>216s | 240<br>288s | 300<br>360s |
|-------------------|------|------|------|-----------|-------------|-------------|-------------|-------------|
| 33-1              | 28.4 | 18.5 | 15.9 | 13.4      | 13.0        | 12.9        | 12.6        | 12.4        |
| 33-2              | 24.3 | 15.2 | 14.5 | 12.8      | 12.2        | 11.6        | 11.3        | 11.6        |
| 33-3              | 32.4 | 20.0 | 19.3 | 16.7      | 16.6        | 15.2        | 15.1        | 14.7        |
| 33-4              | 36.2 | 22.3 | 21.0 | 17.4      | 16.2        | 15.7        | 15.8        | 15.6        |
| 33-5              | 31.8 | 19.3 | 16.9 | 14.3      | 13.4        | 12.9        | 12.9        | 12.7        |
| 33-6              | 37.2 | 22.0 | 20.6 | 16.4      | 15.7        | 15.4        | 15.3        | 15.0        |
| Ave.              | 31.7 | 19.6 | 18.0 | 15.2      | 14.5        | 14.0        | 13.8        | 13.7        |
| S.D.              | 4.8  | 2.6  | 2.7  | 1.9       | 1.9         | 1.7         | 1.8         | 1.6         |
| 95% C.I.          | 5.0  | 2.7  | 2.8  | 2.0       | 2.0         | 1.8         | 1.9         | 1.7         |

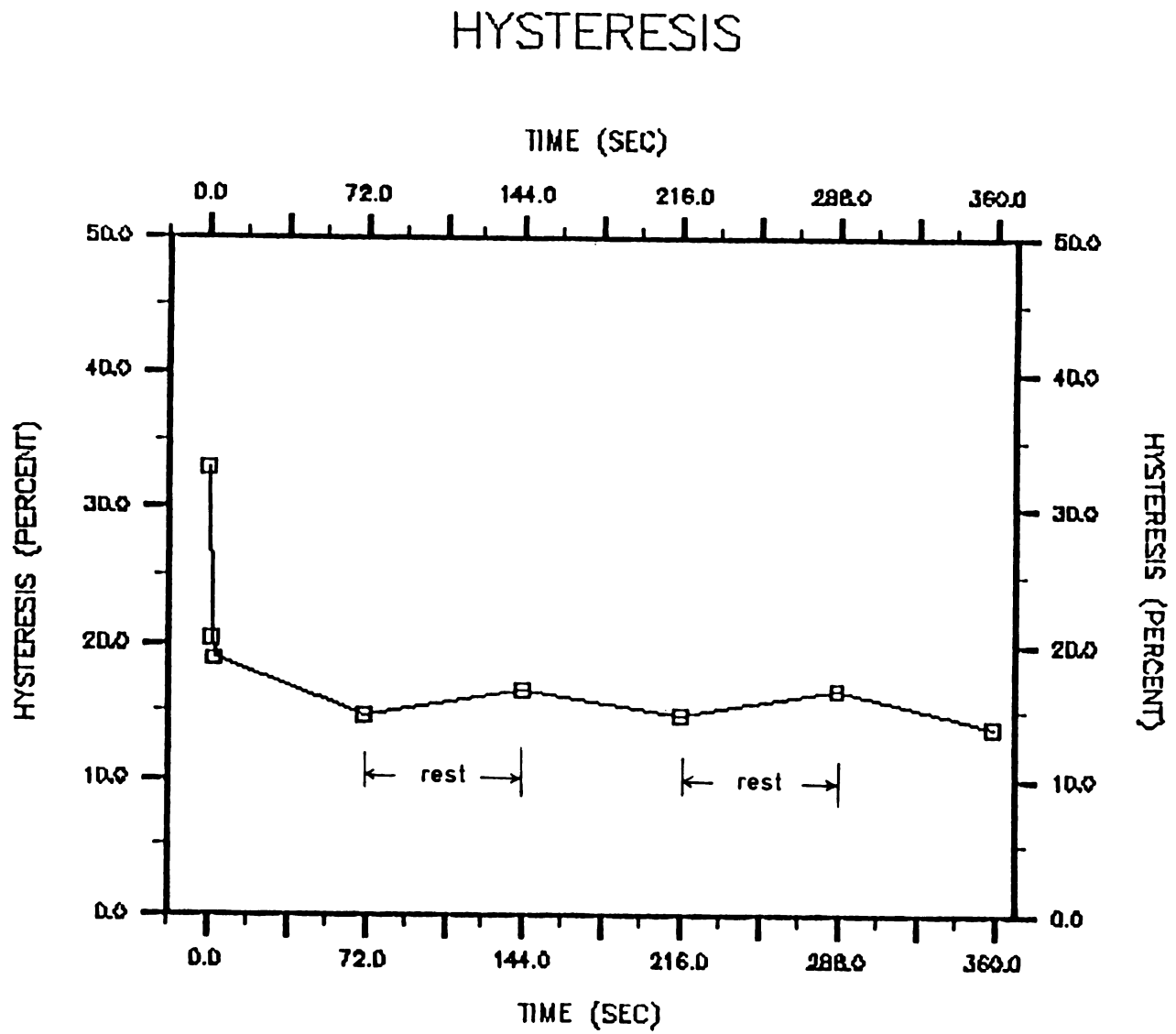


Fig. 3-14 Average hysteresis (%) in 3% constant peak strain level tests with rest periods (B-type test, see Fig. 2-1)

Table 3-11

Summary of Hysteresis (%) in 3% Constant Peak Strain  
Level Tests with Rest Periods (B-type test. See Fig. 2-1)

| Cycle No.<br>Time | 1    | 2    | 3    | 60<br>72s | 61<br>144s | 120<br>216s | 121<br>288s | 180<br>360s |
|-------------------|------|------|------|-----------|------------|-------------|-------------|-------------|
| 30-1              | 29.1 | 17.2 | 15.8 | 12.0      | 13.6       | 12.3        | 14.3        | 11.8        |
| 30-2              | 30.7 | 17.5 | 16.6 | 13.1      | 14.3       | 11.9        | 14.5        | 12.0        |
| 30-3              | 32.2 | 19.7 | 17.6 | 13.9      | 15.5       | 13.6        | 15.6        | 13.0        |
| 30-4              | 29.0 | 18.3 | 16.4 | 13.0      | 15.2       | 12.8        | 14.8        | 12.5        |
| 30-5              | 50.5 | 31.7 | 30.2 | 23.2      | 26.7       | 24.3        | 26.3        | 21.1        |
| 30-6              | 25.4 | 17.4 | 16.6 | 12.4      | 14.0       | 12.8        | 13.6        | 11.7        |
| Ave.              | 32.8 | 20.3 | 18.9 | 14.6      | 16.6       | 14.6        | 16.5        | 13.7        |
| S.D.              | 8.9  | 5.7  | 5.6  | 4.3       | 5.0        | 4.8         | 4.8         | 3.7         |
| 95% C.I.          | 9.3  | 6.0  | 5.9  | 4.5       | 5.2        | 5.0         | 5.0         | 3.9         |

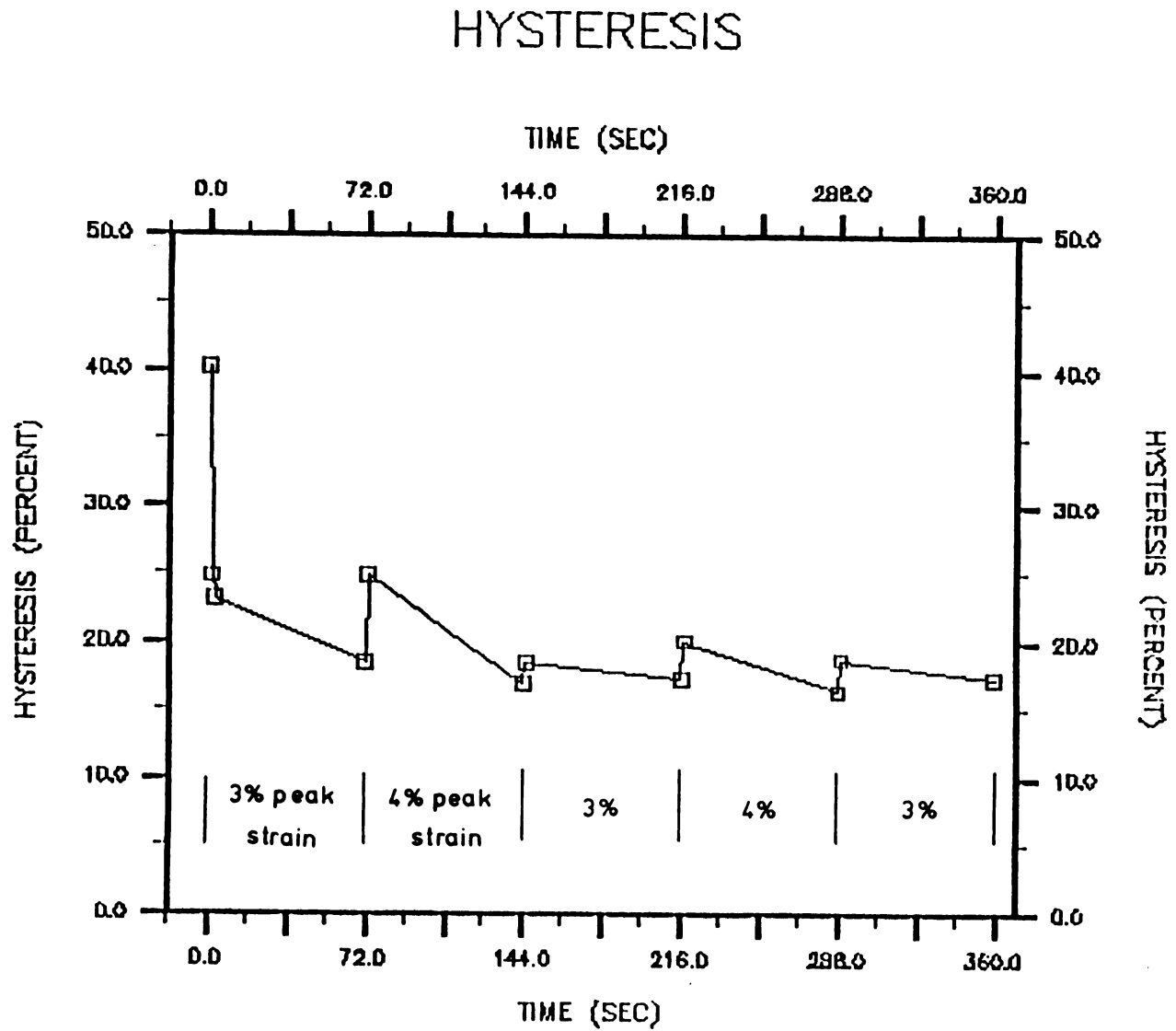


Fig. 3-15 Average hysteresis (%) in 3-4% different peak strain level tests (C-type test, see Fig. 2-1)

Table 3-12

Summary of Hysteresis (%) in 3-4% Different Peak  
Strain Level Tests (C-type test, see Fig. 2-1)

| Cyc No.  | 1    | 2    | 3    | 60   | 61   | 105  | 106  | 165  | 166  | 210  | 211  | 270  |
|----------|------|------|------|------|------|------|------|------|------|------|------|------|
| Time     |      |      |      | 72s  |      | 144s |      | 216s |      | 288s |      | 360s |
| PKSL     | 3    | 3    | 3    | 3    | 4    | 4    | 3    | 3    | 4    | 4    | 3    | 3    |
| 34-1     | 35.0 | 21.4 | 18.9 | 14.4 | 19.5 | 14.1 | 16.2 | 14.6 | 17.2 | 15.6 | 16.0 | 14.8 |
| 34-2     | 41.1 | 23.7 | 21.6 | 18.1 | 24.6 | 16.5 | 17.7 | 16.1 | 17.4 | 13.7 | 17.8 | 15.2 |
| 34-3     | 35.9 | 22.6 | 20.9 | 16.6 | 23.0 | 16.3 | 17.0 | 17.0 | 19.5 | 15.5 | 17.2 | 16.6 |
| 34-4     | 34.8 | 20.9 | 20.0 | 15.8 | 21.7 | 15.2 | 16.8 | 16.1 | 17.8 | 14.9 | 17.1 | 15.9 |
| 34-5     | 56.2 | 36.3 | 34.4 | 27.9 | 38.0 | 24.1 | 23.8 | 24.4 | 30.8 | 24.2 | 25.9 | 24.7 |
| 34-6     | 38.4 | 24.1 | 22.6 | 18.4 | 22.3 | 14.9 | 18.9 | 15.0 | 17.9 | 13.8 | 18.0 | 16.2 |
| Ave.     | 40.2 | 24.8 | 23.1 | 18.5 | 24.9 | 16.9 | 18.4 | 17.2 | 20.1 | 16.3 | 18.7 | 17.2 |
| S.D.     | 8.2  | 5.8  | 5.7  | 4.8  | 6.7  | 3.7  | 2.8  | 3.6  | 5.3  | 4.0  | 3.6  | 3.7  |
| 95% C.I. | 8.6  | 6.1  | 6.0  | 5.0  | 7.0  | 3.9  | 2.9  | 3.8  | 5.6  | 4.2  | 3.8  | 3.8  |

Cyc No.: Cycle Number

PKSL: Peak Strain Level (%)

### III.3.c. Slack strain

As the distance between the grips increases in a test, loading slack strain is the first occurring and smallest strain for which tensile stress is applied in the tendon specimen. As the distance between the grips decreases in a test, unloading slack strain is the first occurring and largest strain for which tensile stress is no longer applied in the tendon specimen.

Figure 3-16 shows the average values of loading and unloading slack strains throughout the 3% constant peak strain level tests (A-type test, see Figure 2-1). The statistical summaries of slack strains are listed in Table 3-13 for loading and Table 3-14 for unloading. The slack strains rapidly increase for the first few cycles of testing then continue to increase to a lesser degree. The range of average values for loading slack strains is from an initial value of 0.0% to a final value of 1.08%. For unloading slack strains, this range is from 0.80% to 1.32%.

Figure 3-17 shows the average values of loading and unloading slack strains throughout the 3% constant peak strain level tests with two rest periods (B-type test, see Figure 2-1). The statistical summaries of slack strains are listed in Table 3-15 for loading and Table 3-16 for unloading. Slack strains increase within each cyclic block, and recovery (decreasing of the slack strain) occurs after each rest period. These tables show that individual

recovery for each test is nonzero in each rest period. The average values of recovery in the 72 sec rest periods for both loading and unloading are 0.09% for the first rest period and 0.11% for the second rest period. Hubbard and Chun [23] found that the average values of recovery in loading slack strains during 1800 sec rest periods were 0.20% for the first rest period and 0.17% for the second rest period. Thus, there is more recovery with a longer rest period. Slack strain in each cycle for loading and unloading for a B-type test is not statistically different from that in corresponding cycles in the A-type tests via a t-test at  $p = 0.05$ .

Figure 3-18 shows the average values of loading and unloading slack strains throughout the 3-4% different peak strain level tests (C-type test, see Figure 2-1). The statistical summaries of slack strains are listed in Table 3-17 for loading and Table 3-18 for unloading. Slack strains rapidly increase for the first few cycles of testing then continue to increase to a lesser degree. There is an abrupt increase at the change from 3% to 4% peak strain. Slack strains recover (decrease) with return to 3% maximum strain in the third cyclic block (from 144 to 216 sec) and fifth cyclic block (from 288 to 360 sec) as in the cases of the normalized cyclic load and hysteresis. The unloading slack strains decrease at 144 and 288 sec while the loading slack strains increase at these times in the C-type test. Slack strain from the 1st to 60th cycle is not statistically different from that in corresponding cycles in the A and B-type tests via a t-test at  $p = 0.05$ .

At the beginning of the test, the initial length of the tendon specimen was adjusted so that a tendon specimen was slightly extended and bearing a small load of 0.13 N. Thus, there was no slack strain at the 1st loading. The effect of each rest period was to reduce the slack strain, which then increased during the following cycles. The changes in slack strain accompany the changes in peak load and hysteresis. The average value of the first unloading slack strain is 0.85% for all eighteen specimens. This average value of unloading slack strain from the first cycle will be used as input to the constitutive model for comparison of predicted results with measured data.

# SLACK STRAIN

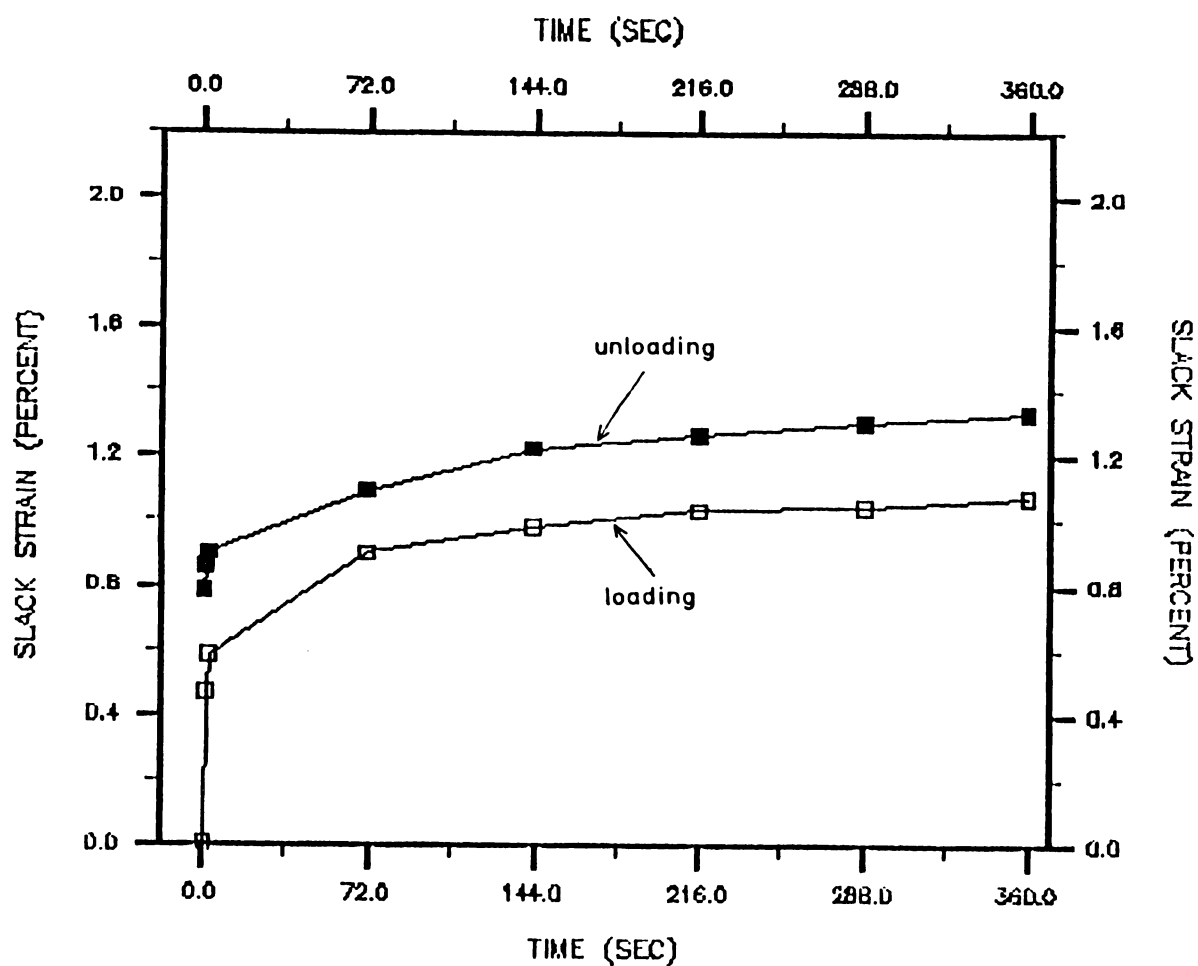


Fig. 3-16 Average slack strain (%) in 3% constant peak strain level tests (A-type test, see Fig. 2-1)

Table 3-13

Summary of Loading Slack Strain (%) in 3% Constant  
Peak Strain Level Tests (A-type test, see Fig. 2-1)

| Cycle No. | 1    | 2    | 3    | 60   | 120  | 180  | 240  | 300  |
|-----------|------|------|------|------|------|------|------|------|
| Time      |      |      |      | 72s  | 144s | 216s | 288s | 360s |
| 33-1      | 0.0  | 0.3  | 0.4  | 0.7  | 0.8  | 0.9  | 0.9  | 1.0  |
| 33-2      | 0.0  | 0.4  | 0.5  | 0.8  | 0.8  | 0.9  | 0.9  | 0.9  |
| 33-3      | 0.0  | 0.4  | 0.6  | 0.9  | 1.0  | 1.0  | 1.0  | 1.0  |
| 33-4      | 0.0  | 0.7  | 0.8  | 1.1  | 1.1  | 1.2  | 1.2  | 1.2  |
| 33-5      | 0.0  | 0.3  | 0.5  | 0.8  | 0.9  | 0.9  | 0.9  | 1.0  |
| 33-6      | 0.0  | 0.7  | 0.8  | 1.2  | 1.3  | 1.3  | 1.3  | 1.4  |
| Ave.      | 0.00 | 0.47 | 0.60 | 0.92 | 0.98 | 1.03 | 1.03 | 1.08 |
| S.D.      | 0.00 | 0.19 | 0.17 | 0.19 | 0.19 | 0.18 | 0.18 | 0.18 |
| 95% C.I.  | 0.00 | 0.20 | 0.18 | 0.20 | 0.20 | 0.19 | 0.19 | 0.19 |

Table 3-14

Summary of Unloading Slack Strain (%) in 3% Constant  
Peak Strain Level Tests (A-type test, see Fig. 2-1)

| Cycle No. | 1    | 2    | 3    | 60   | 120  | 180  | 240  | 300  |
|-----------|------|------|------|------|------|------|------|------|
| Time      |      |      |      | 72s  | 144s | 216s | 288s | 360s |
| 33-1      | 0.6  | 0.7  | 0.7  | 0.9  | 1.0  | 1.1  | 1.1  | 1.1  |
| 33-2      | 0.6  | 0.7  | 0.7  | 0.9  | 1.0  | 1.1  | 1.1  | 1.1  |
| 33-3      | 1.0  | 1.0  | 1.1  | 1.2  | 1.3  | 1.3  | 1.4  | 1.4  |
| 33-4      | 1.0  | 1.0  | 1.1  | 1.1  | 1.4  | 1.5  | 1.5  | 1.6  |
| 33-5      | 0.7  | 0.8  | 0.8  | 1.0  | 1.1  | 1.1  | 1.2  | 1.2  |
| 33-6      | 0.9  | 1.0  | 1.1  | 1.4  | 1.4  | 1.5  | 1.5  | 1.5  |
| Ave.      | 0.80 | 0.87 | 0.92 | 1.08 | 1.20 | 1.27 | 1.30 | 1.32 |
| S.D.      | 0.19 | 0.15 | 0.20 | 0.19 | 0.19 | 0.20 | 0.19 | 0.21 |
| 95% C.I.  | 0.20 | 0.16 | 0.21 | 0.20 | 0.20 | 0.21 | 0.20 | 0.22 |

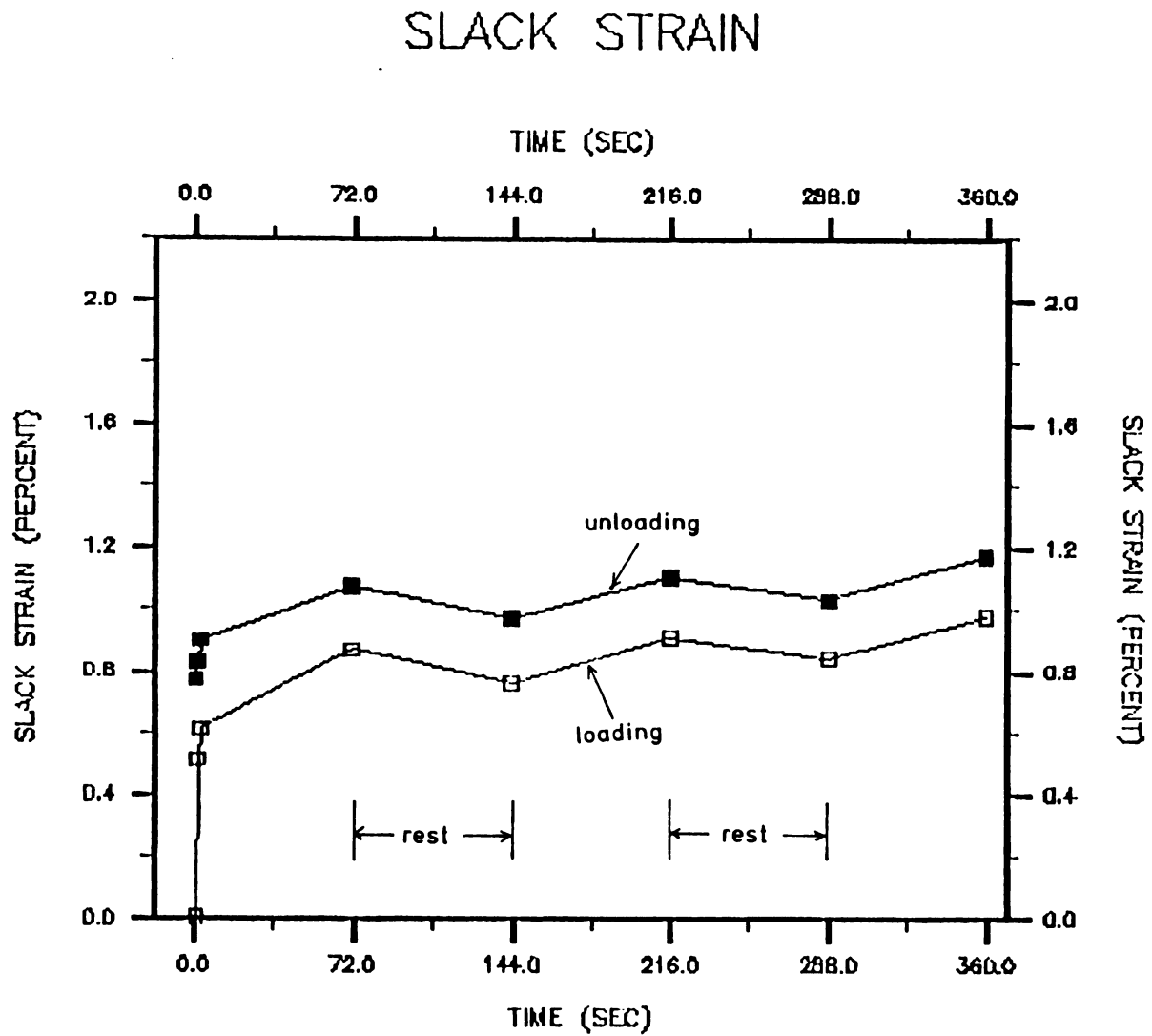


Fig. 3-17 Average slack strain (%) in 3% constant peak strain level tests with rest periods (B-type test, see Fig. 2-1)

Table 3-15

Summary of Loading Slack Strain (%) in 3% Constant Peak Strain  
Level Tests with Rest Periods (B-type test, see Fig. 2-1)

| Cycle No. | 1    | 2    | 3    | 60   | 61   | 120  | 121  | 180  |
|-----------|------|------|------|------|------|------|------|------|
| Time      |      |      |      | 72s  | 144s | 216s | 288s | 360s |
| 30-1      | 0.0  | 0.4  | 0.5  | 0.8  | 0.7  | 0.9  | 0.8  | 0.9  |
| 30-2      | 0.0  | 0.6  | 0.7  | 0.9  | 0.9  | 1.0  | 0.9  | 1.1  |
| 30-3      | 0.0  | 0.6  | 0.7  | 0.9  | 0.8  | 1.0  | 0.9  | 1.1  |
| 30-4      | 0.0  | 0.5  | 0.7  | 0.9  | 0.8  | 0.9  | 0.8  | 0.9  |
| 30-5      | 0.0  | 0.5  | 0.7  | 0.9  | 0.8  | 0.9  | 0.8  | 0.9  |
| 30-6      | 0.0  | 0.4  | 0.5  | 0.8  | 0.7  | 0.9  | 0.7  | 0.9  |
| Ave.      | 0.00 | 0.50 | 0.63 | 0.87 | 0.78 | 0.93 | 0.82 | 0.97 |
| S.D.      | 0.00 | 0.09 | 0.10 | 0.05 | 0.08 | 0.05 | 0.08 | 0.10 |
| 95% C.I.  | 0.00 | 0.09 | 0.10 | 0.05 | 0.08 | 0.05 | 0.08 | 0.10 |

Table 3-16

Summary of Unloading Slack Strain (%) in 3% Constant Peak Strain  
Level Tests with Rest Periods (B-type test, See Fig. 2-1)

| Cycle No. | 1    | 2    | 3    | 60   | 61   | 120  | 121  | 180  |
|-----------|------|------|------|------|------|------|------|------|
| Time      |      |      |      | 72s  | 144s | 216s | 288s | 360s |
| 30-1      | 0.8  | 0.8  | 0.9  | 1.1  | 0.9  | 1.1  | 1.0  | 1.1  |
| 30-2      | 0.9  | 0.9  | 1.0  | 1.2  | 1.1  | 1.2  | 1.1  | 1.3  |
| 30-3      | 0.9  | 0.9  | 0.9  | 1.1  | 1.0  | 1.1  | 1.1  | 1.3  |
| 30-4      | 0.8  | 0.8  | 0.9  | 1.0  | 1.0  | 1.1  | 1.0  | 1.1  |
| 30-5      | 0.7  | 0.8  | 0.9  | 1.1  | 1.1  | 1.2  | 1.1  | 1.2  |
| 30-6      | 0.7  | 0.8  | 0.8  | 0.9  | 0.8  | 1.0  | 0.9  | 1.0  |
| Ave.      | 0.80 | 0.83 | 0.90 | 1.07 | 0.98 | 1.12 | 1.03 | 1.17 |
| S.D.      | 0.09 | 0.05 | 0.06 | 0.10 | 0.12 | 0.08 | 0.08 | 0.12 |
| 95% C.I.  | 0.09 | 0.05 | 0.06 | 0.10 | 0.13 | 0.08 | 0.08 | 0.13 |

## SLACK STRAIN

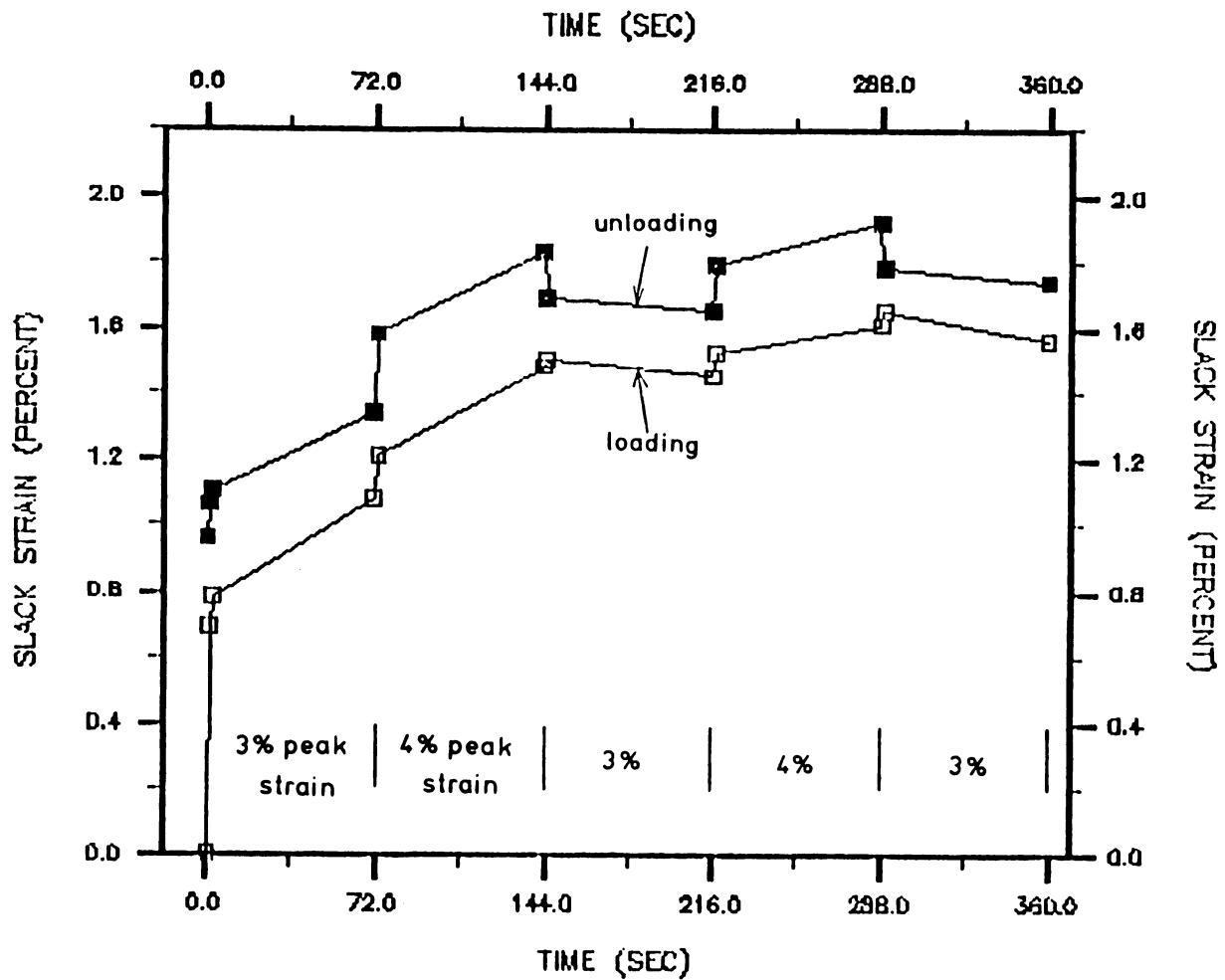


Fig. 3-18 Average slack strain (%) in 3-4% different peak strain level tests (C-type test, see Fig. 2-1)

Table 3-17

Summary of Loading Slack Strain (%) in 3-4s  
Different Peak Strain Level Tests (C-type test, see Fig. 2-1)

| Cyc No. | 1    | 2    | 3    | 60   | 61   | 105  | 106  | 165  | 166  | 210  | 211  | 270  |
|---------|------|------|------|------|------|------|------|------|------|------|------|------|
| Time    |      |      |      | 72s  |      | 144s |      | 216s |      | 288s |      | 360s |
| PKSL    | 3    | 3    | 3    | 3    | 4    | 4    | 3    | 3    | 4    | 4    | 3    | 3    |
| 34-1    | 0.0  | 0.7  | 0.8  | 1.0  | 1.1  | 1.4  | 1.4  | 1.4  | 1.4  | 1.4  | 1.6  | 1.4  |
| 34-2    | 0.0  | 0.8  | 0.9  | 1.2  | 1.2  | 1.6  | 1.6  | 1.5  | 1.5  | 1.6  | 1.6  | 1.6  |
| 34-3    | 0.0  | 0.6  | 0.7  | 1.0  | 1.1  | 1.4  | 1.5  | 1.4  | 1.5  | 1.5  | 1.5  | 1.5  |
| 34-4    | 0.0  | 0.6  | 0.7  | 1.1  | 1.3  | 1.5  | 1.5  | 1.5  | 1.6  | 1.6  | 1.6  | 1.6  |
| 34-5    | 0.0  | 0.7  | 0.8  | 1.0  | 1.3  | 1.5  | 1.5  | 1.5  | 1.6  | 1.9  | 1.9  | 1.8  |
| 34-6    | 0.0  | 0.8  | 0.9  | 1.2  | 1.3  | 1.5  | 1.5  | 1.5  | 1.6  | 1.6  | 1.7  | 1.6  |
| Ave.    | 0.00 | 0.70 | 0.80 | 1.08 | 1.22 | 1.48 | 1.50 | 1.47 | 1.53 | 1.60 | 1.65 | 1.58 |
| S.D.    | 0.00 | 0.09 | 0.09 | 0.10 | 0.10 | 0.08 | 0.06 | 0.05 | 0.08 | 0.17 | 0.14 | 0.13 |
| 95% CI  | 0.00 | 0.09 | 0.09 | 0.10 | 0.10 | 0.08 | 0.06 | 0.05 | 0.08 | 0.18 | 0.15 | 0.14 |

Cyc No: Cycle Number

PKSL: Peak Strain Level (%)

Table 3-18

Summary of Unloading Slack Strain (%) in 3-4%  
Different Peak Strain Level Tests (C-type test, see Fig. 2-1)

| Cyc No. | 1    | 2    | 3    | 60   | 61   | 105  | 106  | 165  | 166  | 210  | 211  | 270  |
|---------|------|------|------|------|------|------|------|------|------|------|------|------|
| Time    |      |      |      | 72s  |      | 144s |      | 216s |      | 288s |      | 360s |
| PKSL    | 3    | 3    | 3    | 3    | 4    | 4    | 3    | 3    | 4    | 4    | 3    | 3    |
| 34-1    | 0.8  | 1.0  | 1.1  | 1.2  | 1.4  | 1.6  | 1.5  | 1.5  | 1.6  | 1.7  | 1.6  | 1.6  |
| 34-2    | 1.0  | 1.1  | 1.1  | 1.4  | 1.6  | 1.8  | 1.7  | 1.7  | 1.9  | 1.9  | 1.8  | 1.8  |
| 34-3    | 1.0  | 1.0  | 1.0  | 1.2  | 1.5  | 1.7  | 1.6  | 1.6  | 1.7  | 1.8  | 1.7  | 1.6  |
| 34-4    | 1.0  | 1.0  | 1.1  | 1.4  | 1.7  | 1.9  | 1.7  | 1.6  | 1.8  | 1.9  | 1.8  | 1.7  |
| 34-5    | 1.0  | 1.2  | 1.2  | 1.4  | 1.8  | 2.2  | 2.0  | 1.8  | 2.0  | 2.3  | 2.1  | 2.1  |
| 34-6    | 1.0  | 1.1  | 1.2  | 1.5  | 1.5  | 1.8  | 1.7  | 1.7  | 1.9  | 1.9  | 1.8  | 1.7  |
| Ave.    | 0.97 | 1.07 | 1.12 | 1.35 | 1.58 | 1.83 | 1.70 | 1.65 | 1.82 | 1.92 | 1.80 | 1.75 |
| S.D.    | 0.08 | 0.08 | 0.08 | 0.12 | 0.15 | 0.21 | 0.17 | 0.11 | 0.15 | 0.20 | 0.17 | 0.19 |
| 95% CI  | 0.08 | 0.08 | 0.08 | 0.13 | 0.16 | 0.22 | 0.18 | 0.12 | 0.16 | 0.21 | 0.18 | 0.20 |

Cyc No.: Cycle Number

PKSL: Peak Strain Level (%)

### III.3.d. Power fit coefficients

As in previous work [23,43], log-log, stress-strain responses were fit with a linear regression equation of the form:

$$\text{Log}(\text{stress}) = \text{Log}(C) + d [\text{Log}(\text{strain} - \text{slack strain})].$$

This fitting resulted in high correlation coefficients of 0.99 or greater.

Taking the antilog of this relation yields:

$$\text{Stress} = C (\text{strain} - \text{slack strain})^d$$

$$\text{or, } \sigma = C (\epsilon - \epsilon_s)^d$$

where  $\epsilon$  is the strain,

$\epsilon_s$  is the slack strain,

$d$  is the power coefficient,

$C$  is the scale factor.

Figure 3-19 shows typical stress-strain data from a test with a maximum strain of 3% and the regression curve superimposed over

it. Figure 3-20 shows typical stress-strain data for the first, 60th, and 300th cycles using the same method as Figure 3-19.

Tables 3-19 through 24 list the summary of power coefficient  $d$  from log-log, stress-strain fits for all three types of tests (A, B, and C-type). The range of values of  $d$  for the first cycle of loading is from 1.67 to 2.48, and for the first cycle of unloading the range in values of  $d$  is from 1.60 to 3.12. The average values of  $d$  for the first cycle of loading is 2.05 and unloading is 2.30 for all eighteen specimens, but these values are not statistically different at  $p = 0.05$  level. Hubbard and Chun [23] found that the values of  $d$  for loading were from 1.41 to 2.45, with most values around 2.0. Haut and Little [22] and Jenkins and Little [28] also selected the value of 2.0 for this power coefficient for collagenous tissues.

Tables 3-25 through 30 list the summary of the coefficient  $C$  from log-log, stress-strain fits. The coefficient  $C$  acts as a scale factor in the regression similar to a modulus in a linear stress-strain relationship. The range of values of  $C$  for the first cycle of loading is from 0.86 to 64.01 GPa and for unloading is from 9.73 to 353.23 GPa. Large scatter for  $C$  is shown in these tables both from cycle to cycle within a specimen and between specimens. Both types of scatter may in part be due to the interaction between values of the coefficients  $C$  and  $d$  for the best fitting of the measured data. The cycle to cycle scatter indicates changes in responses during the tests with the only significant difference

being the increase between the first and second cycles. The scatter between specimens is different from other specimens. This difference is examined further in section V.2 below and is probably related to differences in tissue fiber composition and geometry.

For rat tail tendons, Haut and Little [22] reported that  $C$  varied between 18.0 and 31.4 GPa, but the average value of  $C$  was 23.06 GPa with a standard deviation of 3.75 GPa at various strain rates. Recently, Hubbard and Chun [23] found, for canine tendons like those in the present study, that the average value of  $C$  for the first cycle of loading was about 17.0 GPa with large standard deviation of 16.6 GPa.

## STRESS VS. STRAIN

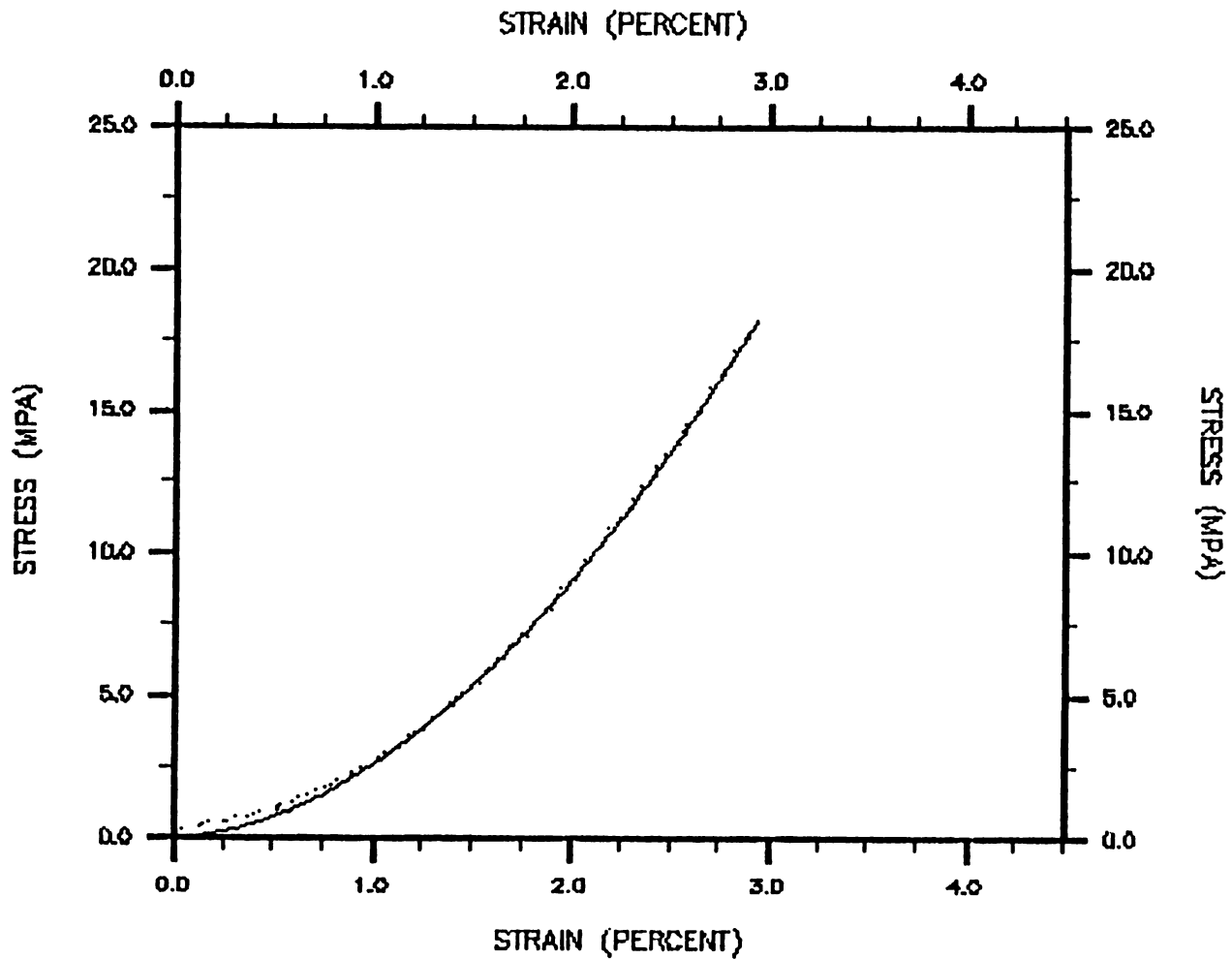


Fig. 3-19 Typical stress-strain response at a 3% peak strain level as measured and fitted with the log-log fit (..... : experimental data, \_\_\_\_\_ : fitted line).

## STRESS VS. STRAIN

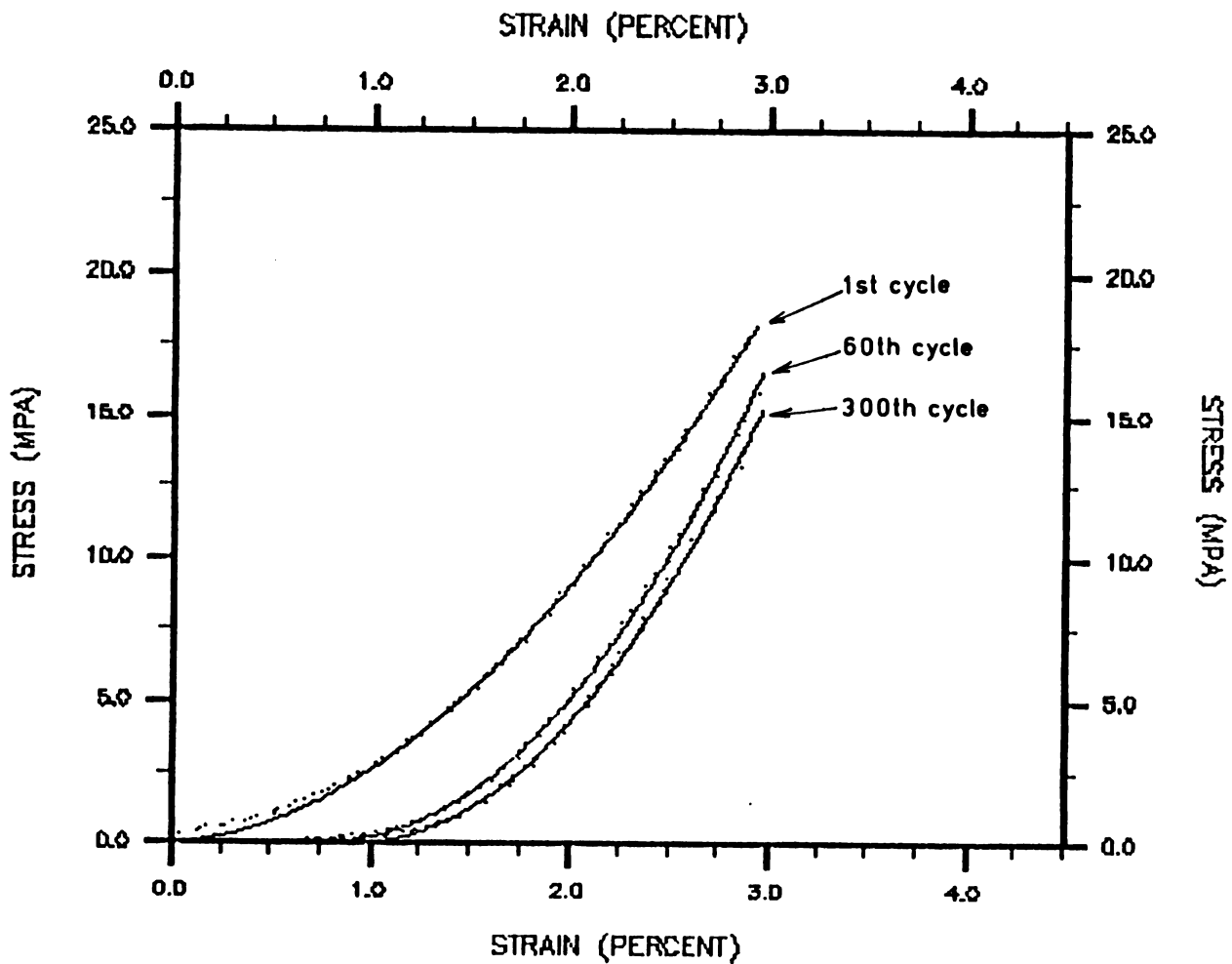


Fig. 3-20 Typical stress-strain responses with cycle at a 3% peak strain level as measured and fitted with log-log fit  
(..... : experimental data, \_\_\_\_\_ : fitted line)

Table 3-19

Summary of Loading Power (d) from Log-Log, Stress-Strain  
Fits at 3% Constant Peak Strain Level Test  
(A-type test, see Fig. 2-1)

$$\sigma = C (\epsilon - \epsilon_s)^d$$

| Cycle No. | 1    | 2    | 3    | 60   | 120  | 180  | 240  | 300  |
|-----------|------|------|------|------|------|------|------|------|
| Time      |      |      |      | 72s  | 144s | 216s | 288s | 360s |
| 33-1      | 1.68 | 1.81 | 1.86 | 1.79 | 1.75 | 1.68 | 1.68 | 1.63 |
| 33-2      | 1.94 | 1.94 | 1.83 | 1.73 | 1.71 | 1.68 | 1.67 | 1.65 |
| 33-3      | 2.17 | 2.30 | 2.11 | 2.15 | 2.13 | 2.13 | 2.17 | 2.11 |
| 33-4      | 2.26 | 2.22 | 2.17 | 2.15 | 2.22 | 2.15 | 2.16 | 2.18 |
| 33-5      | 1.83 | 2.14 | 2.06 | 2.08 | 1.96 | 2.00 | 1.94 | 1.97 |
| 33-6      | 2.03 | 1.96 | 1.97 | 1.94 | 1.89 | 1.68 | 1.70 | 1.71 |
| Ave.      | 1.99 | 2.06 | 2.00 | 1.97 | 1.94 | 1.89 | 1.89 | 1.88 |
| S.D.      | 0.21 | 0.19 | 0.14 | 0.18 | 0.20 | 0.23 | 0.24 | 0.24 |
| 95% C.I.  | 0.22 | 0.20 | 0.15 | 0.19 | 0.21 | 0.24 | 0.25 | 0.25 |

Table 3-20

Summary of Unloading Power (d) from Log-Log, Stress-Strain  
Fits at 3% Constant Peak Strain Level Test  
(A-type test, see Fig. 2-1)

$$\sigma = C (\epsilon - \epsilon_s)^d$$

| Cycle No.<br>Time | 1    | 2    | 3    | 60<br>72s | 120<br>144s | 180<br>216s | 240<br>288s | 300<br>360s |
|-------------------|------|------|------|-----------|-------------|-------------|-------------|-------------|
| 33-1              | 1.84 | 1.87 | 1.85 | 1.87      | 1.77        | 1.61        | 1.69        | 1.71        |
| 33-2              | 1.92 | 1.93 | 1.89 | 1.80      | 1.76        | 1.72        | 1.68        | 1.70        |
| 33-3              | 2.08 | 2.08 | 2.10 | 2.12      | 2.05        | 2.06        | 2.01        | 1.99        |
| 33-4              | 2.51 | 2.46 | 2.39 | 2.65      | 2.18        | 2.13        | 2.18        | 2.09        |
| 33-5              | 2.10 | 2.09 | 2.06 | 2.06      | 1.91        | 1.95        | 1.91        | 1.89        |
| 33-6              | 2.19 | 1.92 | 1.86 | 1.94      | 1.82        | 1.83        | 1.79        | 1.82        |
| Ave.              | 2.11 | 2.06 | 2.03 | 2.07      | 1.92        | 1.88        | 1.88        | 1.87        |
| S.D.              | 0.24 | 0.22 | 0.21 | 0.31      | 0.17        | 0.20        | 0.20        | 0.16        |
| 95% C.I.          | 0.25 | 0.23 | 0.22 | 0.33      | 0.18        | 0.21        | 0.21        | 0.17        |

Table 3-21

Summary of Loading Power (d) from Log-Log. Stress-Strain  
Fits at 3% Constant Peak Strain Level Test with Rest Periods  
(B-type test, see Fig. 2-1)

$$\sigma = C (\epsilon - \epsilon_s)^d$$

| Cycle No.<br>Time | 1    | 2    | 3    | 60<br>72s | 61<br>144s | 120<br>216s | 121<br>288s | 180<br>360s |
|-------------------|------|------|------|-----------|------------|-------------|-------------|-------------|
| 30-1              | 1.67 | 1.75 | 1.77 | 1.60      | 1.75       | 1.60        | 1.64        | 1.58        |
| 30-2              | 2.15 | 1.98 | 1.98 | 1.98      | 1.99       | 2.06        | 1.99        | 1.88        |
| 30-3              | 1.97 | 1.88 | 1.86 | 1.96      | 1.98       | 1.96        | 1.94        | 1.84        |
| 30-4              | 1.87 | 1.84 | 1.78 | 1.77      | 1.79       | 1.83        | 1.82        | 1.79        |
| 30-5              | 2.00 | 2.60 | 2.54 | 3.08      | 3.16       | 3.26        | 3.22        | 3.31        |
| 30-6              | 2.42 | 2.32 | 2.29 | 2.31      | 2.34       | 2.17        | 2.32        | 2.17        |
| Ave.              | 2.01 | 2.06 | 2.04 | 2.12      | 2.17       | 2.15        | 2.16        | 2.10        |
| S.D.              | 0.25 | 0.33 | 0.31 | 0.53      | 0.53       | 0.58        | 0.57        | 0.62        |
| 95% C.I.          | 0.26 | 0.35 | 0.33 | 0.56      | 0.56       | 0.61        | 0.60        | 0.65        |

Table 3-22

Summary of Unloading Power (d) from Log-Log, Stress-Strain  
Fits at 3% Constant Peak Strain Level Test with Rest Periods  
(B-type test, see Fig. 2-1)

$$\sigma = C (\epsilon - \epsilon_s)^d$$

| Cycle No.<br>Time | 1    | 2    | 3    | 60<br>72s | 61<br>144s | 120<br>216s | 121<br>288s | 180<br>360s |
|-------------------|------|------|------|-----------|------------|-------------|-------------|-------------|
| 30-1              | 1.60 | 1.62 | 1.62 | 1.56      | 1.71       | 1.60        | 1.71        | 1.61        |
| 30-2              | 2.06 | 2.08 | 2.07 | 2.00      | 2.10       | 2.02        | 2.09        | 1.90        |
| 30-3              | 2.07 | 2.08 | 2.08 | 2.05      | 2.18       | 2.08        | 2.14        | 1.86        |
| 30-4              | 1.94 | 1.92 | 1.87 | 1.93      | 1.95       | 1.91        | 1.96        | 1.87        |
| 30-5              | 3.12 | 3.22 | 3.15 | 3.52      | 3.53       | 3.64        | 3.62        | 3.74        |
| 30-6              | 2.45 | 2.39 | 2.36 | 2.43      | 2.54       | 2.43        | 2.43        | 2.36        |
| Ave.              | 2.21 | 2.22 | 2.19 | 2.25      | 2.34       | 2.28        | 2.33        | 2.22        |
| S.D.              | 0.52 | 0.55 | 0.53 | 0.68      | 0.65       | 0.72        | 0.68        | 0.78        |
| 95% C.I.          | 0.55 | 0.58 | 0.56 | 0.71      | 0.68       | 0.76        | 0.71        | 0.82        |

Table 3-23

Summary of Loading Power (d) from Log-Log. Stress Strain Fits  
at 3-4% Different Peak Strain Level Test  
(C-type test, See Fig. 2-1)

$$\sigma = C (\epsilon - \epsilon_s)^d$$

| Cycle No. | 1    | 2    | 3    | 60   | 61   | 105  | 106  | 165  | 166  | 210  | 211  | 270  |
|-----------|------|------|------|------|------|------|------|------|------|------|------|------|
| Time      |      |      |      | 72s  |      | 144s |      | 216s |      | 288s |      | 360s |
| PKSL      | 3    | 3    | 3    | 3    | 4    | 4    | 3    | 3    | 4    | 4    | 3    | 3    |
| 34-1      | 1.99 | 1.99 | 1.99 | 2.08 | 1.88 | 1.83 | 1.85 | 1.96 | 1.78 | 1.91 | 1.71 | 1.94 |
| 34-2      | 2.15 | 2.23 | 2.20 | 2.36 | 2.27 | 2.14 | 1.95 | 2.20 | 2.14 | 2.26 | 2.09 | 2.36 |
| 34-3      | 2.21 | 2.22 | 2.29 | 2.28 | 2.00 | 1.88 | 1.91 | 2.04 | 1.76 | 1.72 | 1.93 | 1.93 |
| 34-4      | 2.31 | 2.37 | 2.43 | 2.27 | 1.84 | 1.87 | 1.94 | 2.04 | 1.70 | 1.65 | 1.83 | 1.89 |
| 34-5      | 1.74 | 2.60 | 2.63 | 3.13 | 3.20 | 3.60 | 3.08 | 3.21 | 3.43 | 3.40 | 3.11 | 3.27 |
| 34-6      | 2.48 | 2.51 | 2.47 | 2.62 | 2.44 | 2.60 | 2.38 | 2.52 | 2.43 | 2.40 | 2.32 | 2.57 |
| Ave.      | 2.15 | 2.32 | 2.34 | 2.46 | 2.27 | 2.32 | 2.19 | 2.33 | 2.21 | 2.22 | 2.17 | 2.33 |
| S.D.      | 0.26 | 0.22 | 0.23 | 0.37 | 0.51 | 0.69 | 0.48 | 0.48 | 0.66 | 0.65 | 0.51 | 0.54 |
| 95% C.I.  | 0.27 | 0.23 | 0.24 | 0.39 | 0.54 | 0.72 | 0.50 | 0.50 | 0.69 | 0.68 | 0.54 | 0.57 |

Cycle No.: Cycle Number

PKSL: Peak Strain Level (%)

Table 3-24

Summary of Unloading Power (d) from Log-Log, Stress-Strain  
Fits at 3-4% Different Peak Strain Level Test  
(C-type test, see Fig. 2-1)

$$\sigma = C (\epsilon - \epsilon_s)^d$$

| Cyc No.  | 1    | 2    | 3    | 60   | 61   | 105  | 106  | 165  | 166  | 210  | 211  | 270  |
|----------|------|------|------|------|------|------|------|------|------|------|------|------|
| Time     |      |      |      | 72s  |      | 144s |      | 216s |      | 288s |      | 360s |
| PKSL     | 3    | 3    | 3    | 3    | 4    | 4    | 3    | 3    | 4    | 4    | 3    | 3    |
| 34-1     | 2.30 | 2.16 | 2.14 | 2.20 | 1.95 | 1.93 | 2.17 | 2.07 | 1.90 | 1.47 | 2.00 | 2.04 |
| 34-2     | 2.54 | 2.50 | 2.44 | 2.44 | 2.25 | 2.26 | 2.49 | 2.42 | 2.17 | 2.22 | 2.55 | 2.67 |
| 34-3     | 2.31 | 2.37 | 2.35 | 2.43 | 2.02 | 1.97 | 2.10 | 2.23 | 1.96 | 1.60 | 2.20 | 2.25 |
| 34-4     | 2.38 | 2.40 | 2.36 | 2.19 | 1.80 | 1.76 | 1.98 | 2.09 | 1.86 | 1.47 | 2.11 | 2.15 |
| 34-5     | 3.10 | 3.10 | 3.36 | 3.70 | 3.36 | 3.38 | 3.41 | 3.48 | 3.63 | 3.37 | 3.47 | 3.56 |
| 34-6     | 2.81 | 2.79 | 2.76 | 2.71 | 2.70 | 2.54 | 2.93 | 2.82 | 2.48 | 2.17 | 2.87 | 2.72 |
| Ave.     | 2.57 | 2.56 | 2.57 | 2.61 | 2.35 | 2.31 | 2.51 | 2.52 | 2.33 | 2.05 | 2.53 | 2.59 |
| S.D.     | 0.32 | 0.33 | 0.44 | 0.57 | 0.59 | 0.59 | 0.58 | 0.55 | 0.68 | 0.73 | 0.56 | 0.56 |
| 95% C.I. | 0.34 | 0.35 | 0.46 | 0.60 | 0.62 | 0.62 | 0.61 | 0.58 | 0.71 | 0.77 | 0.59 | 0.59 |

Cyc No.: Cycle Number

PKSL: Peak Strain Level (%)

Table 3-25

Summary of Loading Scale Factor (C) from Log-Log, Stress-Strain  
Fits (GPa) at 3% Constant Peak Strain Level Test  
(A-type test, see Fig. 2-1)

$$\sigma = C (\epsilon - \epsilon_s)^d$$

| Cycle No. | 1     | 2     | 3     | 60    | 120   | 180   | 240   | 300   |
|-----------|-------|-------|-------|-------|-------|-------|-------|-------|
| Time      |       |       |       | 72s   | 144s  | 216s  | 288s  | 360s  |
| 33-1      | 11.66 | 21.95 | 25.88 | 23.64 | 21.11 | 16.86 | 16.60 | 14.13 |
| 33-2      | 27.30 | 32.42 | 24.65 | 19.53 | 17.67 | 16.21 | 15.31 | 14.96 |
| 33-3      | 24.20 | 48.93 | 29.57 | 40.73 | 39.30 | 38.66 | 44.93 | 37.76 |
| 33-4      | 26.58 | 38.30 | 35.64 | 41.31 | 52.39 | 41.74 | 45.61 | 49.54 |
| 33-5      | 11.51 | 43.25 | 34.88 | 42.75 | 30.01 | 34.04 | 28.90 | 31.83 |
| 33-6      | 13.52 | 17.44 | 19.00 | 21.31 | 18.47 | 8.60  | 9.68  | 10.47 |
| Max.      | 27.30 | 48.93 | 35.64 | 42.75 | 52.39 | 41.74 | 45.61 | 49.54 |
| Median    | 18.86 | 35.36 | 27.73 | 32.19 | 25.56 | 25.45 | 22.75 | 23.40 |
| Min.      | 11.51 | 17.44 | 19.00 | 21.31 | 17.67 | 8.60  | 9.68  | 10.47 |

Table 3-26

Summary of Unloading Scale Factor (C) from Log-log, Stress-Strain  
Fits (GPa) at 3% Constant Peak Strain Level Test  
(A-type test, see Fig. 2-1)

$$\sigma = C (\epsilon - \epsilon_s)^d$$

| Cycle No.<br>Time | 1     | 2      | 3      | 60<br>72s | 120<br>144s | 180<br>216s | 240<br>288s | 300<br>360s |
|-------------------|-------|--------|--------|-----------|-------------|-------------|-------------|-------------|
| 33-1              | 31.07 | 34.88  | 31.61  | 37.16     | 27.15       | 14.79       | 20.83       | 22.48       |
| 33-2              | 39.29 | 39.56  | 36.74  | 28.80     | 25.22       | 21.70       | 18.80       | 21.19       |
| 33-3              | 41.29 | 39.13  | 43.66  | 52.38     | 42.06       | 43.61       | 38.09       | 36.82       |
| 33-4              | 16.83 | 144.96 | 119.79 | 308.61    | 65.39       | 58.71       | 77.27       | 55.12       |
| 33-5              | 51.76 | 52.62  | 46.49  | 50.92     | 32.47       | 36.25       | 32.54       | 30.22       |
| 33-6              | 57.48 | 24.48  | 20.59  | 30.78     | 20.27       | 21.01       | 18.40       | 20.99       |
| Max.              | 57.48 | 144.96 | 119.76 | 308.61    | 65.39       | 58.71       | 77.27       | 55.12       |
| Median            | 40.29 | 39.35  | 40.20  | 44.04     | 29.81       | 28.98       | 26.69       | 26.35       |
| Min.              | 16.83 | 24.48  | 20.59  | 28.80     | 20.27       | 14.79       | 18.40       | 20.99       |

Table 3-27

Summary of Loading Scale Factor (C) from Log-Log. Stress-Strain  
Fits (GPa) at 3% Constant Peak Strain Level Test  
with Rest Periods (B-type test, see Fig. 2-1)

$$\sigma = C (\epsilon - \epsilon_s)^d$$

| Cycle No.<br>Time | 1     | 2     | 3     | 60<br>72s | 61<br>144s | 120<br>216s | 121<br>288s | 180<br>360s |
|-------------------|-------|-------|-------|-----------|------------|-------------|-------------|-------------|
| 30-1              | 7.42  | 12.00 | 13.77 | 8.63      | 13.39      | 8.54        | 9.60        | 8.21        |
| 30-2              | 47.01 | 37.64 | 40.30 | 47.75     | 45.91      | 61.03       | 47.07       | 33.13       |
| 30-3              | 14.69 | 16.20 | 15.32 | 25.33     | 24.91      | 25.31       | 22.87       | 17.05       |
| 30-4              | 13.48 | 16.44 | 14.02 | 15.56     | 15.63      | 18.70       | 17.71       | 16.32       |
| 30-5              | 4.10  | 49.30 | 45.58 | 354.10    | 418.33     | 686.48      | 563.02      | 841.28      |
| 30-6              | 64.10 | 65.02 | 62.41 | 76.23     | 80.50      | 50.69       | 76.75       | 49.95       |
| Max.              | 64.10 | 65.02 | 62.41 | 354.10    | 418.33     | 686.48      | 563.02      | 841.28      |
| Median            | 14.09 | 27.04 | 27.81 | 36.54     | 35.41      | 38.00       | 34.97       | 25.09       |
| Min.              | 4.10  | 12.00 | 13.77 | 8.63      | 15.63      | 8.54        | 9.60        | 8.21        |

Table 3-28

Summary of Unloading Scale Factor (C) from Log-Log, Stress-Strain  
Fits (GPa) at 3% Constant Peak Strain Level Test  
with Rest Periods (B-type test, see Fig. 2-1)

$$\sigma = C (\epsilon - \epsilon_s)^d$$

| Cycle No. | 1      | 2      | 3      | 60      | 61      | 120     | 121     | 180     |
|-----------|--------|--------|--------|---------|---------|---------|---------|---------|
| Time      |        |        |        | 72s     | 144s    | 216s    | 288s    | 360s    |
| 30-1      | 9.73   | 10.31  | 10.44  | 8.90    | 14.32   | 10.37   | 14.81   | 10.74   |
| 30-2      | 69.26  | 71.18  | 72.79  | 62.56   | 85.23   | 64.68   | 87.22   | 44.30   |
| 30-3      | 41.31  | 43.19  | 44.37  | 44.18   | 63.79   | 46.77   | 58.56   | 22.96   |
| 30-4      | 29.52  | 28.63  | 24.42  | 31.83   | 33.41   | 30.03   | 35.50   | 26.30   |
| 30-5      | 478.32 | 723.64 | 668.06 | 3054.92 | 2893.33 | 5206.33 | 4101.15 | 7595.01 |
| 30-6      | 131.80 | 116.71 | 109.12 | 147.29  | 198.49  | 151.35  | 141.19  | 118.14  |
| Max.      | 478.32 | 723.64 | 668.06 | 3054.92 | 2893.33 | 5206.33 | 4101.15 | 7595.01 |
| Median    | 55.28  | 57.19  | 58.58  | 53.37   | 74.51   | 55.73   | 72.89   | 35.30   |
| Min.      | 9.73   | 10.31  | 10.44  | 8.90    | 14.32   | 10.37   | 14.81   | 10.74   |

Table 3-29

Summary of Loading Scale Factor (C) from Log-Log, Stress-Strain  
Fits (GPa) at 3-4% Different Peak Strain Level Test  
(C-type test, see Fig. 2-1)

$$\sigma = C (\epsilon - \epsilon_s)^d$$

| Cyc No. | 1     | 2     | 3     | 60     | 61     | 105     | 106    | 165    | 166     | 210     | 211    | 270    |
|---------|-------|-------|-------|--------|--------|---------|--------|--------|---------|---------|--------|--------|
| Time    |       |       |       | 72s    |        | 144s    |        | 216s   |         | 288s    |        | 360s   |
| PKSL    | 3     | 3     | 3     | 3      | 4      | 4       | 3      | 3      | 4       | 4       | 3      | 3      |
| 34-1    | 12.35 | 20.24 | 21.45 | 34.28  | 14.87  | 13.39   | 16.83  | 24.19  | 11.47   | 17.82   | 10.54  | 23.76  |
| 34-2    | 25.71 | 59.26 | 58.66 | 136.57 | 83.53  | 65.22   | 31.40  | 78.96  | 63.87   | 97.25   | 54.95  | 155.49 |
| 34-3    | 28.84 | 48.34 | 64.88 | 79.80  | 24.08  | 18.37   | 21.90  | 38.60  | 12.24   | 10.78   | 24.85  | 26.29  |
| 34-4    | 33.08 | 69.34 | 93.10 | 69.54  | 13.28  | 15.93   | 24.99  | 35.95  | 9.27    | 7.99    | 17.16  | 20.81  |
| 34-5    | 0.86  | 30.45 | 38.04 | 266.94 | 409.76 | 1956.60 | 156.01 | 370.56 | 1074.72 | 1485.82 | 479.82 | 708.96 |
| 34-6    | 26.66 | 57.32 | 55.95 | 132.75 | 66.55  | 134.17  | 56.50  | 104.66 | 76.29   | 70.33   | 51.69  | 126.99 |
| Max.    | 33.08 | 69.34 | 93.10 | 266.94 | 409.76 | 1956.60 | 156.01 | 370.56 | 1074.72 | 1485.82 | 479.82 | 708.96 |
| Median  | 26.19 | 52.86 | 57.31 | 106.19 | 45.32  | 41.80   | 28.20  | 58.78  | 38.06   | 44.08   | 38.27  | 76.64  |
| Min.    | 0.86  | 20.24 | 21.45 | 34.28  | 13.28  | 13.39   | 16.83  | 24.19  | 9.27    | 7.99    | 10.54  | 2.81   |

Cyc No.: Cycle Number

PKSL: Peak Strain Level (%)

Table 3-30

Summary of Unloading Scale Factor (C) from Log-Log. Stress-Strain  
Fits (GPa) at 3-4% Different Peak Strain Level Test  
(C-type test, see Fig. 2-1)

$$\sigma = C (\epsilon - \epsilon_s)^d$$

| Cyc No. | 1      | 2      | 3       | 60      | 61      | 105     | 106     | 165     | 166     | 210     | 211     | 270     |
|---------|--------|--------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| Time    |        |        |         | 72s     |         | 144s    |         | 216s    |         | 288s    |         | 360s    |
| PKSL    | 3      | 3      | 3       | 3       | 4       | 4       | 3       | 3       | 4       | 4       | 3       | 3       |
| 34-1    | 79.20  | 58.66  | 50.55   | 68.41   | 23.90   | 22.72   | 74.82   | 46.25   | 20.60   | 4.33    | 39.57   | 47.11   |
| 34-2    | 275.43 | 245.61 | 203.57  | 295.22  | 113.65  | 133.57  | 417.71  | 273.52  | 97.73   | 119.09  | 537.08  | 856.18  |
| 34-3    | 100.27 | 126.44 | 124.36  | 185.67  | 34.64   | 31.97   | 62.13   | 107.61  | 30.14   | 8.23    | 100.98  | 123.38  |
| 34-4    | 110.88 | 121.83 | 112.55  | 71.82   | 15.06   | 14.06   | 37.97   | 57.30   | 19.01   | 4.79    | 70.48   | 79.94   |
| 34-5    | 353.23 | 417.57 | 1157.73 | 5499.13 | 1570.60 | 2625.69 | 3098.91 | 2729.86 | 4690.31 | 2818.63 | 6178.25 | 5034.19 |
| 34-6    | 261.57 | 236.69 | 253.51  | 292.76  | 210.58  | 154.02  | 821.37  | 513.70  | 121.63  | 39.89   | 682.72  | 332.57  |
| Max.    | 353.23 | 417.57 | 1157.73 | 5499.13 | 1570.60 | 2625.69 | 3098.91 | 2729.86 | 4690.31 | 2818.63 | 6178.25 | 5034.19 |
| Median  | 186.23 | 181.57 | 163.96  | 239.22  | 74.15   | 82.77   | 246.27  | 190.57  | 63.94   | 24.06   | 319.03  | 227.98  |
| Min.    | 79.20  | 58.66  | 50.55   | 68.41   | 15.06   | 14.06   | 37.97   | 46.25   | 19.01   | 4.33    | 39.57   | 47.11   |

Cyc No.: Cycle Number

PKSL: Peak Strain Level (%)

#### III.4. Sectional and Anatomical Differences in Response

In the previous section, the values of the scale factor (C) for the measured stress-strain responses were found to vary widely. To study this variation further, this section presents the ability of specimens from different parts of the same tendons to resist deformation. These results are a subset of the results presented in the previous section. This subset is presented here to focus on differences in the responses of parts of the same tendons.

Table 3-6 shows anatomical sites, tendon status (pair, same), and peak load for each tendon specimen. Selected tendon specimens were called the same tendon in Table 3-6 and were divided into three sections (bone end section, mid-portion, muscle end section) from long tendons.

Figure 3-21 shows load versus time responses for three sections of the same tendon of peroneus longus with cycles at 3% maximum strain level. In this figure, the peak loads in each section from the same tendon are shown as normalized so that the peak of the first cycle of the bone end section has a value of 1.0. The bone end section is stiffer and carries more load for the peak strain of 3% than the other sections, and the mid-portion is softest and carries smallest load. Figure 3-22 shows this phenomena in stress-strain plots with loading and unloading curves at the first cycle for each section.

Figure 3-23 shows a normalized (to the muscle end section at the first peak) load versus time response for a tendon of peroneus longus with rest periods (B-type test, see Figure 2-1). Here, a sample from the bone end section was not available.

Figure 3-24 shows a normalized (to the bone end section at the first peak) load versus time response for a tendon of flexor digitorum longus with rest periods (B-type test, see Figure 2-1). In this figure, the load versus time response of mid-portion is much less than that of bone end section. Figure 3-25 shows these phenomena in stress-strain plots with loading and unloading curves at the first cycle. Here, a sample from the muscle end section was not available.

Figure 3-26 shows a normalized (to the bone end section at the 1st peak) load versus time response for a tendon of flexor digitorum longus at 3-4% different peak strain level test (C-type test, see Figure 2-1). In this figure, the bone end section carries much more load for the same strains than the mid-portion throughout the test. The peak loads during the lower maximum strain level (3%) cyclic blocks in the bone end section are greater than those during the higher maximum strain level (4%) cyclic blocks in the mid-portion. Here, a sample from the muscle end section was not available.

Figure 3-27 shows stress-strain responses in the paired tendons. Figure 3-28 shows stress-strain responses in the different (independent) tendons. Comparing the above figures it is apparent

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that anatomically paired tendons are more similar in mechanical responses than tendons from different anatomical sites.

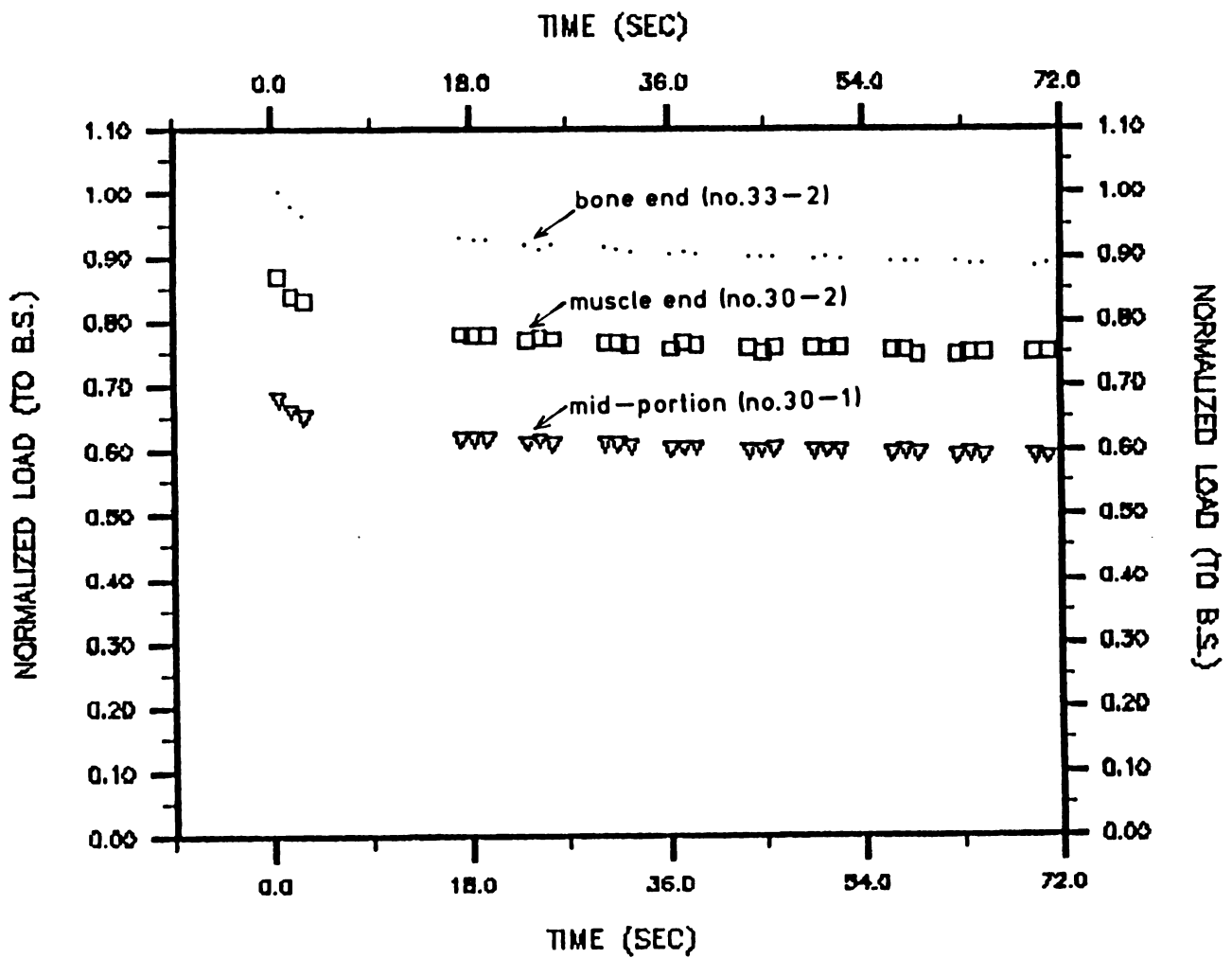


Fig. 3-21 Normalized load versus time response for a tendon of peroneous longus with cycles

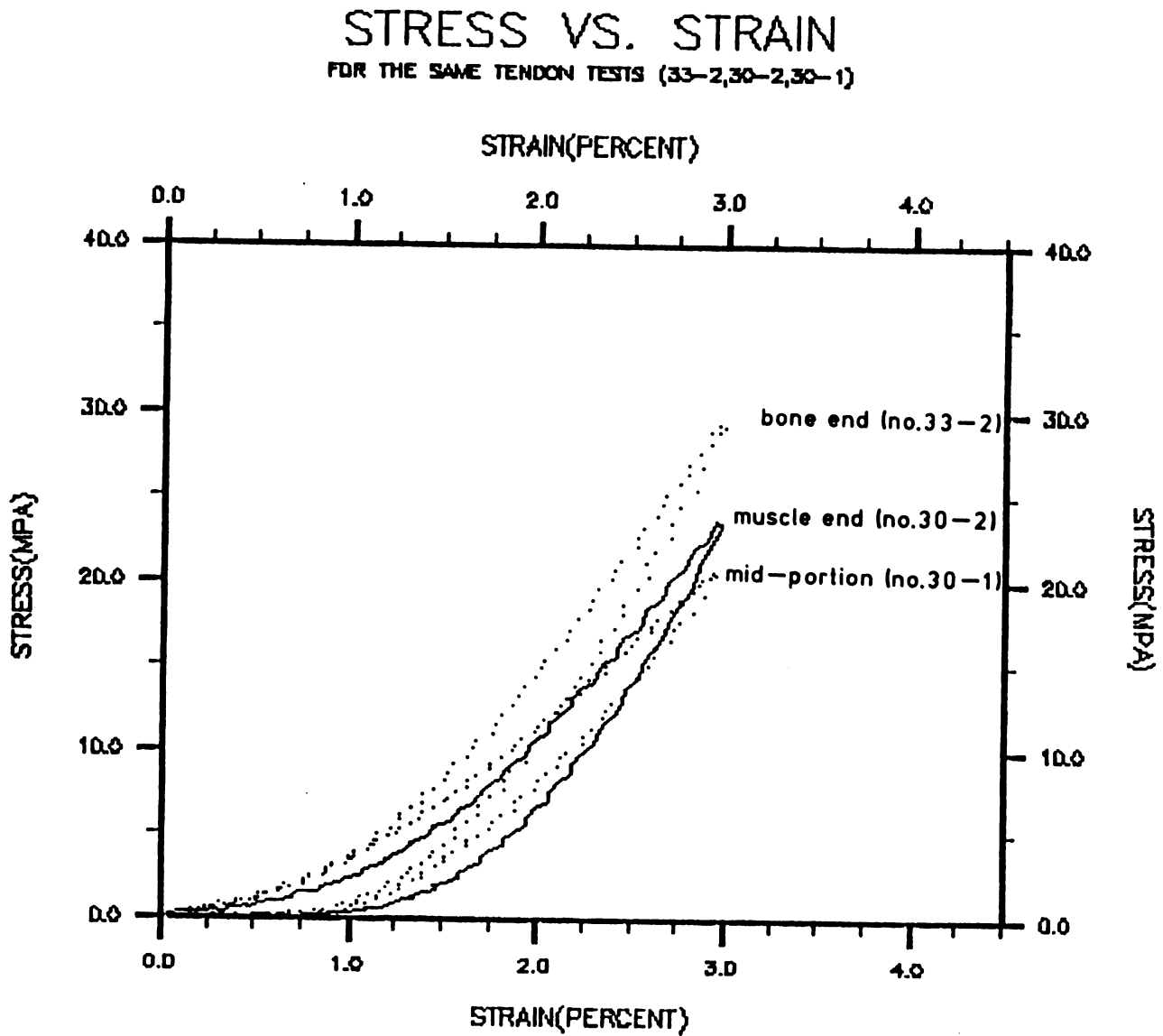


Fig. 3-22 Stress-strain responses for a tendon of peroneus longus at the 1st cycle

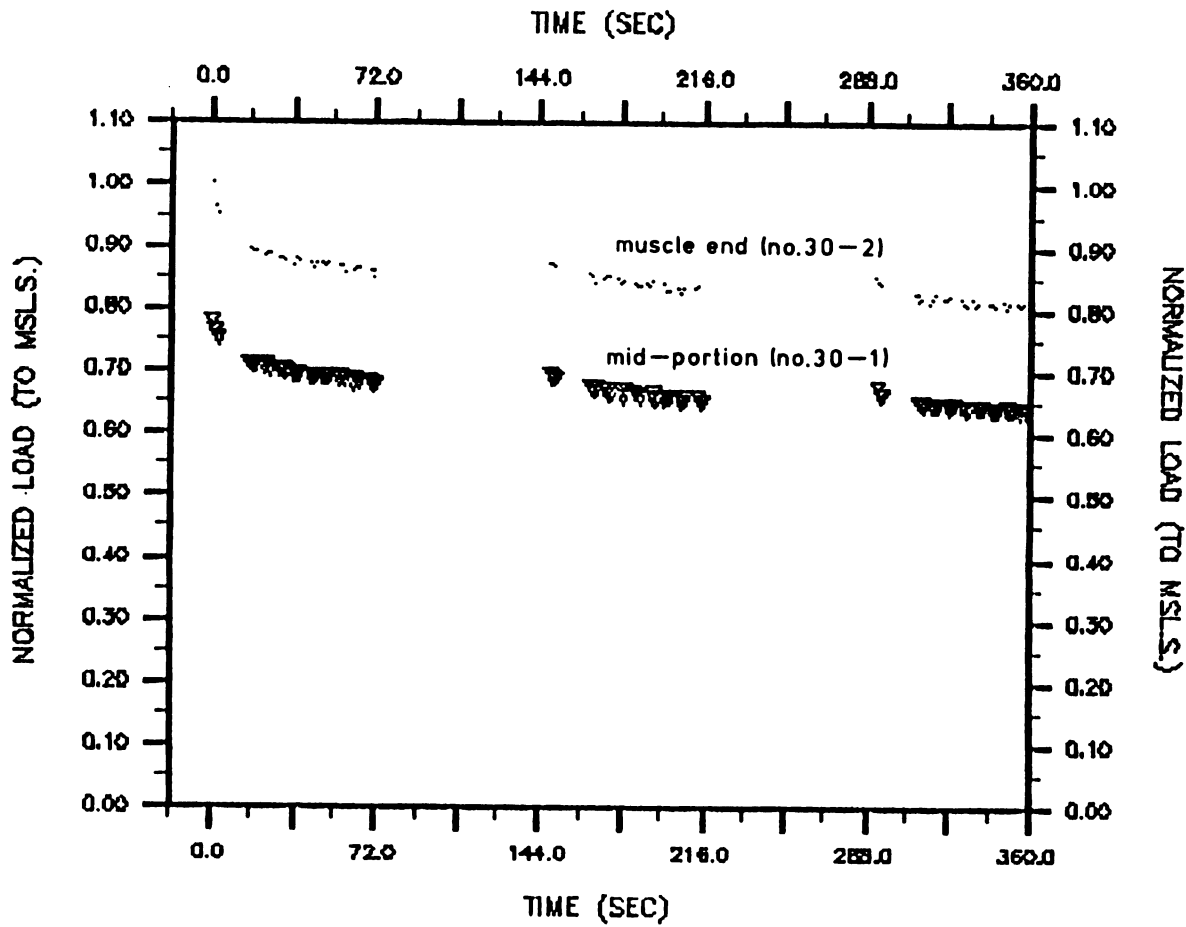


Fig. 3-23 Normalized load versus time response for a tendon of peroneus longus with rest periods (B-type test, see Fig. 2-1)

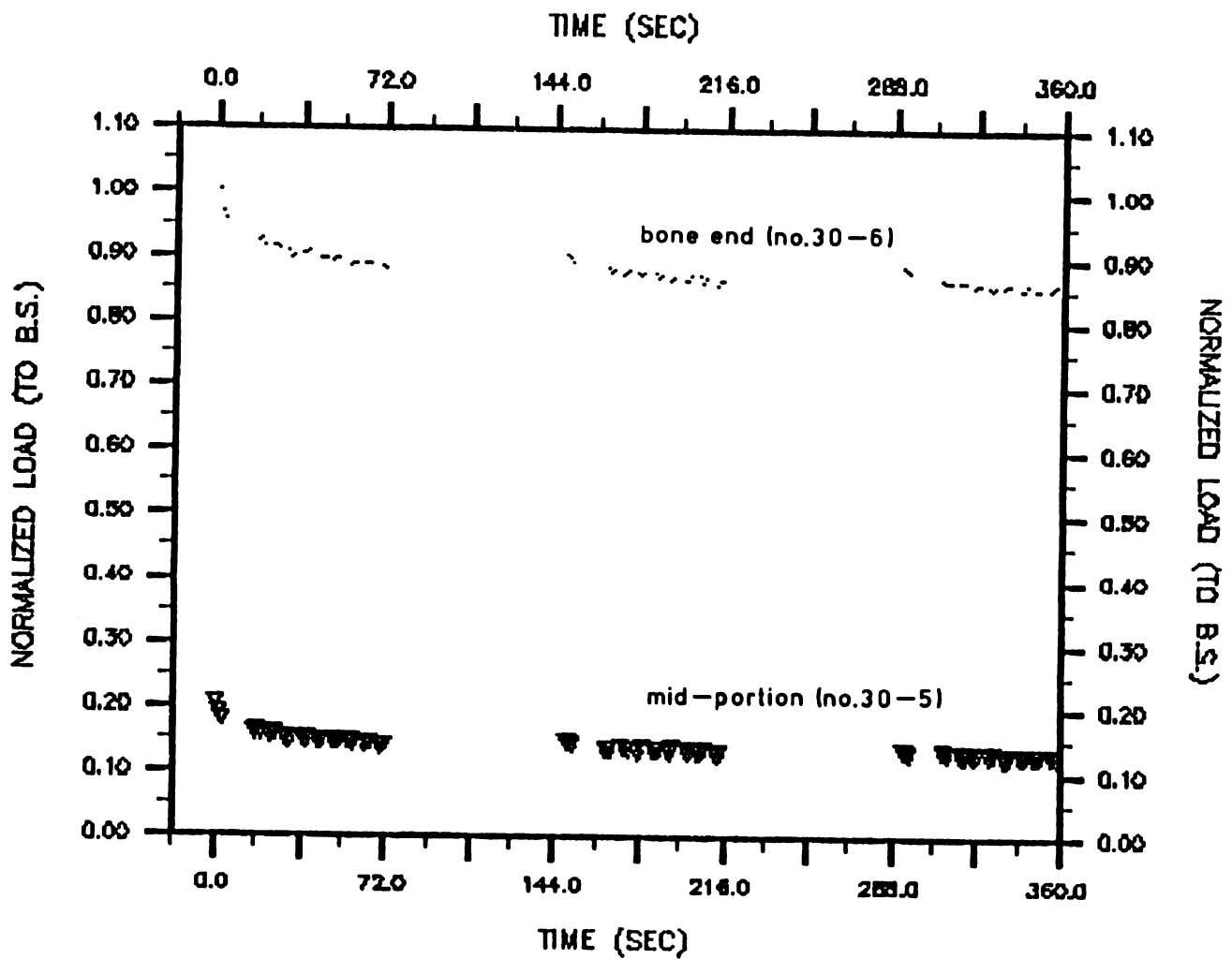


Fig. 3-24 Normalized load versus time response for a tendon of flexor digitorum longus with rest periods (B-type test, see Fig. 2-1)

15.0

10.0

STRESS(MPA)

5.0

0.0

# STRESS VS. STRAIN

FOR THE SAME TENDON TESTS (30-5, 30-6)

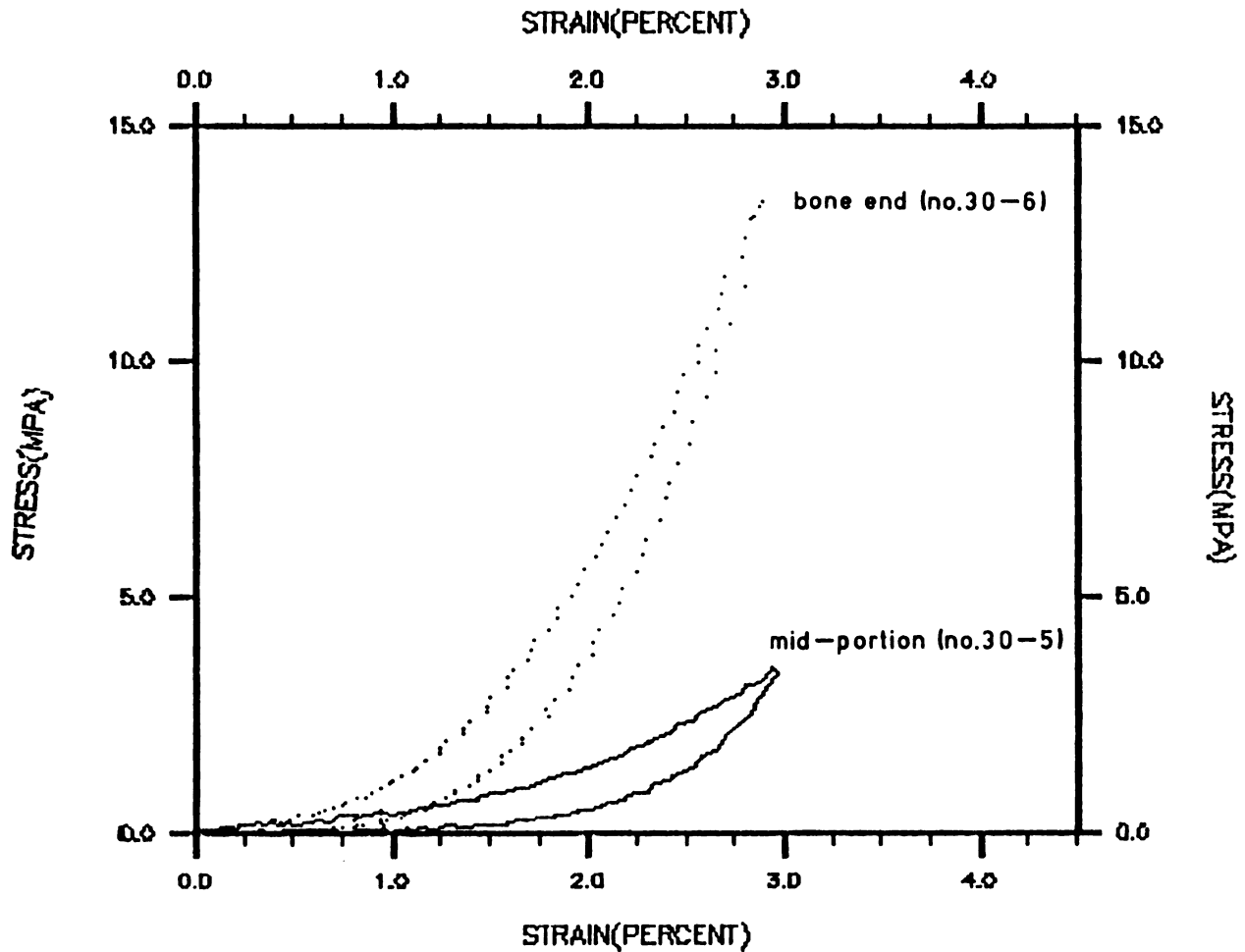


Fig. 3-25 Stress-strain responses for a tendon of flexor digitorum longus at the 1st cycle

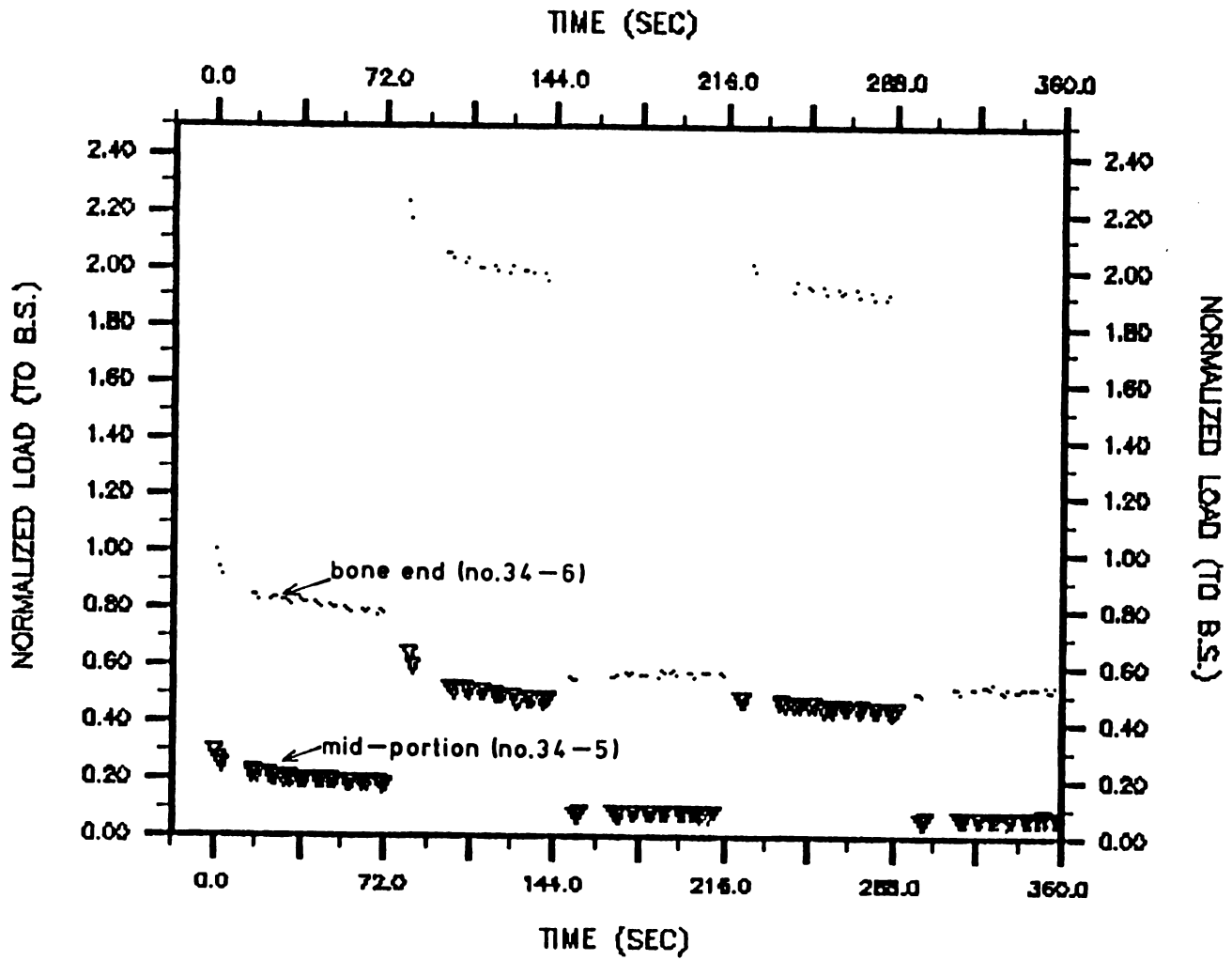


Fig. 3-26 Normalized load versus time response for a tendon of flexor digitorum longus at 3-4% different peak strain level test (C-type test, see Fig. 2-1)

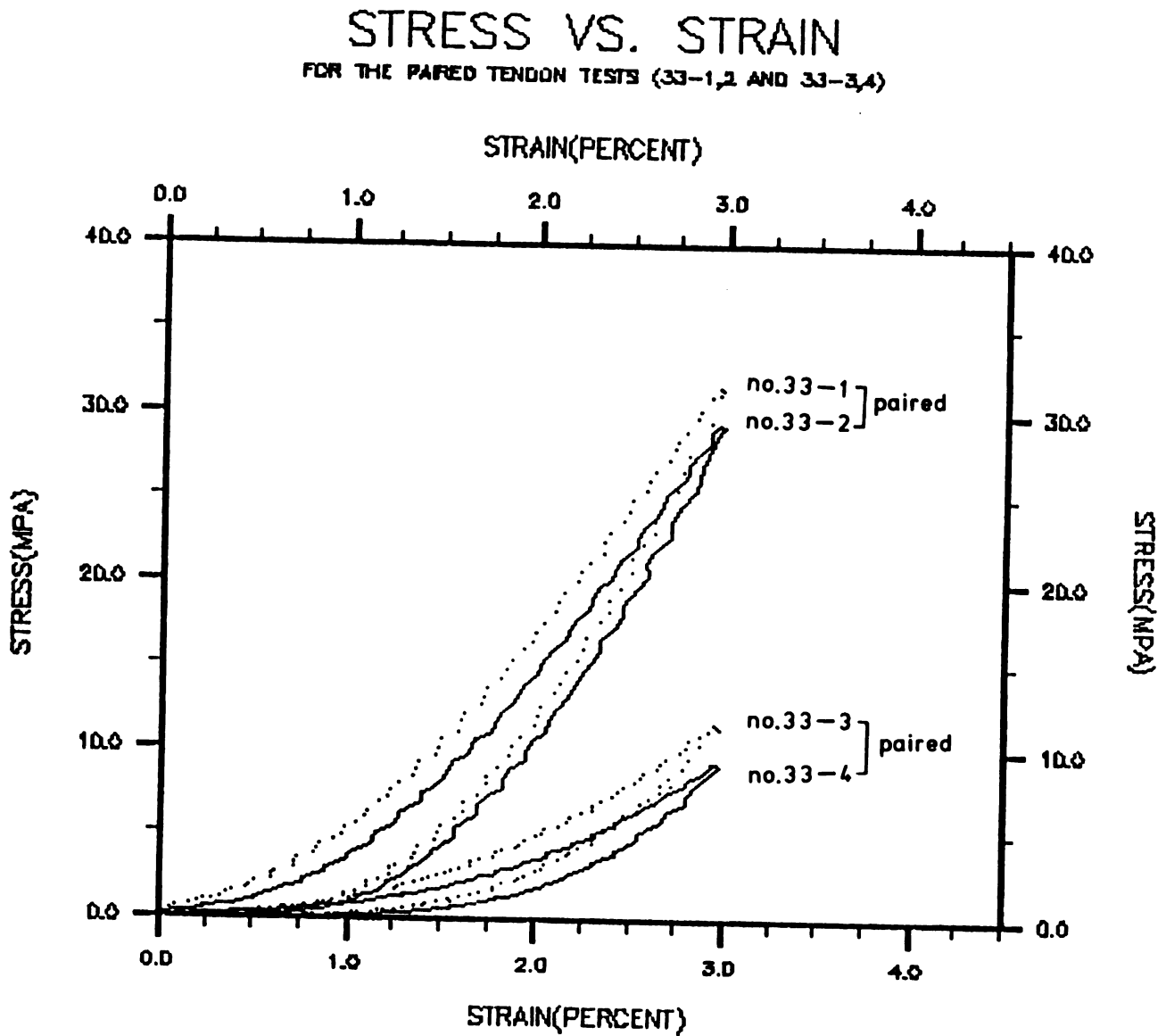


Fig. 3-27 Stress-strain responses in the paired tendons

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30.  
STRESS (MPa)  
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0.  
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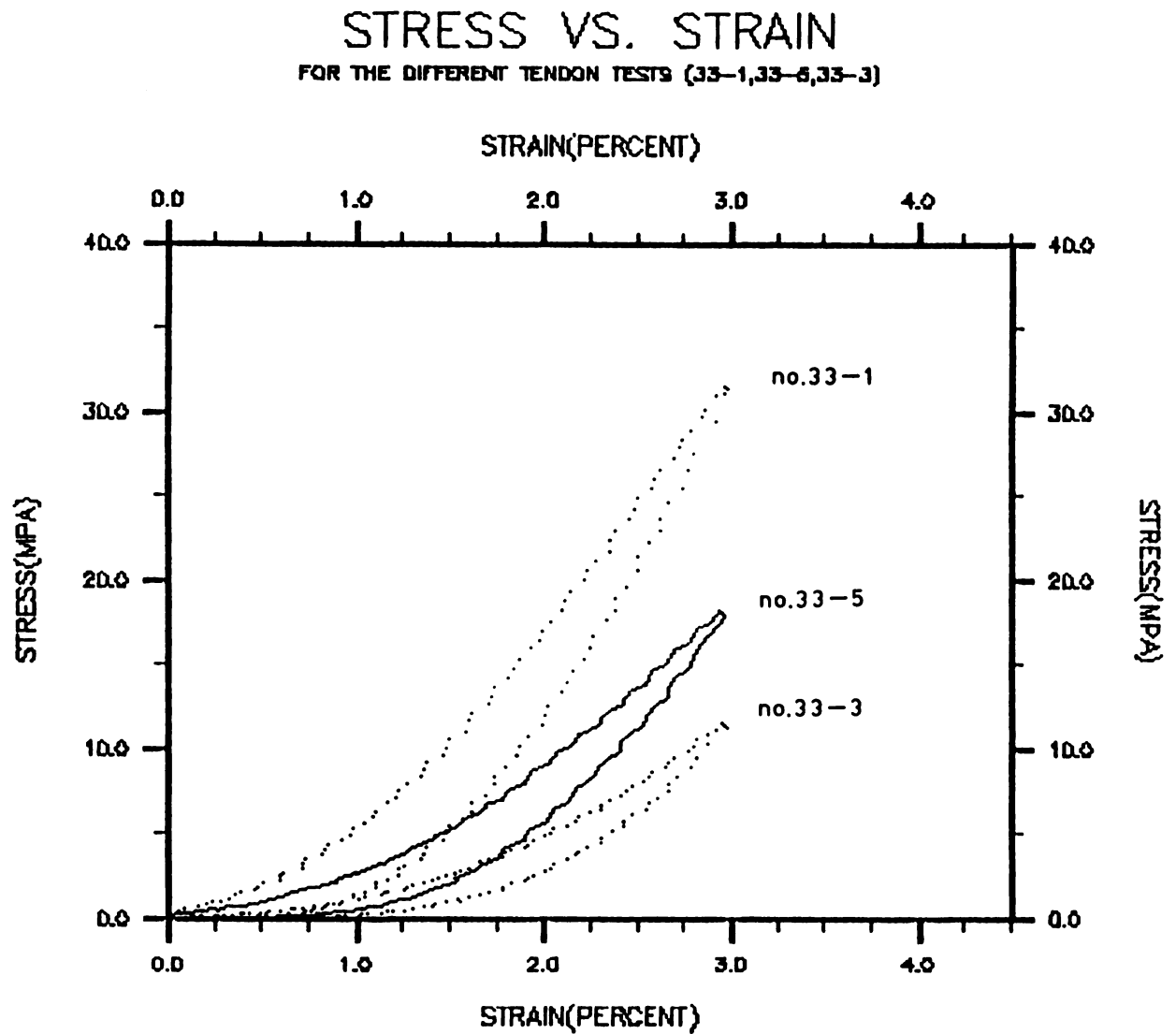


Fig. 3-28 Stress-strain responses in the different (independent) tendons

### III.5. Measurements of Surface Strains

#### III.5.a. Photographic results from relaxation tests:

As described in Chapter II, pictures were taken during the relaxation tests before and just after initial extension to the constant strain level on each tendon specimen. The specimens were marked with dye into three segments of approximately equal length. Figure 3-29 shows the illustration of tendon segment with two dyed marks between grips. The film was developed and photographs were measured with a micrometer.

Table 3-31 presents the photographic measurement results for paired tendons as percent increases from the initial length right before testing and the final length right after initial extension. Also, Appendix 3 presents a summary of surface deformation in millimeters with a scale factor (S.F.) calculated directly from photographic measurements. It appears, with few exceptions, that the local surface strains near the gripped ends are greater than the tendon (overall) surface strains, and that the local surface strains in the middle segment (segment 2) are smaller than the tendon (overall) surface strains. Anatomically paired tendons do not show similarity in surface strain. Figure 3-30 shows a plot of the average value of surface strain in tendons as a function of tendon segment for 3% and 4% strain level tests. Table 3-31 and Figure 3-30 indicate that the local surface strains near the gripped ends

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(segment 1 and segment 3) are much greater than the local surface strain at the middle segment (segment 2). This phenomenon is referred to as the grip effect of the tendon.

No slippage at the gripped ends was detected during testing. All measured responses were consistent and exhibited no sudden decreases in load transmission as would be the case for slippage.

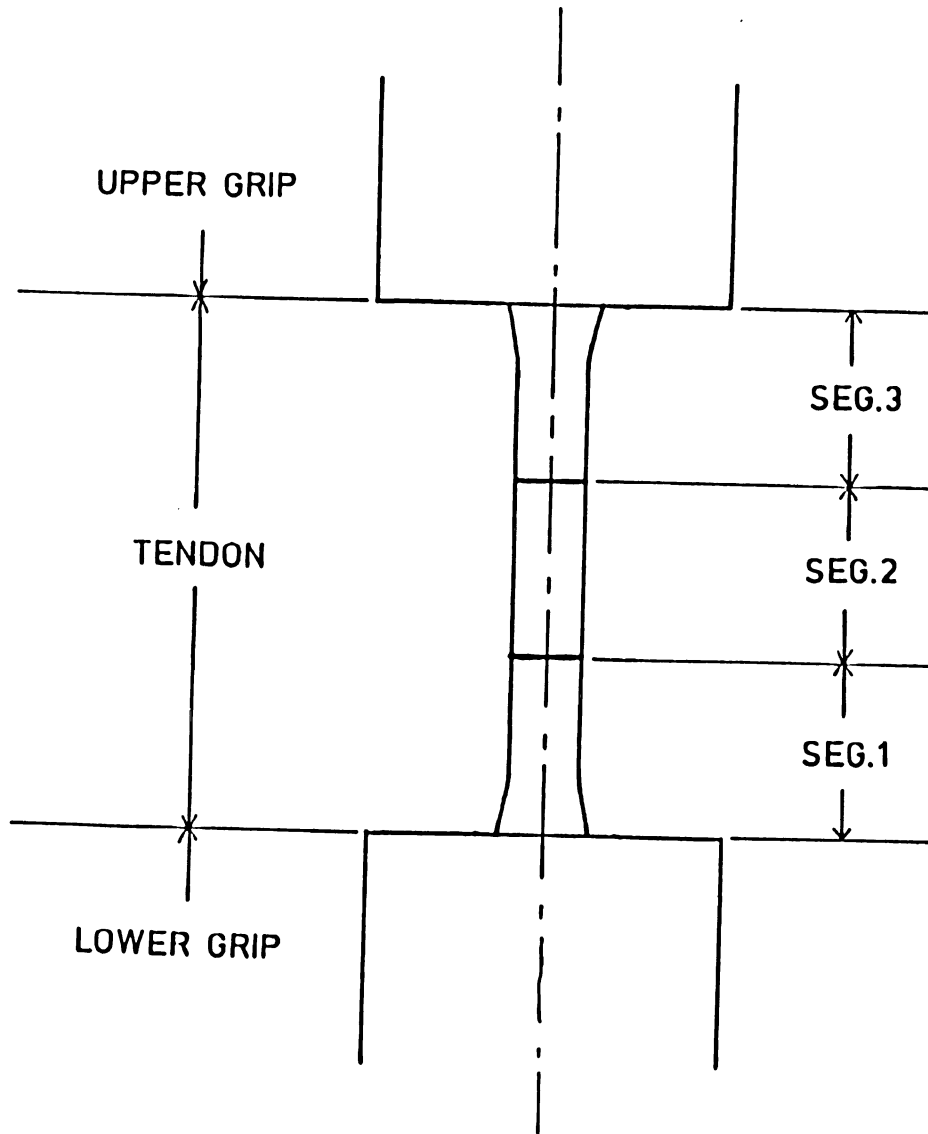


Fig. 3-29 Illustration of tendon segments

Table 3-31

Summary of Surface Strains (%) from Photographic Results  
in Relaxation Tests for Paired Tendons

| Strain Level | Test Number | Seg.1 | Seg.2 | Seg.3 | Tendon overall |
|--------------|-------------|-------|-------|-------|----------------|
| 3%           | 1           | 3.24  | 3.05  | 2.30  | 2.83           |
|              | 2           | 4.02  | 2.08  | 2.63  | 2.94           |
|              | 3           | 3.91  | 0.91  | 3.28  | 2.81           |
|              | 4           | 3.01  | 0.68  | 5.95  | 3.61           |
|              | 5           | 5.78  | 0.60  | 2.61  | 3.05           |
|              | 6           | 3.89  | 1.05  | 3.70  | 2.98           |
|              | Ave.        | 3.98  | 1.40  | 3.41  | 2.96           |
|              | S.D.        | 0.97  | 0.97  | 1.34  | 0.13           |
|              | 95% C.I.    | 1.02  | 1.02  | 1.41  | 0.14           |
|              |             |       |       |       |                |
| 4%           | 1           | 3.37  | 3.93  | 4.36  | 3.84           |
|              | 2           | 4.85  | 1.73  | 4.83  | 3.87           |
|              | 3           | 4.46  | 2.78  | 3.92  | 3.82           |
|              | 4           | 3.33  | 2.47  | 6.13  | 4.13           |
|              | 5           | 4.77  | 3.33  | 4.45  | 4.23           |
|              | 6           | 5.07  | 1.88  | 4.67  | 3.99           |
|              | Ave.        | 4.31  | 2.69  | 4.73  | 3.98           |
|              | S.D.        | 0.77  | 0.85  | 0.75  | 0.17           |
|              | 95% C.I.    | 0.81  | 0.89  | 0.79  | 0.19           |
|              |             |       |       |       |                |

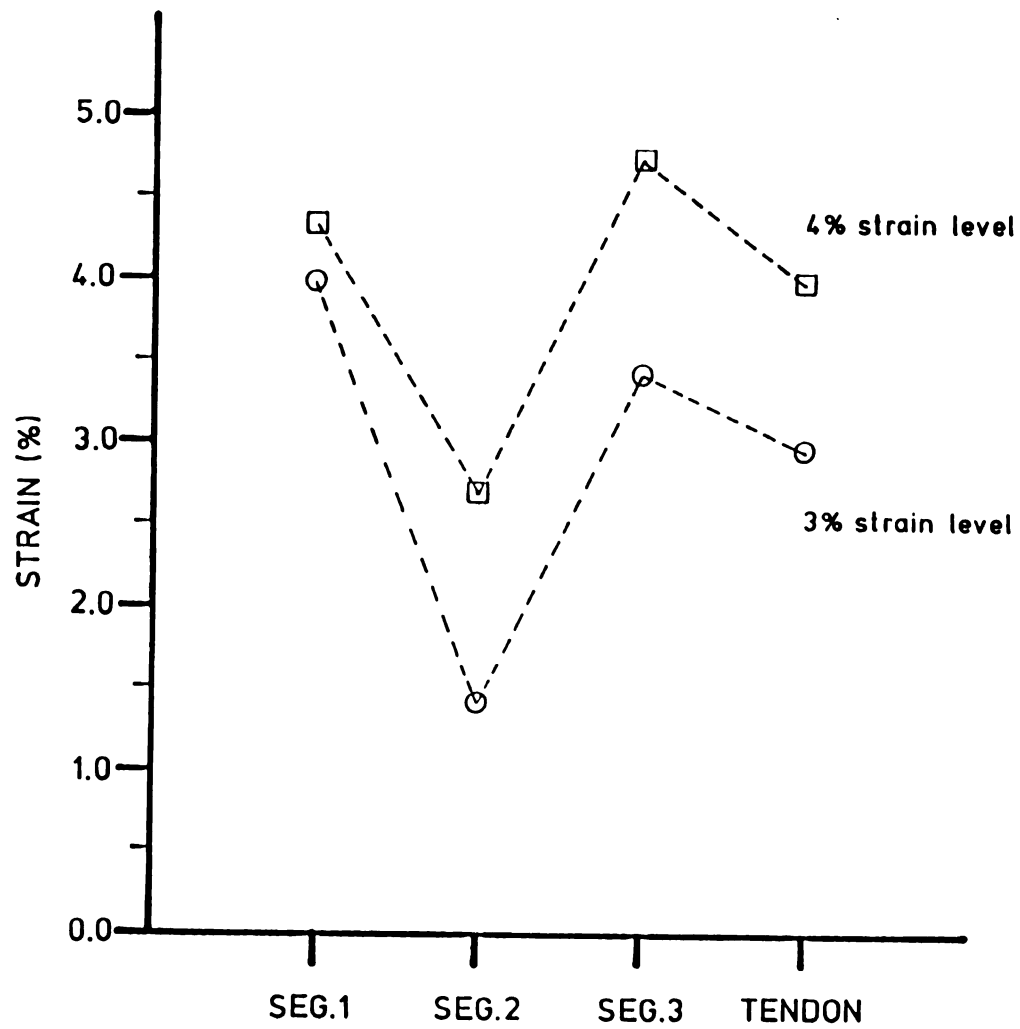


Fig. 3-30 Average value of the surface strains in tendon segment

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III.5.b. Optical results from cyclic tests:

A special series of multiple cyclic extension tests were performed to study surface deformations with the Reticon camera. So that the data from the Reticon camera could be acquired with the other data (load and grip motion), the tests were performed at a slower strain rate (2% per sec) and for a shorter period than the other multiple cyclic tests. Tests were performed with the maximum strain level of 3% in two blocks of cycles (20 sec each) separated by one rest period (120 sec) to investigate recovery effects of the surface deformations. Two targets of self-adhesive, stiff, and narrow (about 0.5 mm) plastic were glued approximately 10 mm apart with cellulose nitrate [55] to the mid-portion of the tendon. The Reticon line camera scanned these targets and grips for measurement of surface deformation during cyclic extensions. It was assumed that there was no target rotation during cyclic extensions in the tendon specimen.

Table 3-32 presents the characteristics of the tendon specimens used in cyclic tests with the Reticon camera. Figure 3-31 presents the illustration of tendon segments with the scanning line and the back lighting system.

Figures 3-32 through 38 show the surface strains of the tendon segments for seven cycles from specimens CAM30-1 through CAM30-7. It appears, with two exceptions (CAM30-4, 5), that the local surface

strains near the gripped ends (segment 1 and segment 3) are greater than those at the middle segment (segment 2). As mentioned for photographic results, the grip effect may cause this nonuniform distribution of strains on the tendon specimen.

For comparing the surface deformations of specimens from the same tendon, the surface strains of segment 2 were chosen because the grip effect was minimal in this segment. Figure 3-39 shows the surface strains of segment 2 for seven cycles in tests of three specimens from the same tendon. In this figure, the bone end section of the long tendon has the smallest deformation (stiffest) and the mid-portion of the long tendon has the largest deformation (softest) during cyclic extensions. These phenomena are consistent with Figure 3-21 and Figure 3-22 in the previous section.

Figures 3-40, 42, and 44 present the surface strains of the tendon segments with 120 sec rest period for CAM30-1, 4, and 9. Their cyclic load relaxation and recovery responses are shown in Figures 3-41, 43, and 45, respectively. Comparing Figures 3-40 through 3-45, the surface strains in segment 2 after the rest periods are different. However, recovery phenomena for surface strains corresponding to their load recovery after the rest periods are not consistent in this comparison.

Table 3-33 presents the cyclic peak loads and peak surface strains in the tendon segments at corresponding cycles with a 120 sec rest period. In this table, there is load recovery during the rest period from cycles 7 to 8 but there is no consistent evidence

of surface strain recovery (decreasing). Like the photographic results, the surface strains of the gripped ends (segments 1 and 3) are generally greater than those of middle segment (segment 2). Also, all measured responses were consistent from cycle to cycle within a sample and exhibited no sudden decreases in load transmission as would be the case for slippage.

Table 3-32

Tendon Specimen Characteristics in Cyclic Tests  
with the Reticon Camera

| File Name | Anatomical Site           | Tendon Status | Initial Length(mm) | Area (mm <sup>2</sup> ) | Peak Load(N) |
|-----------|---------------------------|---------------|--------------------|-------------------------|--------------|
| CAM30-1   | Peroneus longus (msl.s.)  | same          | 31.52              | 0.76                    | 11.17        |
| CAM30-2   | Peroneus longus (m)       |               | 31.68              | 0.66                    | 10.54        |
| CAM30-3   | Peroneus longus (b.s.)    |               | 32.80              | 0.81                    | 12.85        |
| CAM30-4   | Extensor digitorum longus | pair          | 32.75              | 0.99                    | 11.34        |
| CAM30-5   | Extensor digitorum longus |               | 33.05              | 0.89                    | 14.77        |
| CAM30-6   | Flexor hallucis longus    |               | 32.68              | 1.52                    | 1.38         |
| CAM30-7   | Flexor digitorum brevis   |               | 33.56              | 1.93                    | 3.71         |

b.s. : bone end section,    msl.s. : muscle end section,    m : mid-portion

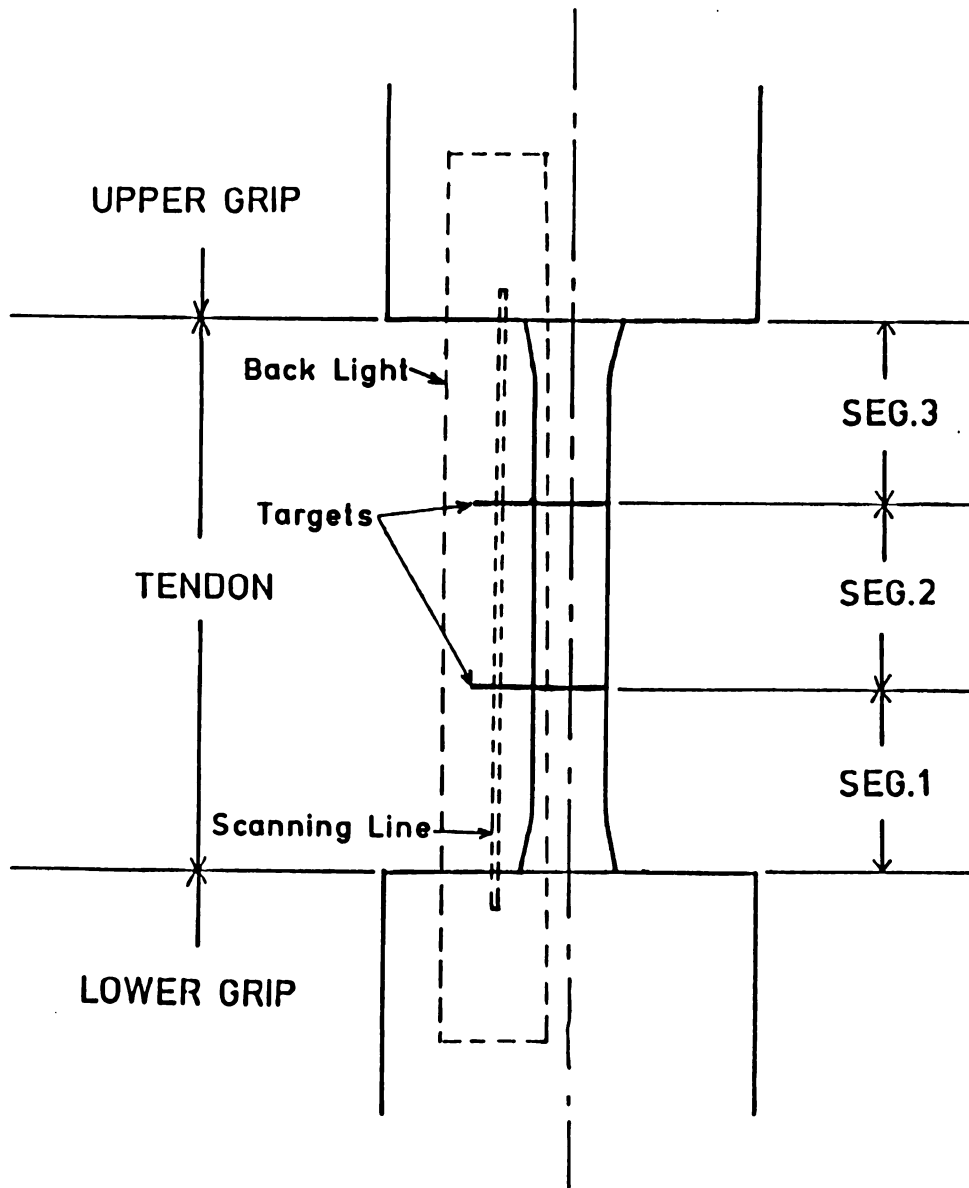


Fig. 3-31 Illustration of tendon segments with the scanning line in the Reticon camera and the back lighting system

## SURFACE STRAIN

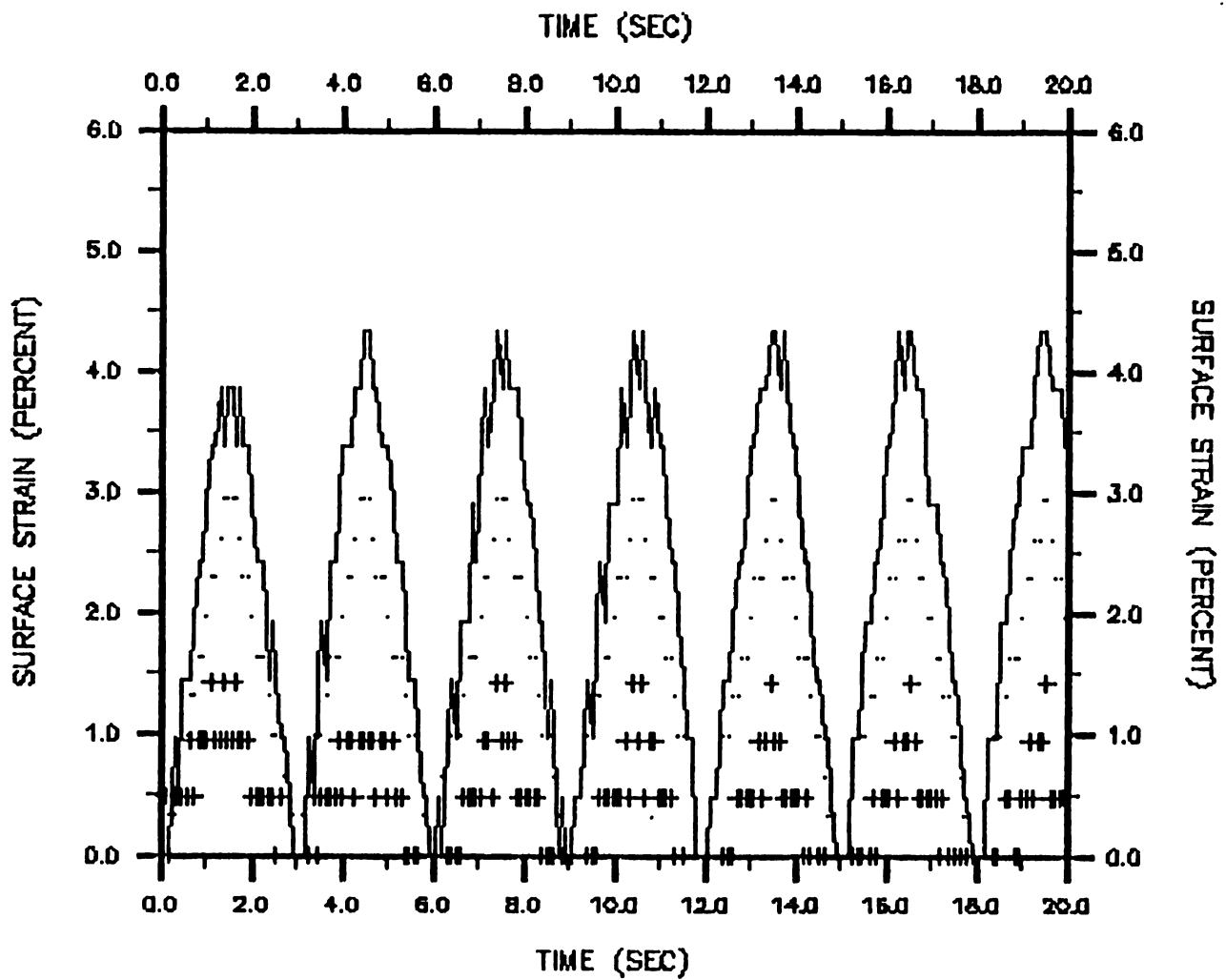


Fig. 3-32 Surface strains of the tendon segments with cycles for CAM30-1 (..... : Seg.1, ++++ : Seg.2, \_\_\_\_\_ : Seg.3)

# SURFACE STRAIN

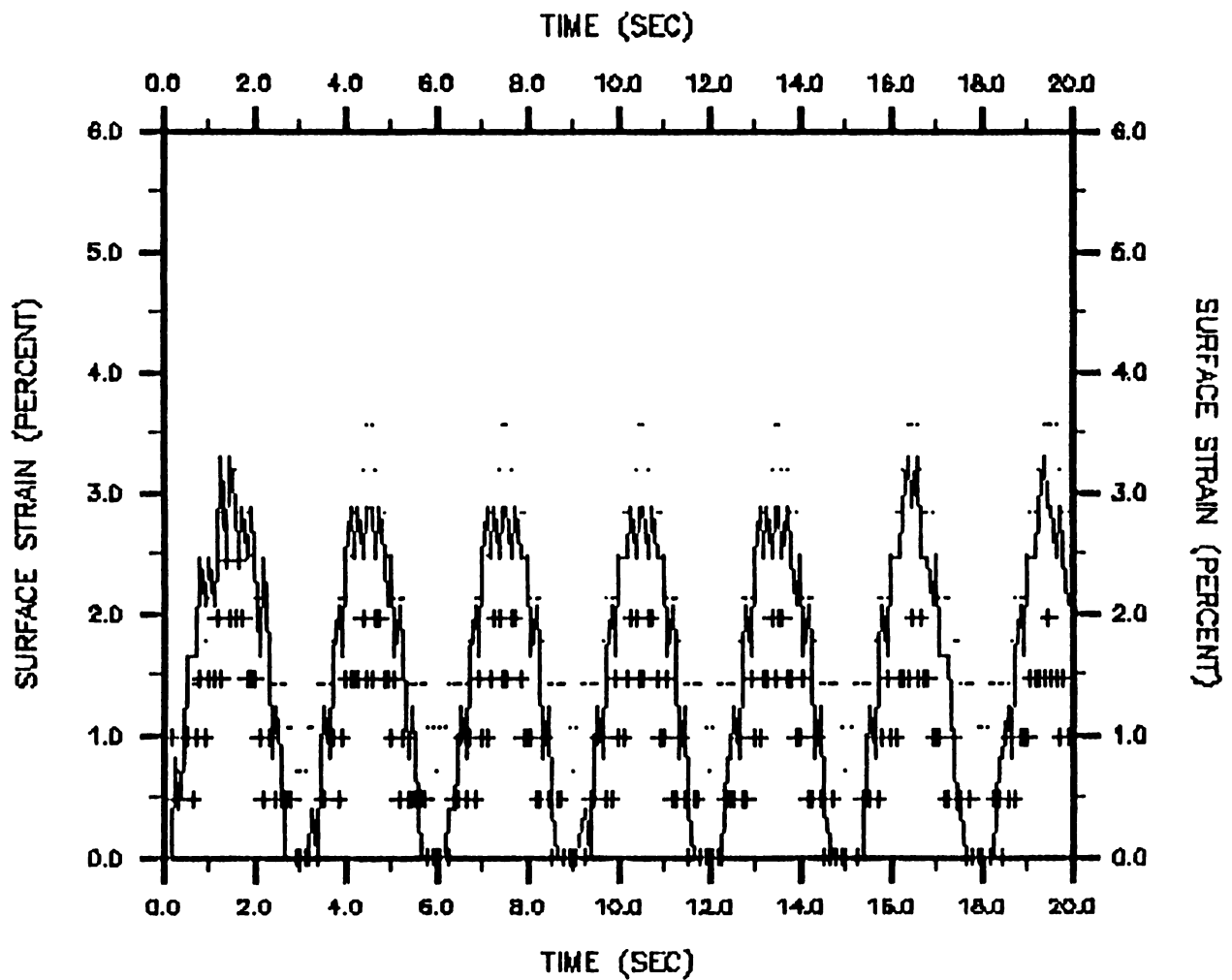


Fig. 3-33 Surface strains of the tendon segments with cycles for CAM30-2 (..... : Seg.1, ++++ : Seg.2, \_\_\_\_\_ : Seg.3)

# SURFACE STRAIN

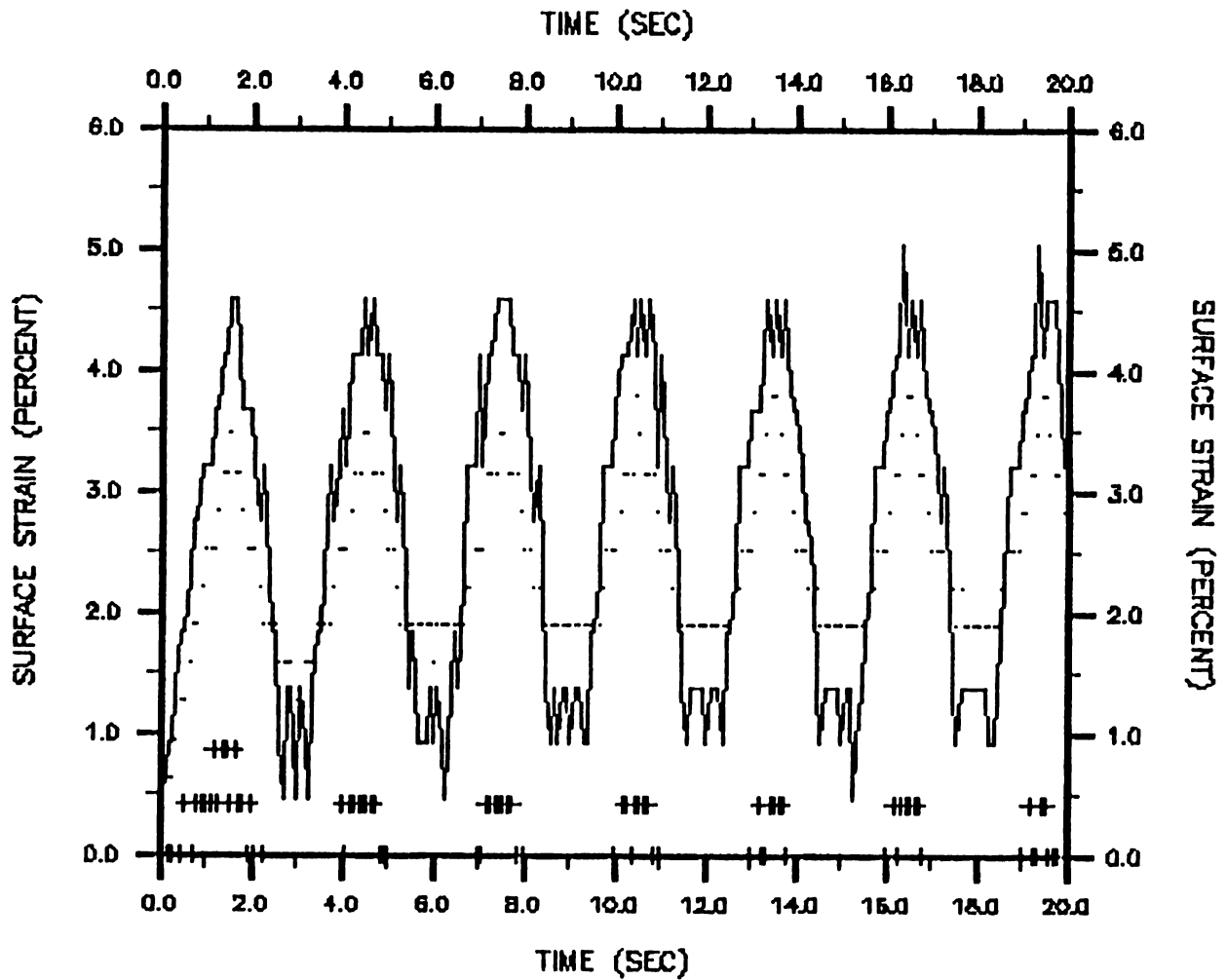


Fig. 3-34 Surface strains of the tendon segments with cycles for CAM30-3 (..... : Seg.1, ++++ : Seg.2, \_\_\_\_ : Seg.3)

## SURFACE STRAIN

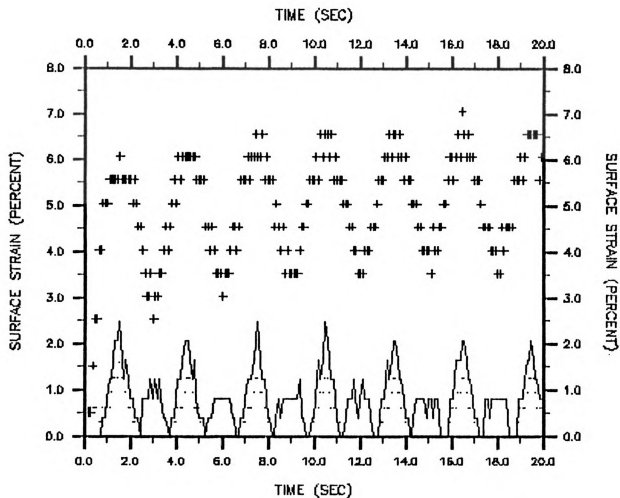


Fig. 3-35 Surface strains of the tendon segments with cycles for CAM30-4 (..... : Seg.1, +++ : Seg.2, \_\_\_\_\_ : Seg.3)

## SURFACE STRAIN

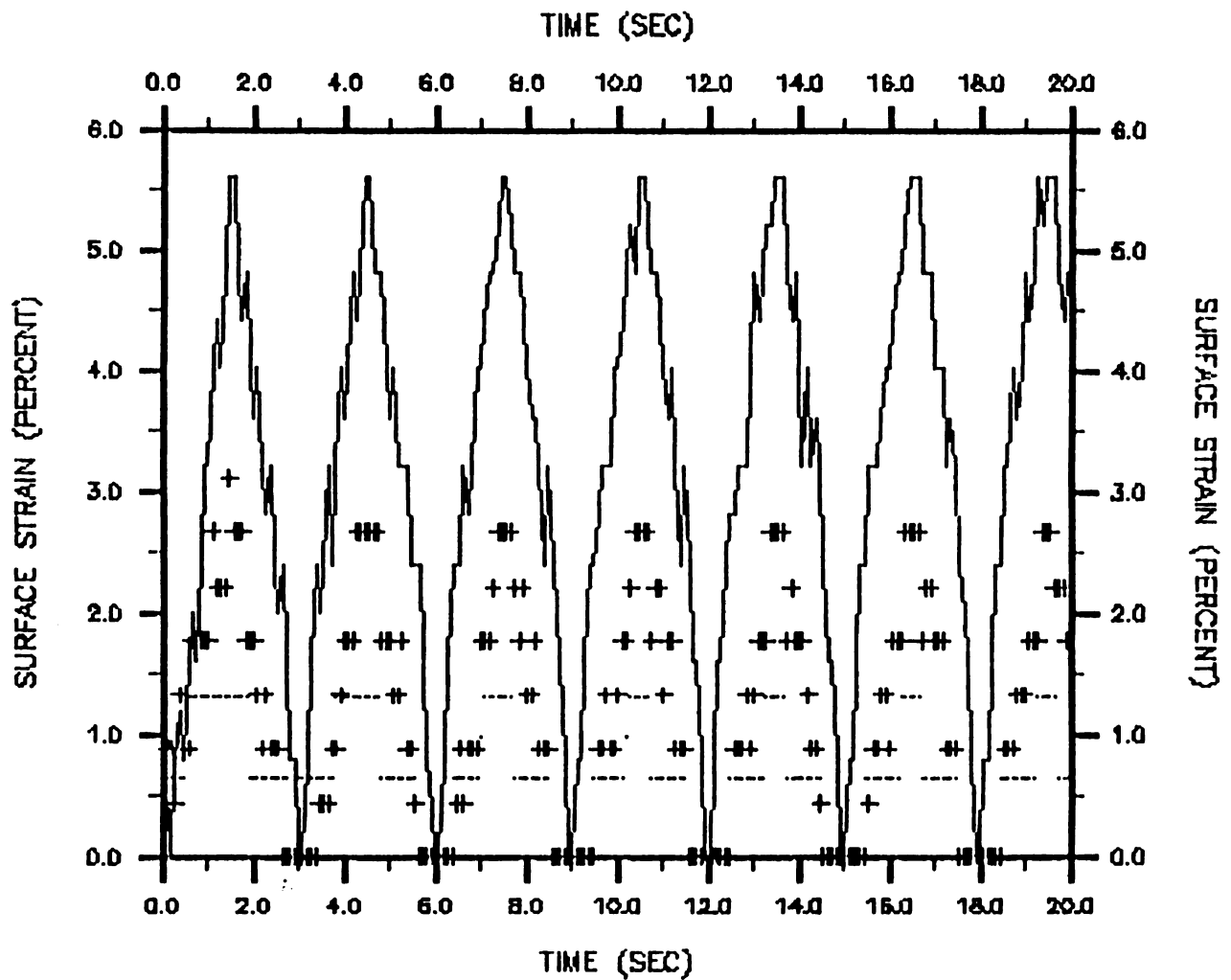


Fig. 3-36 Surface strains of the tendon segments with cycles for CAM30-5 (.... : Seg.1; +++ : Seg.2; — : Seg.3)

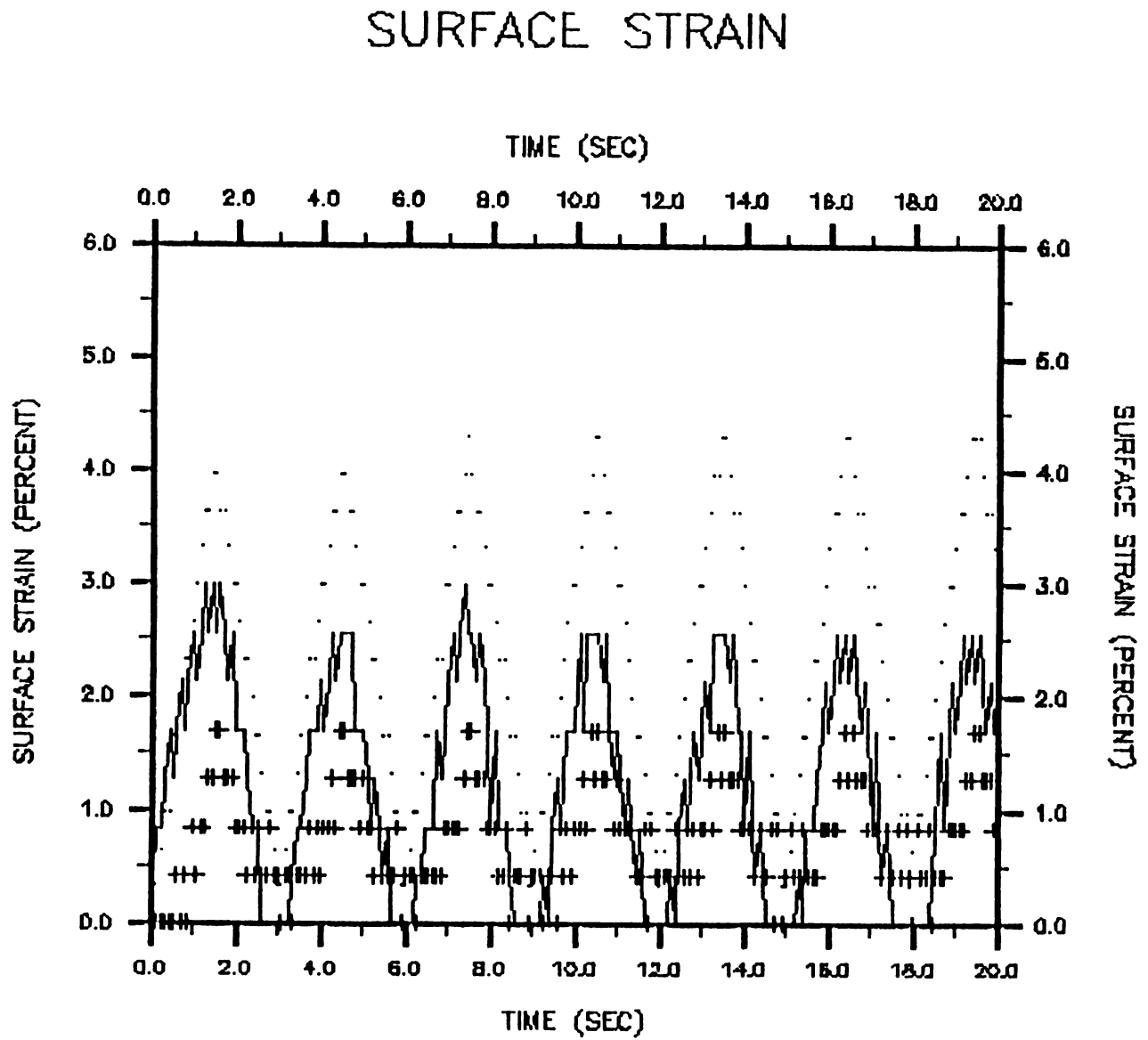


Fig. 3-37 Surface strains of the tendon segments with cycles for CAM30-6 (..... : Seg.1, ++++ : Seg.2, \_\_\_\_ : Seg.3)

# SURFACE STRAIN

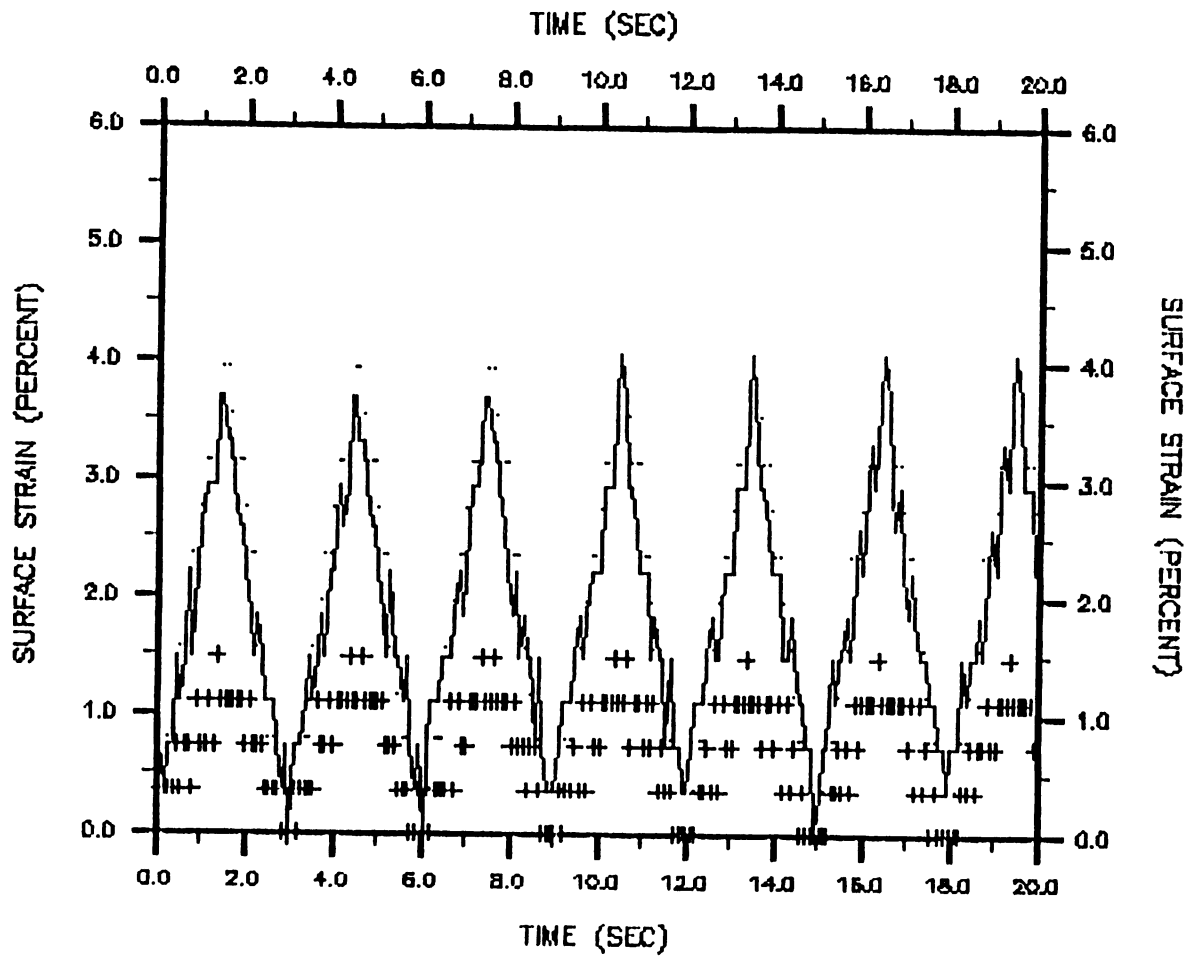


Fig. 3-38 Surface strains of the tendon segments with cycles for CAM30-7 (.... : Seg.1, +++ : Seg.2, \_\_\_\_ : Seg.3)

## SURFACE STRAIN

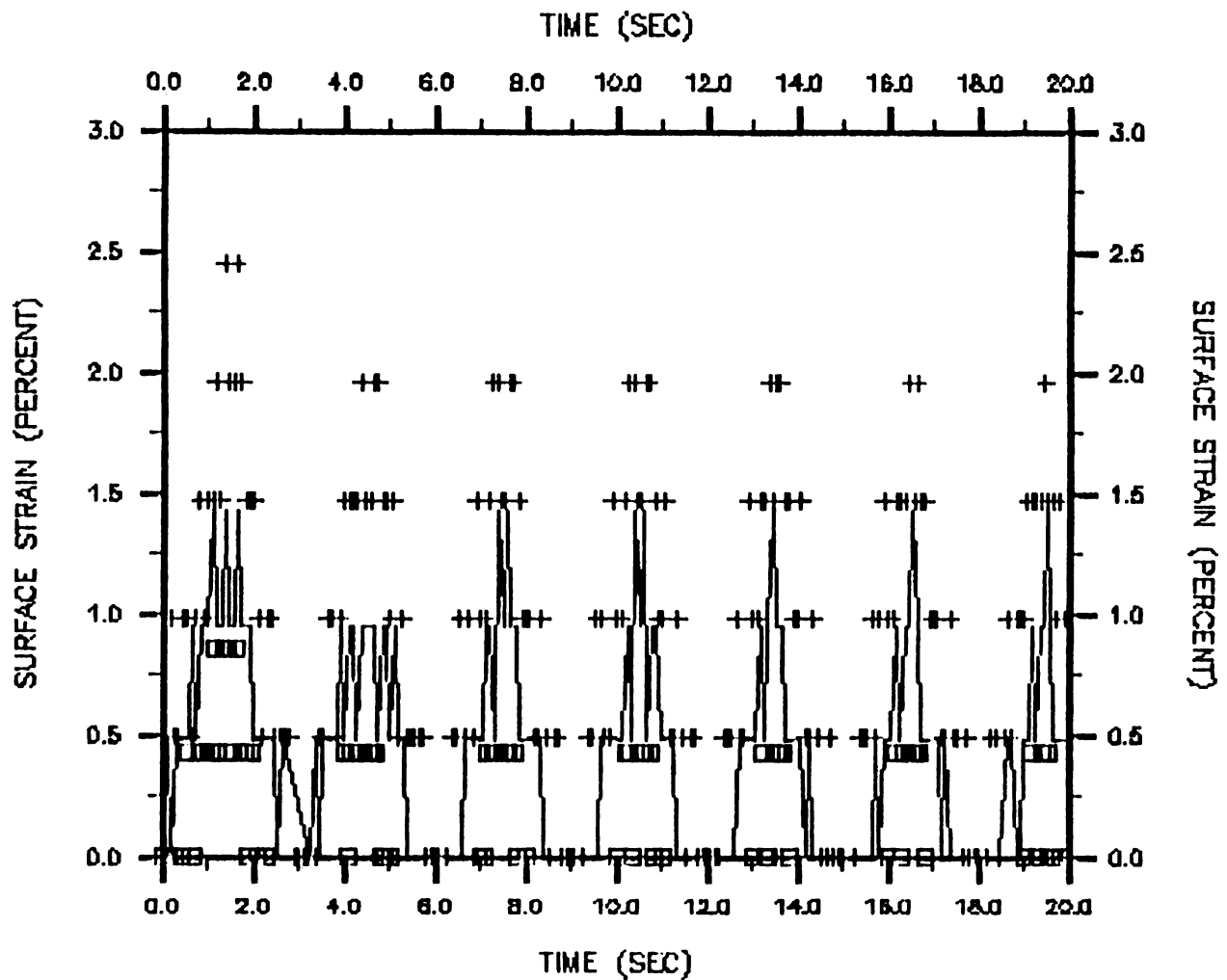


Fig. 3-39 Surface strains in segment 2 with cycles at the same tendon test (\_\_\_\_ : CAM30-1 [muscle end], ++++ : CAM30-2 [mid-portion], □□□□ : CAM30-3 [bone end])

# SURFACE STRAIN

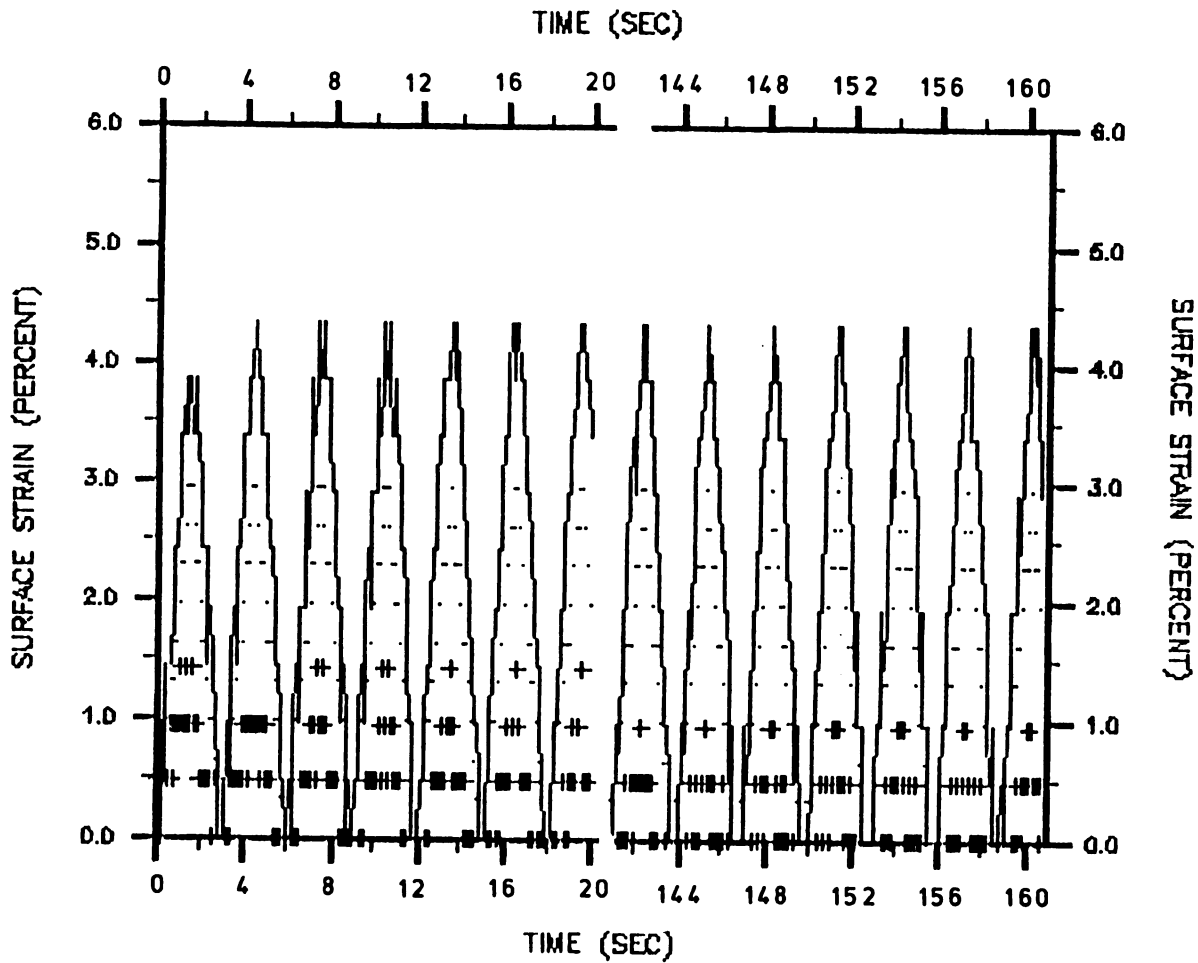


Fig. 3-40 Surface strains of the tendon segments with 120 sec. rest period for CAM30-1  
 (..... : Seg.1, ++++ : Seg.2, \_\_\_\_\_ : Seg.3)

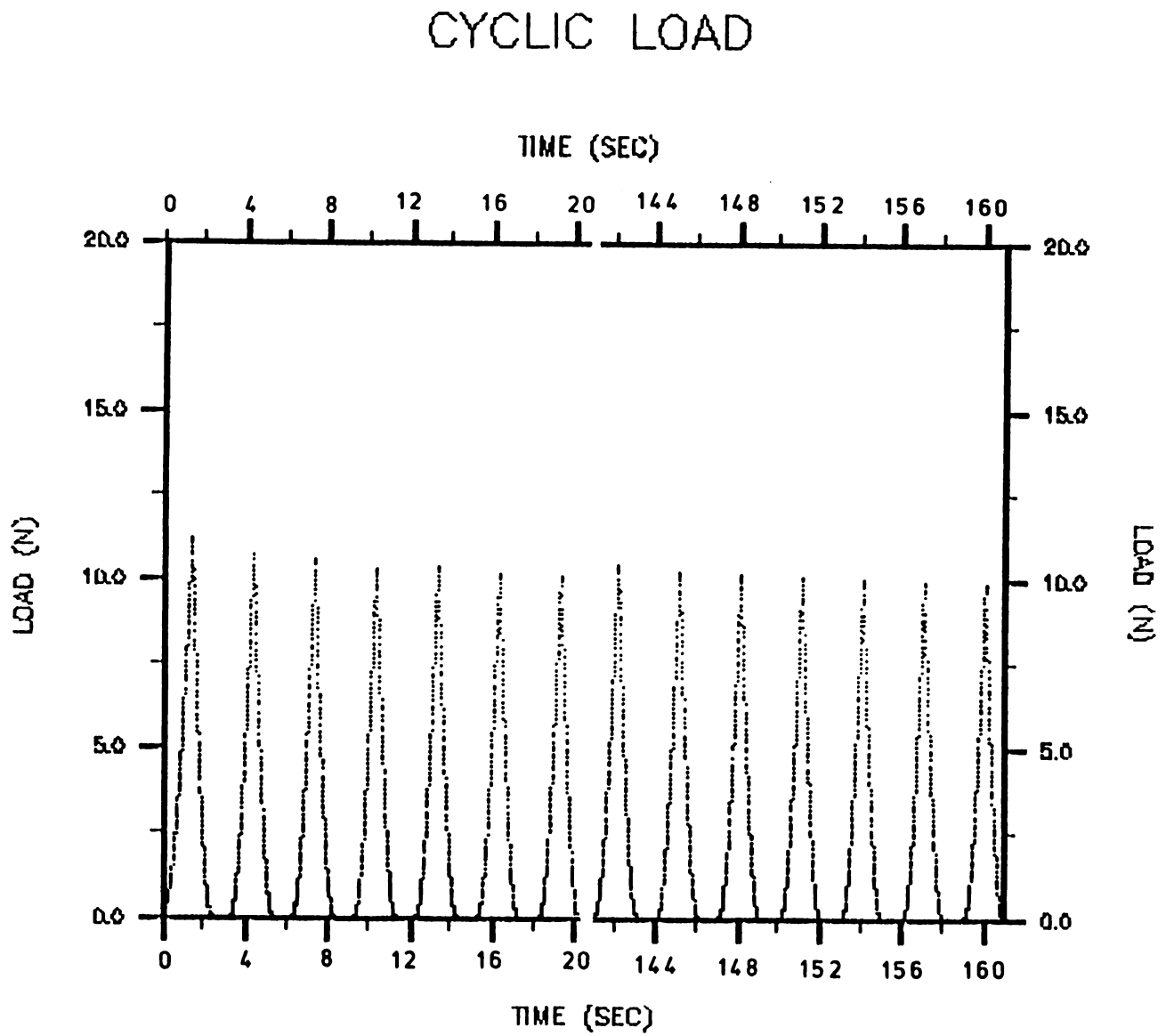


Fig. 3-41 Cyclic load relaxation and recovery with 120 sec. rest period for CAM30-1

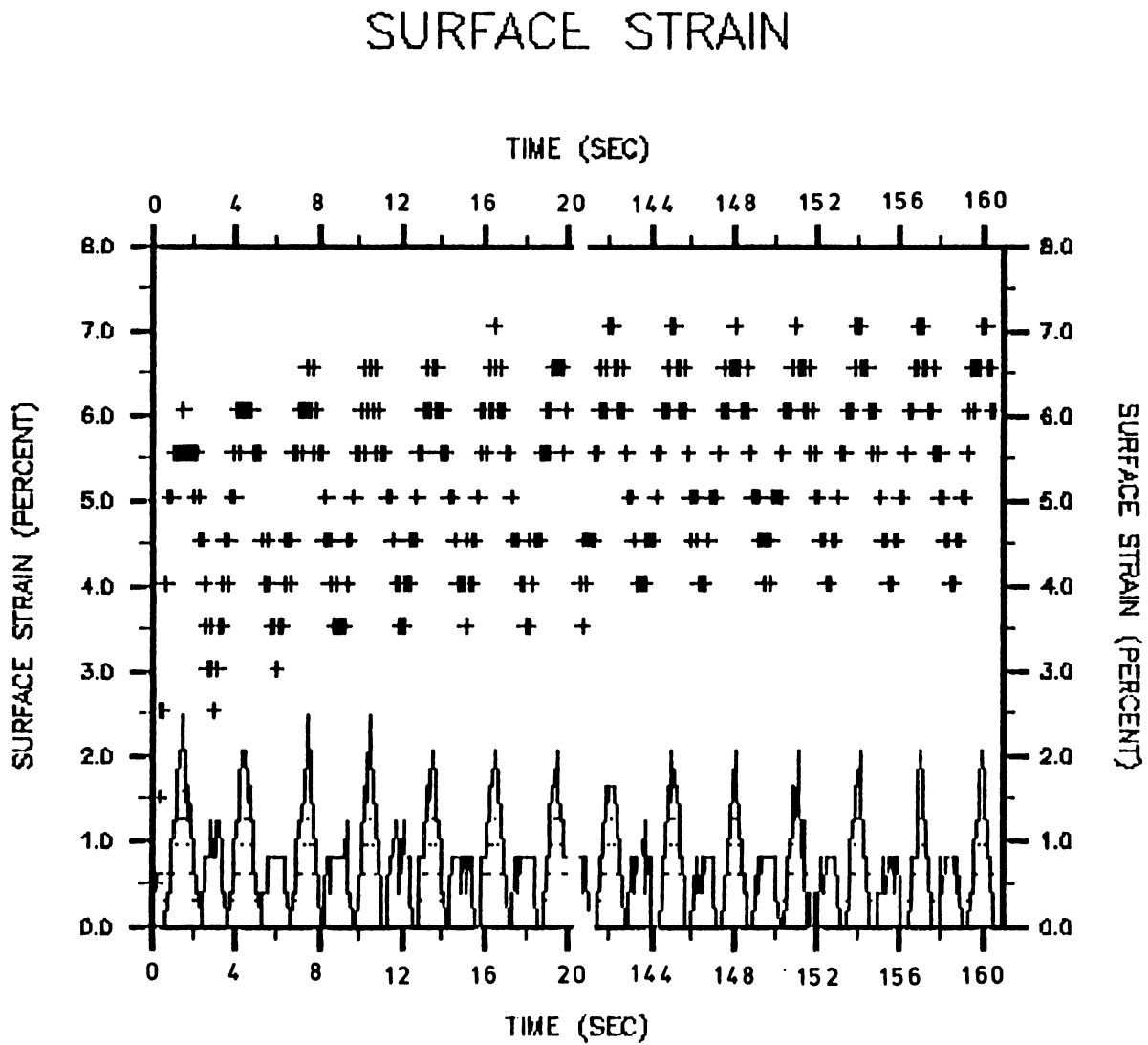


Fig. 3-42 Surface strains of the tendon segments with 120 sec. rest period for CAM30-4  
 (.... : Seg.1, ++++ : Seg.2, \_\_\_\_ : seg.3)

# CYCLIC LOAD

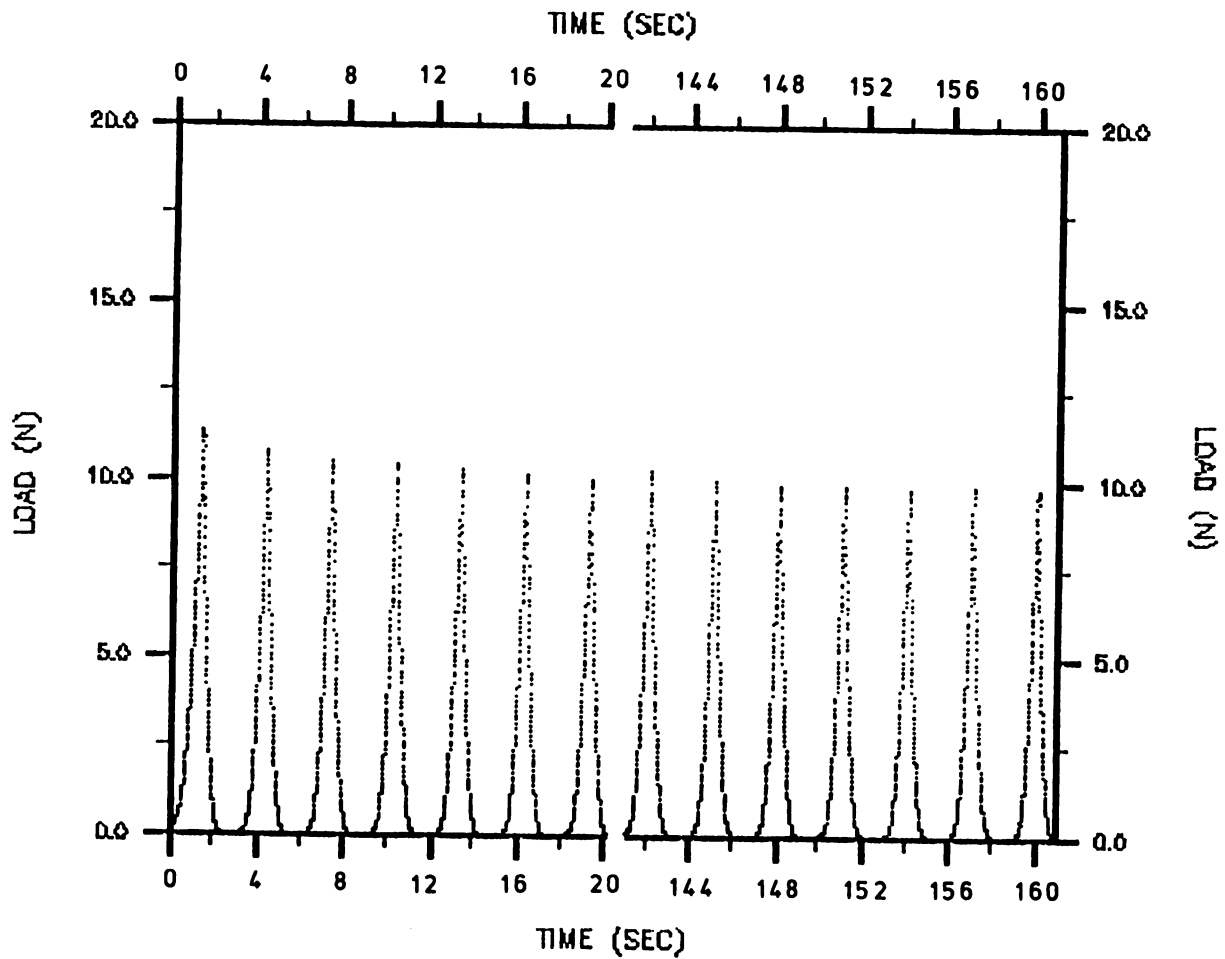


Fig. 3-43 Cyclic load relaxation and recovery with 120 sec. rest period for CAM30-4

# SURFACE STRAIN

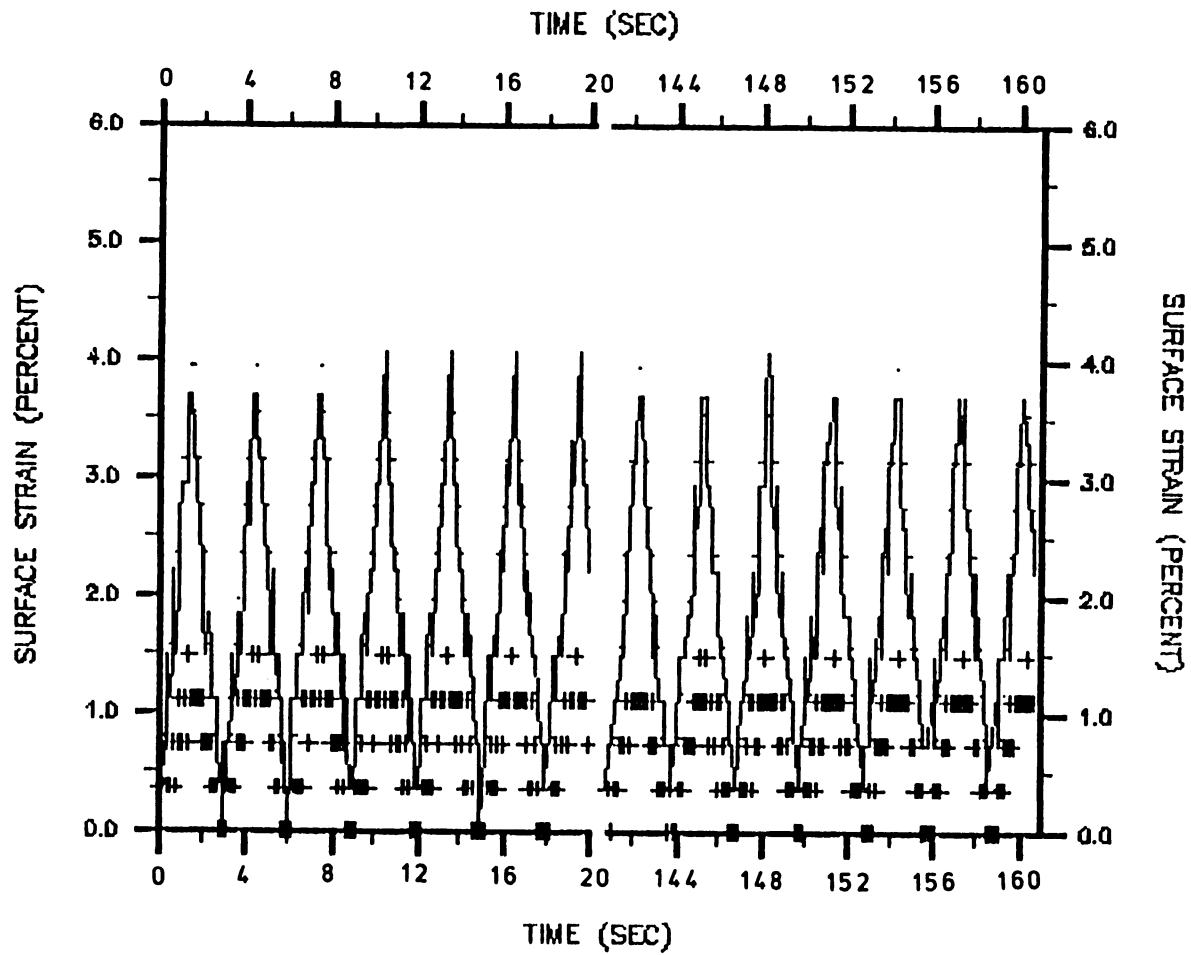


Fig. 3-44 Surface strains of the tendon segments with 120 sec. rest period for CAM30-7  
 (..... : Seg.1, ++++ : Seg.2, \_\_\_\_\_ : Seg.3)

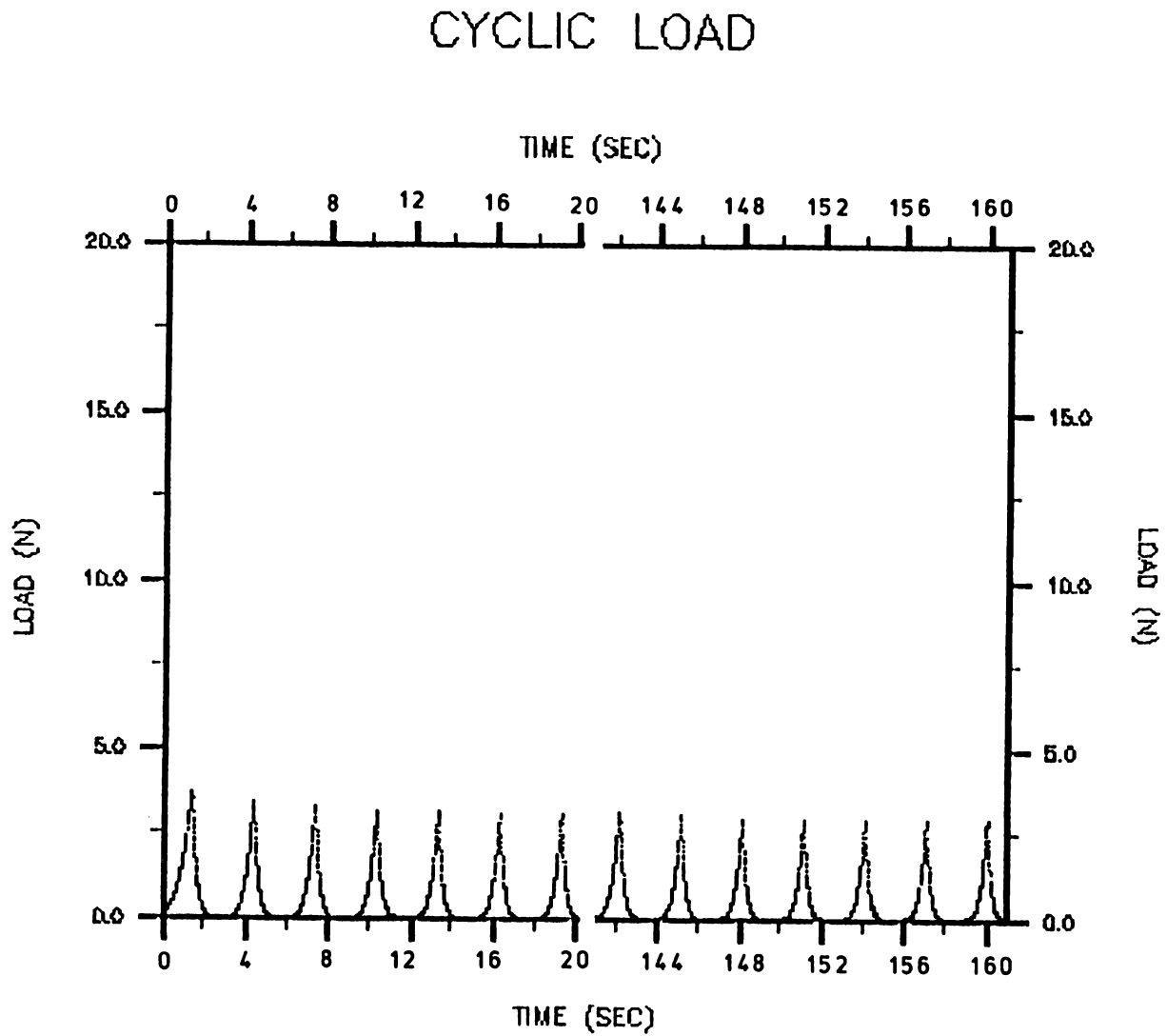


Fig. 3-45 Cyclic load relaxation and recovery with 120 sec. rest period for CAM30-7

Table 3-33

Cyclic Peak Load (N) and Surface Strain (%) at Each Tendon  
Segments with One Rest Period (120 sec.)

| File Name | Cycle No.<br>(Time) | Peak Load(N) | Peak Surface Strain (%) |       |       |        |
|-----------|---------------------|--------------|-------------------------|-------|-------|--------|
|           |                     |              | Seg.1                   | Seg.2 | Seg.3 | Tendon |
| CAM30-1   | 1(1.5)              | 11.17        | 2.94                    | 1.43  | 3.86  | 2.64   |
|           | 7(19.5)             | 10.11        | 2.94                    | 1.43  | 4.35  | 2.64   |
|           | 8(141.5)            | 10.47        | 2.94                    | 0.95  | 4.35  | 2.64   |
|           | 14(159.5)           | 9.90         | 2.94                    | 0.95  | 4.35  | 2.64   |
| CAM30-2   | 1(1.5)              | 10.54        | 3.20                    | 2.45  | 3.29  | 2.62   |
|           | 7(19.5)             | 9.54         | 3.56                    | 1.96  | 3.29  | 2.62   |
|           | 8(141.5)            | 9.88         | 3.56                    | 1.96  | 3.29  | 2.62   |
|           | 14(159.5)           | 9.34         | 3.56                    | 1.96  | 3.29  | 2.62   |
| CAM30-3   | 1(1.5)              | 12.85        | 3.48                    | 0.86  | 4.59  | 2.76   |
|           | 7(19.5)             | 11.65        | 3.80                    | 0.43  | 5.05  | 2.64   |
|           | 8(141.5)            | 11.76        | 3.80                    | 0.43  | 4.59  | 2.64   |
|           | 14(159.5)           | 11.43        | 3.80                    | 0.43  | 4.59  | 2.64   |
| CAM30-4   | 1(1.5)              | 11.34        | 1.58                    | 6.06  | 2.47  | 2.80   |
|           | 7(19.5)             | 10.03        | 1.26                    | 6.57  | 2.06  | 2.80   |
|           | 8(141.5)            | 10.32        | 1.26                    | 7.07  | 1.65  | 2.68   |
|           | 14(159.5)           | 9.79         | 1.26                    | 7.07  | 2.06  | 2.80   |

Table 3-33 (continued)

Cyclic Peak Load (N) and Surface Strain (%) at Each Tendon  
Segments with One Rest Period (120 sec.)

| File Name | Cycle No.<br>(Time) | Peak Load(N) | Peak Surface Strain (%) |       |       |        |
|-----------|---------------------|--------------|-------------------------|-------|-------|--------|
|           |                     |              | Seg.1                   | Seg.2 | Seg.3 | Tendon |
| CAM30-5   | 1(1.5)              | 14.77        | 1.32                    | 3.11  | 5.62  | 2.75   |
|           | 7(19.5)             | 13.21        | 1.32                    | 2.67  | 5.62  | 2.75   |
|           | 8(141.5)            | 13.54        | 1.98                    | 3.56  | 6.43  | 2.75   |
|           | 14(139.5)           | 12.99        | 1.98                    | 3.56  | 6.43  | 2.75   |
| CAM30-6   | 1(1.5)              | 1.38         | 3.97                    | 1.70  | 2.98  | 2.79   |
|           | 7(19.5)             | 1.05         | 4.30                    | 1.70  | 2.55  | 2.79   |
|           | 8(141.5)            | 1.09         | 4.30                    | 1.70  | 2.55  | 2.79   |
|           | 14(159.5)           | 0.98         | 4.30                    | 1.70  | 2.98  | 3.04   |
| CAM30-7   | 1(1.5)              | 3.71         | 3.94                    | 1.11  | 3.69  | 2.83   |
|           | 7(19.5)             | 3.05         | 3.94                    | 1.48  | 4.06  | 2.96   |
|           | 8(141.5)            | 3.14         | 3.94                    | 1.11  | 3.69  | 2.83   |
|           | 14(159.5)           | 2.91         | 3.54                    | 1.48  | 3.69  | 2.71   |

## IV. CONSTITUTIVE MODEL

IV.1. Development of Constitutive Model

For many different biological tissues, a hereditary integral form of the stress-strain constitutive law has been used [12,22,28,31,33,34,45,56]. This type of equation, the quasi-linear viscoelastic law (QVL), has been proposed by Fung [14] in the form:

$$\sigma(t) = \int_{-\infty}^t G(t-\tau) \frac{d\sigma^e[\lambda(\tau)]}{d\lambda} \frac{d\lambda(\tau)}{d\tau} d\tau \quad (4-1)$$

where  $G(t)$  is the reduced relaxation function (normalized stress relaxation function) with  $G(0) = 1.0$ ,

$\sigma^e(\lambda)$  is the elastic response,

$\lambda$  is the stretch ratio,

$t$  is the particular time (usually, current time),

$\tau$  is the variable time for integration.

The equation (4-1) may be written in terms of strain instead of stretch ratio as:

$$\sigma(t) = \int_{-\infty}^t G(t-\tau) \frac{d\sigma^e[\epsilon(\tau)]}{d\epsilon} \frac{d\epsilon(\tau)}{d\tau} d\tau \quad (4-2)$$

where  $\epsilon$  is the strain (  $= \lambda - 1$  ),

$t$  is the particular time (usually, current time),

$\tau$  is the variable time for integration.

The lower limit of integration was taken to be  $-\infty$  in the QVL. Practically, the lower limit should be taken as the origin,  $t = 0$ . If the action starts at time  $t = 0$ , then it is assumed that  $\sigma(t) = 0$  for  $-\infty < t < 0$ . Also,  $\sigma^e = 0$  for  $t < 0$ . In other words, the material is completely free of stress and strain initially. Equation (4-2) may be rewritten as:

$$\begin{aligned} \sigma(t) = & \int_{-\infty}^0 G(t-\tau) \frac{d\sigma^e[\epsilon(\tau)]}{d\epsilon} \frac{d\epsilon(\tau)}{d\tau} d\tau \\ & + \int_0^t G(t-\tau) \frac{d\sigma^e[\epsilon(\tau)]}{d\epsilon} \frac{d\epsilon(\tau)}{d\tau} d\tau \end{aligned} \quad (4-3)$$

where the first term on the right-hand side of this equation is taken to zero. Thus, we obtain the result in the form:

$$\sigma(t) = \int_0^t G(t-\tau) \frac{d\sigma^e[\epsilon(\tau)]}{d\epsilon} \frac{d\epsilon(\tau)}{d\tau} d\tau \quad (4-4)$$

Fung [14] showed the elastic response for rabbit mesentery was an exponential expression, which may be written as:

$$\sigma^e = A \left[ \lambda - \frac{1}{\lambda^2} \right] e^{b\lambda} \quad (4-5)$$

where A and b are constants.

The Lagrangian strain  $\epsilon$  and the stretch ratio  $\lambda$  are defined as follows:

$$\lambda = \frac{L}{L_0},$$

$$\epsilon = \frac{L - L_0}{L_0} = \lambda - 1. \quad (4-6)$$

Thus, equation (4-5) may be rewritten in terms of strain  $\epsilon$  as:

$$\sigma^e = A \left[ \epsilon + 1 - \frac{1}{(\epsilon + 1)^2} \right] e^{b(\epsilon + 1)}. \quad (4-7)$$

Equation (4-7) may be expanded in a Taylor series as follows:

$$\begin{aligned} \sigma^e &= A \left[ \epsilon + 1 - (1 - 2\epsilon + 3\epsilon^2 - 4\epsilon^3 + 5\epsilon^4 - \dots) \right] e^{b(\epsilon + 1)} \\ &= 3Ae^b \left[ \epsilon - \epsilon^2 + \frac{4}{3}\epsilon^3 - \frac{5}{3}\epsilon^4 + \dots \right] e^{b\epsilon} \end{aligned}$$

$$= B \left[ \epsilon - \epsilon^2 + \frac{3}{4}\epsilon^3 - \frac{5}{3}\epsilon^4 + \dots \right] e^{b\epsilon}$$

where  $B$  ( $= 3Ae^b$ ) is constant.

By expanding the exponential term in a Taylor series, we obtain:

$$\sigma^e = B \left[ \epsilon - \epsilon^2 + \frac{4}{3}\epsilon^3 - \frac{5}{3}\epsilon^4 + \dots \right] \left[ 1 + b\epsilon + \frac{(b\epsilon)^2}{2!} + \dots \right]$$

or,

$$\sigma^e = B \left[ \epsilon + (b-1)\epsilon^2 + \left( \frac{b^2}{2} - b + \frac{4}{3} \right) \epsilon^3 + \dots \right]. \quad (4-8)$$

The stress-strain relationship of collagen fibers has led to the choice of the second term of equation (4-8) from a study of rat tail tendons by Haut and Little [22]. Also, this second order relation has been found by Hubbard and Chun [23] in long term cyclic tests of the tendon. For the ligamentum nuchae, Jenkins and Little [28] associated the first term with elastin response and the second term with collagen response. The previous studies and the results presented in Chapter III support the second order term of equation (4-8) to represent the elastic response of tendon.

Rigby, et al. [42] used photographs taken by transmitted polarized light to show that the waviness of collagen fibers straightened during loading and reappeared upon subsequent unloading. Their strain level had not exceeded 4% in a study of wet

rat tail tendons. Viidik [51] found in a study of rat tail tendon that, first, the waviness becomes "shallower" during stretching; second, the tendon bundles straightened out completely at the end of the toe part in the stress-strain curve; and, finally, a short period waviness appeared during unloading. Also, Kastelic [29] showed the same phenomena in his morphological model for the crimp structure of tendon with a polarizing microscope technique. Diamant, et al. [18] reported that the crimp was perfectly reversible at lower strains and acted like a mechanical spring. Lanir [33] reported that three factors may contribute to the recrimping of the collagen: the collagen's own bending rigidity, its interaction with the ground substance, and the stretch exerted by the elastin. Also, Lanir [31] has reported that:

"The QVL has some restrictions with regards to negative strain rate cases; the tissue response is expected to differ from the QVL owing to the anticipated difference between the viscoelastic responses of stretched vs. contracting crimped fibers in unloading phase of cyclic tests".

Recrimping of the collagen during unloading may contribute some degree of the asymmetry of the stress-strain relationship between the loading and unloading phase. In this study, the term instant elastic recovery ( $\epsilon_e$ ) is introduced into the QVL to describe the nonsymmetry phenomena which may be caused by recrimping during unloading.

Based on previous work [18,29,31,33,42,51], it is reasonable to assume that the elastic response for the soft tissues for loading and unloading would be in the form of the general power series:

$$\sigma^e = \sum_m K_m [\epsilon(t) + \epsilon_e]^m \quad (4-9)$$

where  $K_m$  is the scale factor of the elastic response,

$m$  is the power of the elastic response,

$\epsilon_e$  is the instant elastic recovery for unloading (negative strain rate),  $\epsilon_e = 0$  for nonnegative strain rate.

Instant elastic recovery is further defined for the constant strain rate multiple cyclic tests in section IV.4. below.

As discussed above, the value chosen from equation (4-8) for the tendon is  $m = 2$ . Thus, equation (4-9) may be rewritten for the tendon in the form:

$$\sigma^e = K_2 [\epsilon(t) + \epsilon_e]^2. \quad (4-10)$$

Differentiation of equation (4-10) results in:

$$\frac{d\sigma^e}{d\epsilon} = 2K_2 [\epsilon(t) + \epsilon_e]. \quad (4-11)$$

By substituting equation (3-1) and (4-11) into equation (4-4), then the constitutive equation is obtained in the form:

$$\sigma(t) = \int_0^t [\alpha + \beta e^{-\mu(t-\tau)^q}] 2K_2 [\epsilon(\tau) + \epsilon_e] \frac{d\epsilon(\tau)}{d\tau} d\tau$$

or,

$$\sigma(t) = 2K_2 \int_0^t [\alpha + \beta e^{-\mu(t-\tau)^q}] [\epsilon(\tau) + \epsilon_e] \frac{d\epsilon(\tau)}{d\tau} d\tau \quad (4-12)$$

Figure 4-1 shows that the asymmetrical effect of the instant elastic recovery ( $\epsilon_e$ ) during unloading.

#### IV.2. Relaxation Response

In the stress relaxation test under constant strain level, the strain function may be written in the form:

$$\epsilon = \epsilon_0 U(t) \quad (4-13)$$

where  $U(t)$  is the unit step function.

Differentiation of the equation (4-13) yields:

$$\frac{d\epsilon}{dt} = \epsilon_0 \delta(t) \quad (4-14)$$

where  $\delta(t)$  is the Dirac delta function.

By substituting equation (4-13) and (4-14) into equation (4-12) and setting  $\epsilon_e = 0$  (since this is a nonnegative strain rate test), then the constitutive equation yields:

$$\sigma(t) = 2K_2 \int_0^t [\alpha + \beta e^{-\mu(t-\tau)^q}] \epsilon_0 U(\tau) \epsilon_0 \delta(\tau) d\tau. \quad (4-15)$$

By definition of unit step function [1], it might be noted that:

$$U(t) = \begin{cases} 0 & (t < 0) \\ \frac{1}{2} & (t = 0) \\ 1 & (t > 0) \end{cases}$$

And, equation (4-15) is simply integrated by the definition of the Dirac delta function. The result of this integration is:

$$\sigma(t) = K_2 \epsilon_0^2 [\alpha + \beta e^{-\mu t^q}] \quad (4-16)$$

which is the response to a stress relaxation test.

### IV.3. Response in the Constant Strain Rate Test

In the constant strain rate test, the strain function may be written in the form:

$$\epsilon(t) = \gamma t \quad (4-17)$$

where  $\gamma$  is the constant strain rate.

Differentiation of equation (4-17) yields:

$$\frac{d\epsilon(t)}{dt} = \gamma. \quad (4-18)$$

By substituting equation (4-17) and (4-18) into equation (4-12) and setting  $\epsilon_e = 0$  (since this is nonnegative strain rate test), then the constitutive equation yields:

$$\sigma(t) = 2K_2 \int_0^t [\alpha + \beta e^{-\mu(t-\tau)^q}] \gamma \tau \gamma d\tau$$

or,

$$\sigma(t) = 2K_2 \gamma^2 \int_0^t [\alpha + \beta e^{-\mu(t-\tau)^q}] \tau d\tau \quad (4-19)$$

which is the response to a constant strain rate test.

#### IV.4. Response in the Constant Strain Rate Multiple Cyclic Test

In the constant strain rate multiple cyclic tests (see Figure 4-2 which is Figure 2-1 repeated here for reference.), the strain function may be written in the form:

$$\epsilon(t) = (-1)^{n+1} \gamma(t - XINT) \quad (4-20)$$

where  $n$  is the half cycle counting number,

$\gamma$  is the constant strain rate,

$XINT$  is the time for zero strain in the current half cycle.

$XINT$  occurs at the beginning of each loading half cycle  
and at the end of each unloading half cycle.

Differentiation of equation (4-20) yields:

$$\frac{d\epsilon(t)}{dt} = (-1)^{n+1} \gamma. \quad (4-21)$$

In the constant strain rate cyclic tests, we shall assume the following:

$$\epsilon_e = \gamma \epsilon_k \quad (4-22)$$

where  $\epsilon_k$ , the fraction of the instant elastic recovery, is given by

$$\epsilon_k = (\text{first cycle unloading slack strain} - \text{first cycle loading slack strain}) * \frac{1}{N}, \quad (4-23)$$

and N is the full cycle counting number ( = n/2 ).

The loading slack strain for the first cycle of an experiment is usually adjusted to be zero so that the value of  $\epsilon_k$  is equal to the unloading slack strain in the first cycle. This  $\epsilon_k$  value decreases as the number of cycles (N) increases.

Thus, substitution of equations (4-20), (4-21) and (4-22) into equation (4-12) yields:

$$\sigma(t) = 2K_2 \int_0^t [\alpha + \beta e^{-\mu(t-\tau)^q}] [ (-1)^{n+1} \gamma(\tau - XINT) + \gamma\epsilon_k ] [ (-1)^{n+1} \gamma ] d\tau \quad (4-24)$$

or,

$$\sigma(t) = (-1)^{n+1} 2K_2 \gamma^2 \int_0^t [\alpha + \beta e^{-\mu(t-\tau)^q}] [ (-1)^{n+1} (\tau - XINT) + \epsilon_k ] d\tau \quad (4-25)$$

which is the response to a constant strain rate multiple cyclic test.

Equation (4-25) may be rewritten for numerical computation as:

$$\sigma(t) = (-1)^{n+1} 2K_2 \gamma^2 \left\{ \sum_{i=1}^{nt} \int_{t_{i-1}}^{t_{nt}} [ \alpha + \beta e^{-\mu(t-\tau)^q} ] \right. \\ \left. [ (-1)^{n+1} (\tau - XINT) + \epsilon_k ] d\tau + \int_{t_{nt}}^t [ \alpha + \beta e^{-\mu(t-\tau)^q} ] \right. \\ \left. [ (-1)^{n+1} (\tau - XINT) + \epsilon_k ] d\tau \right\} \quad (4-26)$$

where  $n$  is the half cycle counting number in the strain function,

$nt$  is the half cycle counting number at the current time,

$t_{i-1}$  is the peak and valley time at each half cycle

and  $t_0$  (when  $i=1$ ) = 0,

$t$  is the current time (particular time),

$\tau$  is the variable time in integration,

$\gamma$  is the constant strain rate,

$K_2$  is the scale factor of the elastic response for the tendon,

$\epsilon_k$  is the fraction of the instant elastic recovery,

$\alpha$ ,  $\beta$ ,  $\mu$ , and  $q$  are the constants in the reduced relaxation function.

In the constitutive equation (4-26), there are numerical values which are based on measurements of tendon responses. The reduced relaxation function incorporates  $\alpha$ ,  $\beta$ ,  $\mu$ , and  $q$  and their numerical values have been found (in Chapter III) which represent the responses of all the tendon specimens. The elastic response incorporates an exponent ( $m$ ), a scale factor ( $K_2$ ), and an instant elastic recovery ( $\epsilon_k$ ). The exponent ( $m$ ) has been assigned a value of 2. The instant elastic recovery is based on a value of unloading slack strain in the first extension cycle, a representative value of this slack strain has been determined to be 0.85%. The values of the scale factor ( $K_2$ ) will be examined in the next chapter.

The result of the hereditary integral form of a constitutive equation for cyclic tests may be a function of the Heavyside class. The illustration of the results from the constitutive equation with cycles is shown in Figure 4-3. The negative values are retained in the modeling calculations. Although it is unrealistic for the tendon to support longitudinal compressive forces, the retention of negative values in the modeling calculations gives a capability to predict measured responses in multiple cyclic extensions such as relaxation of peak stresses, differences between loading and unloading slack strains, and recovery of stresses during rest periods or during periods of lower strain (3%) after higher strain (4%). Thus, the compressive loading in modeling computations may be considered to be related to energy which is stored in tissue, and

which causes the tissue to shorten during slack periods of zero net tension after an extension. For presentation, however, the negative values from this modeling calculation are set identically to zero in Figure 4-3, because the tendon does not transmit longitudinal compressive stress (load) during unloading in the cyclic test.

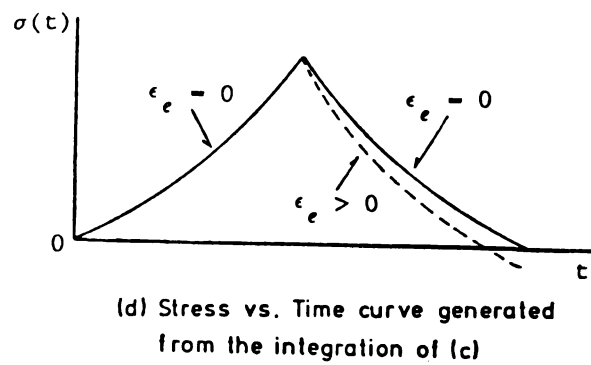
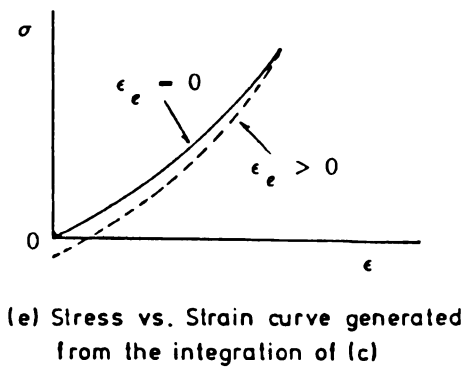
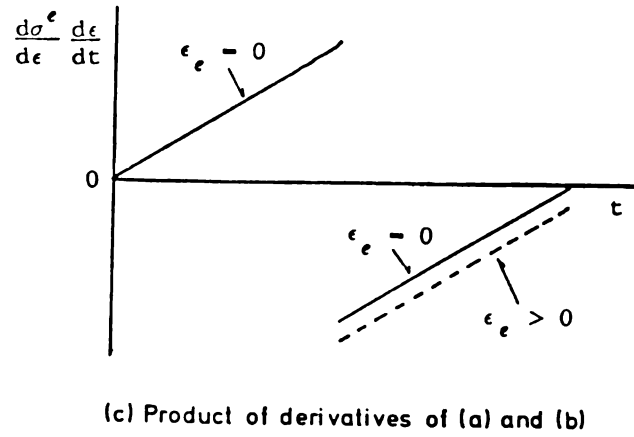
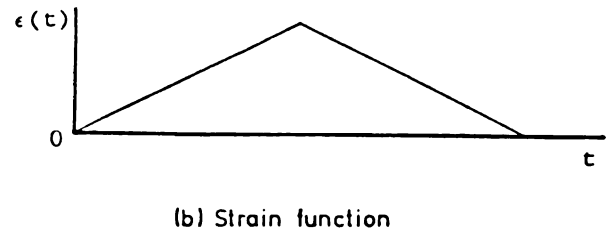
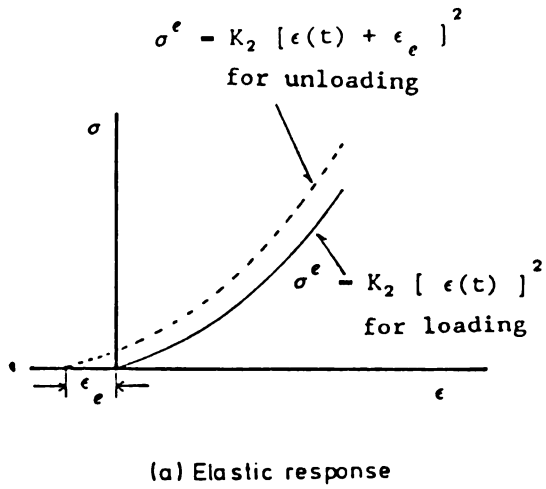
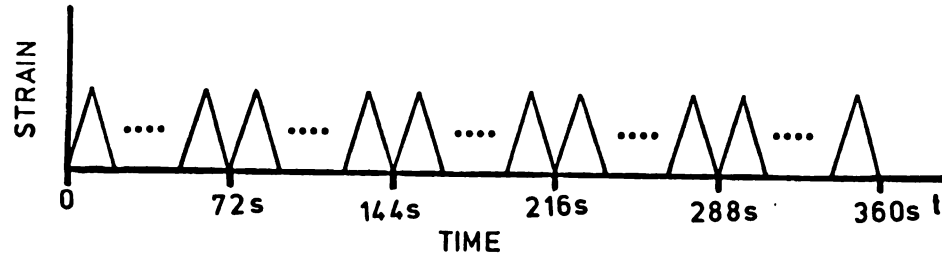
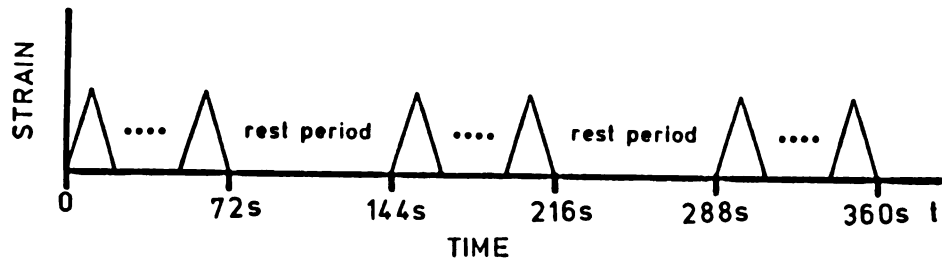


Fig. 4-1 Effect of the instant elastic recovery in equation (4-12) with  $G(t) = 1.0$

A. Constant peak strain level test (A-type)



B. Constant peak strain level test with rest periods (B-type)



C. Different peak strain level test (C-type)

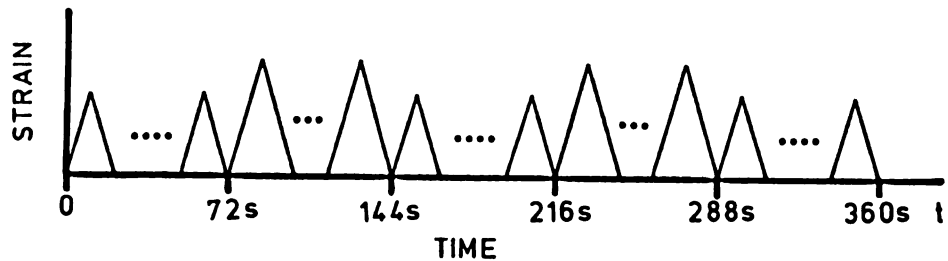


Fig. 4-2 Illustrations of the multiple cyclic test sequences with constant strain rate (This is Fig. 2-1 repeated here for reference.)

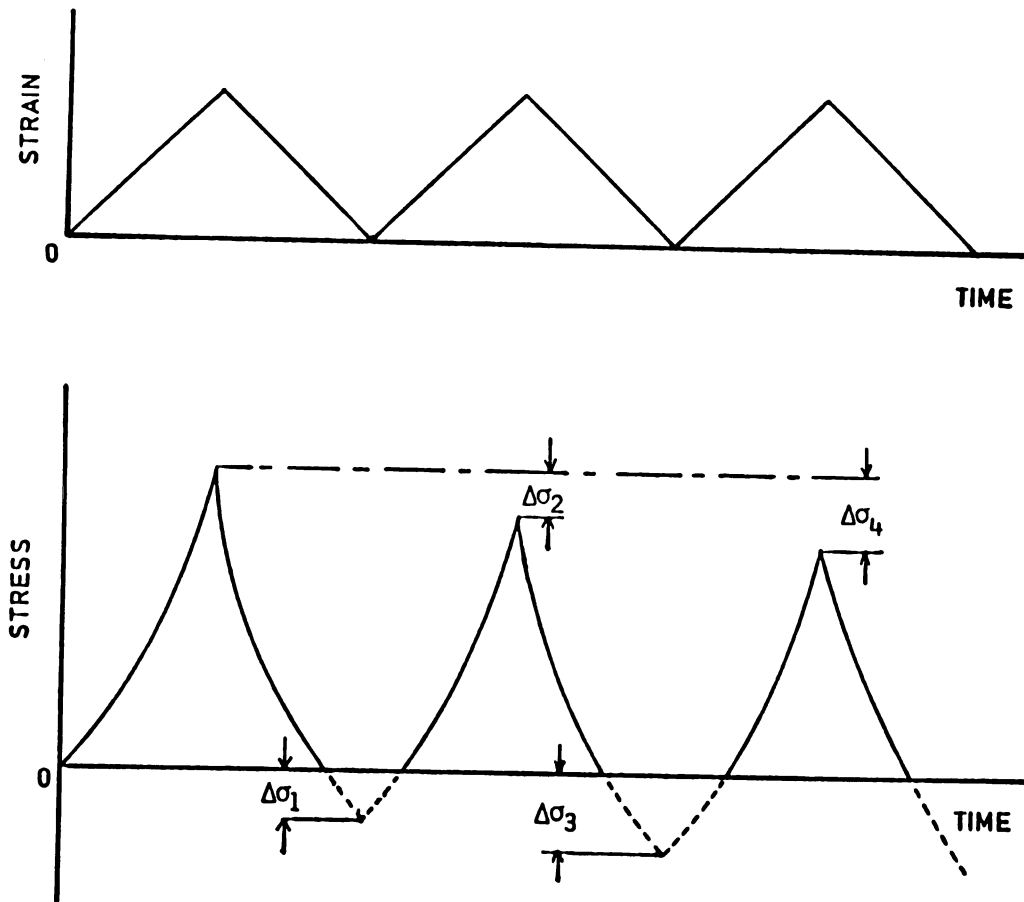


Fig. 4-3 Illustration of the results from the constitutive equation with cycles

## V. DETERMINATION OF THE $K_2$ AND COMPARISON WITH MEASURED RESPONSES

### V.1. Methods

The constitutive model (equation 4-12) incorporates the reduced relaxation function (equation 3-1) and the elastic response (equation 4-10). Within each of these functions are numerical coefficients whose values are based on measured data. Except for  $K_2$  in the elastic response, representative values of all these coefficient values have been determined. In this chapter, two methods for determining values of  $K_2$  from measured data are developed and the resulting values are presented. Comparisons are made between the elastic responses for each specimen, the responses to a single extension to 3% strain as predicted with the constitutive model, and the measured responses with corresponding regression equations.

$K_2$  is a scale factor in the second order elastic stress-strain relationship which is analogous to a modulus of elasticity in a linear stress-strain relation. Relaxation is a part of any measurement of tendon responses so that the elastic response cannot be measured directly. The elastic response can be approached as the strain rate of an extension test approaches infinity. This is not

practical. Thus, determination of  $K_2$  from measured data requires use of the constitutive model which combines the elastic and viscous responses of the tendons.

As developed in the previous chapter, the elastic response for the tendon can be expressed in the form:

$$\sigma^e = K_2 [ \epsilon(t) + \epsilon_e ]^2. \quad (4-9)$$

The coefficients for the elastic response have commonly been determined by the constant strain rate tests [12,22,23,43,56]. In such tests, the instant elastic recovery ( $\epsilon_e$ ) has been defined as zero. Thus, equation (4-9) may be written as:

$$\sigma^e = K_2 [ \epsilon(t) ]^2. \quad (5-1)$$

The parameter  $K_2$  may be determined by the following two methods. In the first method,  $K_2$  may be determined using the constitutive equation for a constant strain rate extension expressed in equation (4-19):

$$\sigma(t) = 2K_2 \gamma^2 \int_0^t [ \alpha + \beta e^{-\mu \tau^q} ] \tau \, d\tau. \quad (4-19)$$



At  $t = t_1$  (the time at peak strain level),

$$\sigma(t_1) = 2K_2\gamma^2 \int_0^{t_1} [\alpha + \beta e^{-\mu t^q}] \tau \, d\tau \quad (5-2)$$

or,

$$K_2 = \frac{\sigma(t_1)}{2\gamma^2 \int_0^{t_1} [\alpha + \beta e^{-\mu t^q}] \tau \, d\tau} \quad (5-3)$$

where  $\sigma(t_1)$  is the peak stress measured from when the strain level reaches the first peak ( $t = t_1$ ). Although the peak stress in a test will be affected by inaccuracies in controlling the peak strain, this measured peak stress is assumed to be the same as the first peak stress calculated from the constitutive model. The relationship between the elastic response and a measured response is further presented for a single extension at a constant strain rate in section V.2. below.

Table 5-1 shows the coefficients ( $K_2$ ,  $m$ ) of the elastic response for the tendon in this study at 3% strain peak level with 5%/sec strain rate tests. The average values of parameters in the reduced relaxation function,  $\alpha = 0.27$ ,  $\beta = 0.73$ ,  $\mu = 0.59$ , and  $q =$

0.129, were chosen from Table 3-3 for the calculating values of  $K_2$  in Table 5-1. In Table 5-1, the median value of  $K_2$  is 18.93 GPa in a range from 2.90 GPa to 47.70 GPa for all eighteen specimens. This variation is too large to choose a  $K_2$  value which is representative of all tendon specimens.

In the second method,  $K_2$  may be determined from the relaxation test results (see Figure 5-1).

Rewriting equation (4-16), we obtain:

$$\sigma(t) = K_2 \epsilon_o^2 [ \alpha + \beta e^{-\mu t^q} ] \quad (4-16)$$

or,

$$\sigma(t) = K_2 \epsilon_o^2 G(t). \quad (5-4)$$

By definition, at  $t = 0$ ,  $G(0) = 1.0$ . Thus, we obtain:

$$K_2 = \frac{\sigma(0)}{\epsilon_o^2} \quad (5-6)$$

where  $\sigma(0)$  is the predicted peak stress at  $t = 0$  in the relaxation test,

$\epsilon_0$  is the constant strain level.

$\sigma(0)$  may be predicted from the reduced relaxation function. Measured peak stress,  $\sigma(t_1)$ , is obtained when the strain level reaches a constant level at time  $t_1$ . Thus, the reduced relaxation function at time  $t_1$  yields:

$$G(t_1) = \alpha + \beta e^{-\mu t_1^q} \quad (5-7)$$

Knowing values of  $\alpha$ ,  $\beta$ ,  $\mu$ ,  $q$ , and  $t_1$ , and that  $G(t_1)$  has a numerical value less than 1.0, we obtain:

$$W = \frac{G(0)}{G(t_1)} > 1.0 \quad (5-8)$$

where  $W$  is the proportion on the reduced relaxation function from  $t = 0$  to  $t_1$  as shown in Figure 5-1.

Now, we may predict  $\sigma(0)$  as follows:

$$\sigma(0) = W \cdot \sigma(t_1). \quad (5-9)$$

By substituting equation (5-9) into equation (5-6), then  $K_2$  may be obtained in the form:

$$K_2 = \frac{W \cdot \sigma(t_1)}{\epsilon_o^2}. \quad (5-10)$$

Table 5-2 presents measured peak stresses at  $t = t_1$ , predicted peak stresses at  $t = 0$ , and  $K_2$  for the results of relaxation tests from Chapter III.

Scatter in the values of  $K_2$  from both methods was too great to choose an average value of  $K_2$  for general use. This scatter indicates that the value of  $K_2$  for a specific tendon should be chosen from that tendon's test result as a scale factor of the elastic response. This large variability may come from the differences in anatomical sites of the tendon specimens and all the history of the animal's life such as age and exercise.

Table 5-1Coefficients ( $K_2$ , m) of the Elastic Response for the Tendonsat 3% Peak Strain Level Tests with 5%/sec Strain Rate

| Test No. | $K_2$ (GPa) | m | Peak Strain(%) | Peak Stress(MPa) |
|----------|-------------|---|----------------|------------------|
| 33-1     | 47.70       | 2 | 3.0            | 31.55            |
| 33-2     | 44.41       | 2 | 3.0            | 29.37            |
| 33-3     | 17.41       | 2 | 3.0            | 11.52            |
| 33-4     | 14.40       | 2 | 3.0            | 9.52             |
| 33-5     | 27.67       | 2 | 3.0            | 18.30            |
| 33-6     | 16.22       | 2 | 3.0            | 10.73            |
| 30-1     | 31.14       | 2 | 3.0            | 20.60            |
| 30-2     | 35.75       | 2 | 3.0            | 23.65            |
| 30-3     | 21.57       | 2 | 3.0            | 14.27            |
| 30-4     | 28.62       | 2 | 3.0            | 18.93            |
| 30-5     | 5.34        | 2 | 3.0            | 3.53             |
| 30-6     | 20.26       | 2 | 3.0            | 13.40            |
| 34-1     | 16.93       | 2 | 3.0            | 11.20            |
| 34-2     | 19.77       | 2 | 3.0            | 13.08            |
| 34-3     | 18.09       | 2 | 3.0            | 11.96            |
| 34-4     | 15.14       | 2 | 3.0            | 10.02            |
| 34-5     | 2.90        | 2 | 3.0            | 1.92             |
| 34-6     | 6.69        | 2 | 3.0            | 4.43             |
| Max.     | 47.70       |   |                | 31.55            |
| Median   | 18.93       |   |                | 12.52            |
| Min.     | 2.90        |   |                | 1.92             |

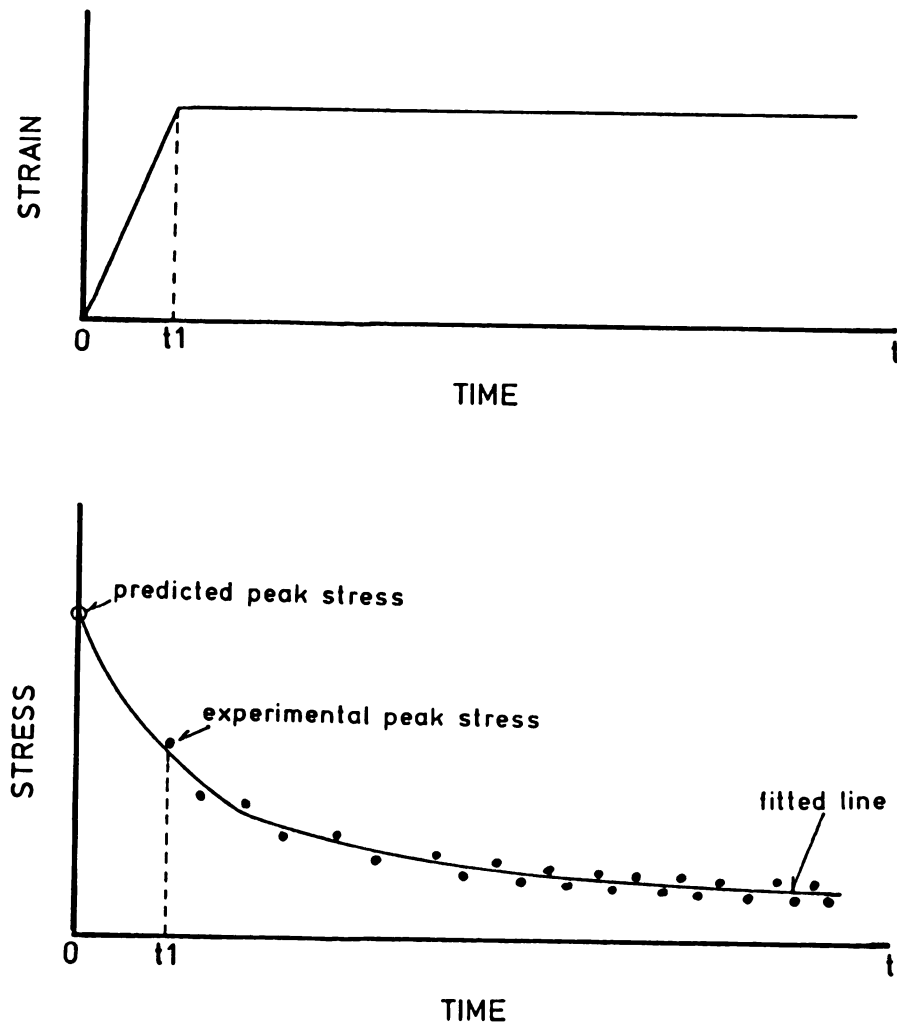


Fig. 5-1 Illustration of the relaxation test and experimental stress and predicted (fitted) stress

Table 5-2

Summary of Measured  $[\sigma(t_1)]$  and Predicted  $[\sigma(0)]$

Peak Stresses (MPa) and  $K_2$  (GPa) with 75%/sec

Strain Rate in the Relaxation Tests

| Strain Level | Test Number | $\sigma(t_1)$ | $\sigma(0)$ | $K_2$ | $t_1(\text{sec})$ |
|--------------|-------------|---------------|-------------|-------|-------------------|
| 3%           | 1           | 14.18         | 18.42       | 20.47 | 0.04              |
|              | 2           | 13.57         | 17.40       | 19.33 | 0.04              |
|              | 3           | 8.03          | 9.91        | 11.01 | 0.04              |
|              | 4           | 3.48          | 4.77        | 5.30  | 0.04              |
|              | 5           | 5.01          | 6.68        | 7.42  | 0.04              |
|              | 6           | 5.77          | 7.59        | 8.43  | 0.04              |
| 4%           | 1           | 16.91         | 19.89       | 12.43 | 0.053             |
|              | 2           | 19.57         | 23.02       | 14.39 | 0.053             |
|              | 3           | 13.86         | 16.70       | 10.44 | 0.053             |
|              | 4           | 31.99         | 39.49       | 24.68 | 0.053             |
|              | 5           | 8.70          | 10.74       | 6.71  | 0.053             |
|              | 6           | 9.63          | 12.51       | 7.82  | 0.053             |

## V.2. Comparison with Measured Data in Constant Strain Rate Tests

In the previous section, values of the coefficient  $K_2$  in the elastic response (equation 5-1) were determined by two methods. For both of these methods, the value of exponent  $m$  in the elastic response was assumed to be equal to 2. In the first method, the peak stress in the first cycle of each of the multiple cyclic tests was used with equation (5-3) to determine  $K_2$  (Table 5-1). In this section, the values of coefficients  $K_2$  from the first method and  $m$  in the elastic response are compared to the values of coefficients  $C$  and  $d$  from the regression fits to the first extension of the multiple cyclic tests. These values of  $C$  and  $d$  are the same as the values in the first columns of Tables 3-25, 27, and 29.

Figure 5-2 is an illustration of the relationships between measured data, the regression fit (with  $C$  and  $d$ ), the elastic response (with  $K_2$  and  $m$ ), and the response from the constitutive equation.

Table 5-3 compares the coefficients  $C$  and  $d$  with the coefficients  $K_2$  and  $m$  for 5%/sec constant strain rate tests. In this table, the median value of  $K_2$  is similar to the median value of  $C$  and the average value of  $d$  is similar to the value of  $m = 2$ . However, in each test, the value of  $K_2$  differs greatly from the value of  $C$ . These differences are due to the interactions between  $C$

and  $d$ , which are both variables determined from regression of the measured data. Also,  $K_2$  is determined with  $m = 2$ , and  $K_2$  (a characteristic of an elastic response) is not directly comparable to  $C$ , which is determined by a regression fit to measured response as shown in Figure 5-2.

Figure 5-3 shows the stress-strain plots for test no. 33-2 and test no. 33-6. The predicted data are calculated from equation (4-19). In this application, the following parameter values were used:  $K_2 = 44.41$  GPa (test no. 33-2) and  $K_2 = 16.22$  GPa (test no. 33-6) from Table 5-1, and  $\alpha = 0.27$ ,  $\beta = 0.73$ ,  $\mu = 0.59$ , and  $q = 0.129$ , which are average values for the reduced relaxation function at 3% strain level from Table 3-4. There is a good agreement between predicted and measured data for test no. 33-6 but the predicted data are a little lower for test no. 33-2. Although the fit for the peak stress values is to be expected because they were used to determine the respective  $K_2$  values, the close agreement throughout the entire curve up to the peak stress shows that the constitutive model is effective in predicting such responses.

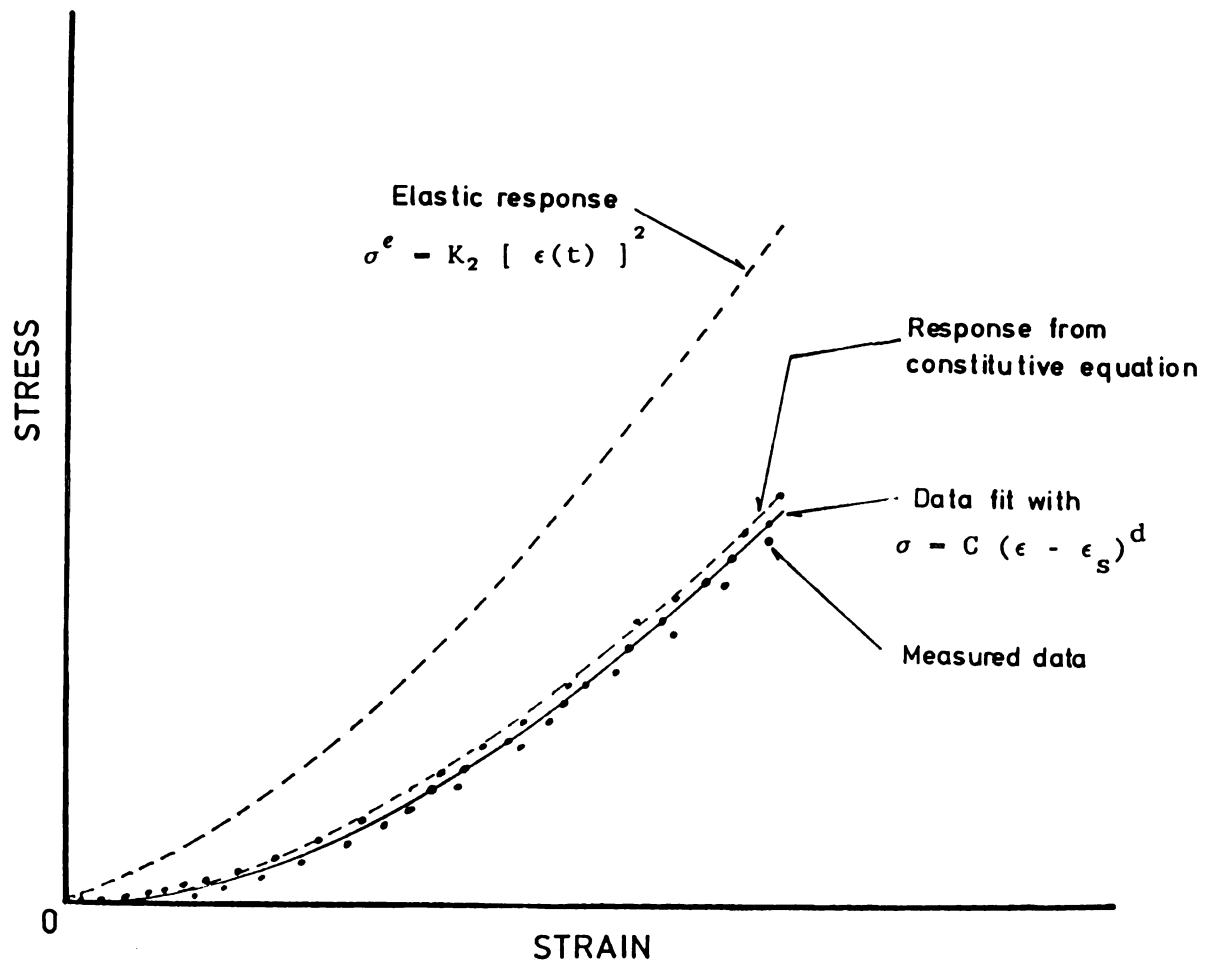


Fig. 5-2 Illustration of relationships between measured data, the regression fit (with  $C$  and  $d$ ), the elastic response (with  $K_2$  and  $m$ ), and response from the constitutive equation

Table 5-3

Comparison between Coefficients (C, d) of the Log-Log,  
Stress-Strain Fits from the Experimental Data and Coefficients  
(K<sub>2</sub>, m) of the Elastic Response at 3% Strain Level Test

| Test<br>No. | C (GPa) | d    | K <sub>2</sub> (GPa) | m |
|-------------|---------|------|----------------------|---|
| 33-1        | 11.66   | 1.68 | 47.40                | 2 |
| 33-2        | 27.30   | 1.94 | 44.41                | 2 |
| 33-3        | 24.20   | 2.17 | 17.41                | 2 |
| 33-4        | 26.58   | 2.26 | 14.40                | 2 |
| 33-5        | 11.51   | 1.83 | 27.67                | 2 |
| 33-6        | 13.52   | 2.03 | 16.22                | 2 |
| 30-1        | 7.42    | 1.67 | 31.14                | 2 |
| 30-2        | 47.01   | 2.15 | 35.75                | 2 |
| 30-3        | 14.69   | 1.97 | 21.57                | 2 |
| 30-4        | 13.48   | 1.87 | 28.62                | 2 |
| 30-5        | 4.10    | 2.00 | 5.34                 | 2 |
| 30-6        | 64.01   | 2.42 | 20.26                | 2 |
| 34-1        | 12.35   | 1.99 | 16.93                | 2 |
| 34-2        | 25.71   | 2.15 | 19.77                | 2 |
| 34-3        | 28.84   | 2.21 | 18.09                | 2 |
| 34-4        | 33.08   | 2.31 | 15.14                | 2 |
| 34-5        | 0.86    | 1.74 | 2.90                 | 2 |
| 34-6        | 26.66   | 2.48 | 6.69                 | 2 |
| Ave.        |         | 2.05 |                      | 2 |
| S.D.        |         | 0.24 |                      | 0 |
| 95% C.I.    |         | 0.12 |                      | 0 |
| Max.        | 64.01   |      | 47.40                |   |
| Median      | 19.44   |      | 18.93                |   |
| Min.        | 0.86    |      | 2.90                 |   |

# STRESS VS. STRAIN

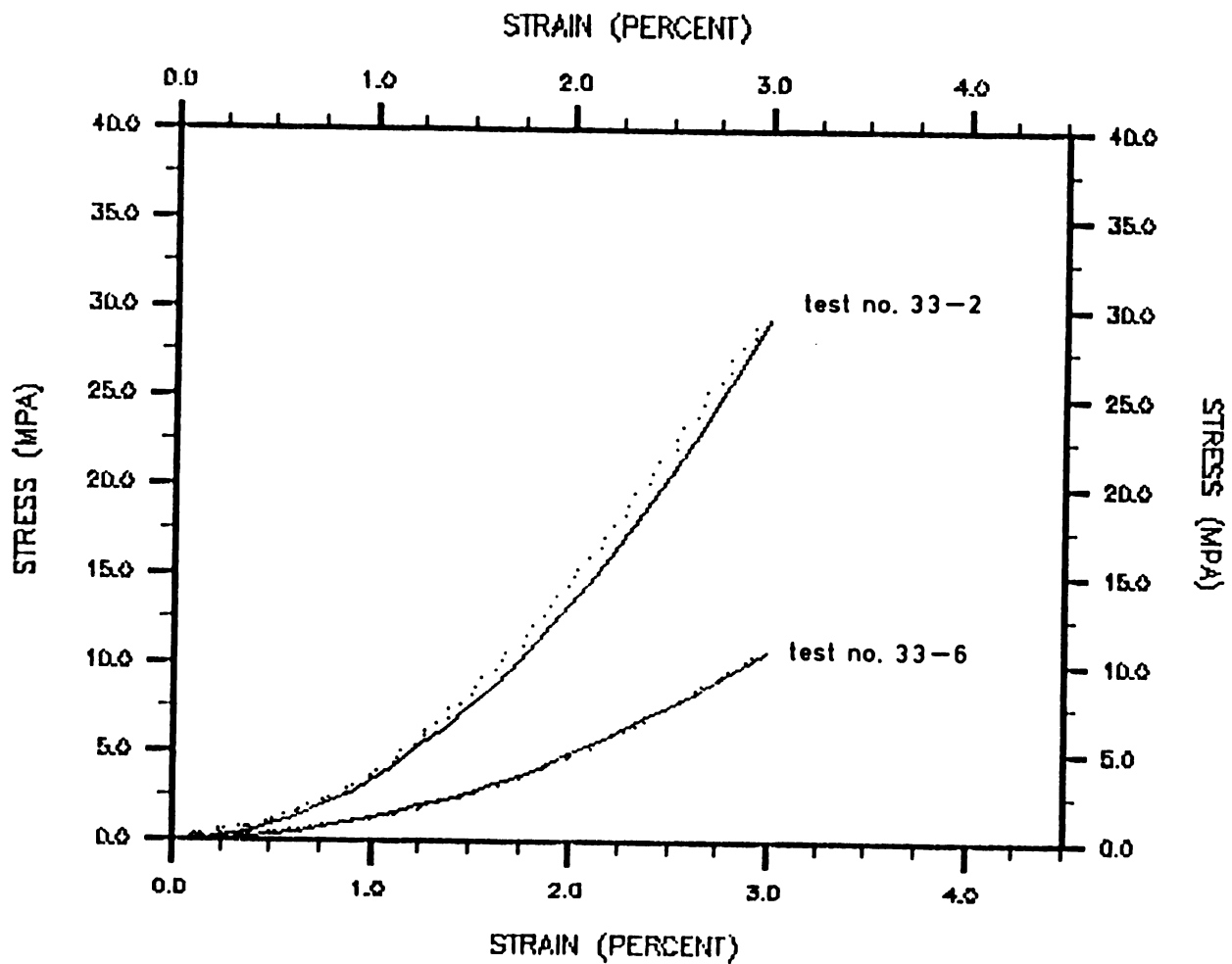


Fig. 5-3 Stress-strain plots for test no. 33-2 ( $K_2 = 44.41$  GPa) and test no. 33-6 ( $K_2 = 16.22$  GPa) with 5%/sec constant strain rate (\_\_\_\_\_ : Predicted data, ..... : Measured data)

## VI. COMPARISON BETWEEN PREDICTED AND MEASURED RESULTS IN MULTIPLE CYCLIC TESTS

### VI.1. Introduction

Knowledge of tendon responses gained from the measured results in Chapter III have influenced the modeling assumptions in Chapter IV. Values of the numerical quantities in the constitutive model have been selected to be representative of measured results. Variability of numerical values in the reduced relaxation function was small enough so that the average values from the 3% constant peak strain relaxation tests are useful in representing the relaxation response of all the tendon specimens. As also used in the previous chapter, these relaxation coefficients are:  $\alpha = 0.27$ ,  $\beta = 0.73$ ,  $\mu = 0.59$ , and  $q = 0.129$ . In the elastic response, a second order function of strain ( $m = 2$ ) was chosen to be representative of all results. Also, there was small variability in the values of the unloading slack strain in the first extension cycle of the multiple cyclic tests. Thus, the average value of this unloading slack strain (0.85%) was used in the calculation of the instant elastic recovery in the model. Because of large variability in values between specimens, the scale factor,  $K_2$ , of the elastic response must be chosen for each specimen; All of the other

numerical values used as input to the constitutive model represent the relaxation or elastic responses of all the tendon specimens.

In the comparison of results from the constitutive model with measured data in the multiple cyclic tests, predicted and measured results will be presented for selected specimens and then predicted results will be compared with measured results which have been statistically summarized.

#### VI.2. A-type Multiple Cyclic Test

Figure 6-1 shows the cyclic stress relaxation for test no. 33-6 (A-type test). Corresponding predicted and measured peak stresses are given in Table 6-1. The predicted results were obtained from equation (4-25) with a value of  $K_2 = 16.22$  GPa. The peak stresses from the model agree very well with the peak stresses from the measured data throughout the entire 300 cycles of test no. 33-6. Figures 6-2 through 6-6 show the stress-strain plots for test no. 33-6 (from the first cycle to 300th cycle). In these figures, the predicted slack strains and peak stresses agree very well with measured data but the predicted hysteresis loops deviate from the measured data.

Figures 6-7 through 6-11 show the stress-strain plots for test no. 33-2 (from the first cycle to 300th cycle) with a value of  $K_2 = 44.42$  GPa. In these figures, the agreement between the predicted

and measured results is better for the hysteresis loops than in the cases of test no. 33-6, but the predicted slack strains and peak stresses deviate from the measured data.

To summarize the measured peak stress values from multiple cyclic tests in Chapter III, it was necessary to normalize these values to the first peak with a value of 100. This normalization removed most of the variance in the measured peak stresses from specimen to specimen; For comparison with the measured results, the predicted results have also been normalized. The effects of different  $K_2$  values are removed by this normalization so that the predictions are the same for all specimens within a test type.

Normalized peak stress values from the model are presented in Table 6-2 with the averages and 95% confidence intervals for measured results from Table 3-7. The predicted values are nearly identical to the average measured values and close to or within the confidence interval throughout the entire 300 cycles.

This close agreement of predicted and measured normalized peak stress values is remarkable since these predictions are based on numerical input to the model, which is representative of all tendons tested. Such close agreement in the peak stress values has never before been attained for cyclic responses of this duration. There are some differences in slack strains and hysteresis which are apparent in Figures 6-2 through 6-11, yet the qualitative agreement

indicates that the modeling assumptions are basically sound for predicting response in this type of test.

### VI.3. B-type Multiple Cyclic Test

Figure 6-12 shows the measured and predicted cyclic stress relaxation for test no. 30-3 (B-type test). Corresponding results are given in Table 6-3. These predicted results were obtained with the parameter  $K_2 = 21.57$  GPa, and the other parameter values were the same as the parameter values for other modeling. As in the A-type test, the agreement in the initial 60 cycles is very good. The recovery in both predicted and measured results after each 72 second rest period at 144 and 288 sec are nearly the same. The predicted peak stresses (relaxation and recovery) from the model agree very well with the measured peak stresses throughout the entire 180 cycles.

Values of normalized peak stress from the model and corresponding average measured values with 95% confidence intervals from Table 3-8 are presented in Table 6-4 for the multiple cyclic test with rest periods (B-type). The agreement for the first 60 cycles is virtually perfect. After the first 72 sec rest period, the model predicts an increase of peak stress (recovery) which is slightly greater than measured average but within the confidence interval. By the end of the second cyclic block (at 120th cycle),

the predicted and measured values are nearly the same. This slightly higher predicted recovery followed by a return to measured responses is repeated in the third cyclic block from the 121st cycle to the 180th cycle.

As with the A-type test, the close agreement between measured and predicted responses is remarkable. The factors which allow the model to recover, including the retention of compressive stresses in the calculations, have led to realistic predictions of responses in multiple cyclic test with rest periods.

#### VI.4. C-type Multiple Cyclic Test

Figure 6-13 shows the measured and predicted cyclic stress relaxation for test no. 34-1 (C-type test). Corresponding results are given in Table 6-5. Predicted results were obtained with the parameter  $K_2 = 16.93$  GPa and the other parameter values were the same as the parameter values for the other modeling. In the first cyclic block at 3% peak strain (0 to 72 sec), the predicted peak stresses agree very well with the measured peak stresses as in the previous cases. When the peak strain increases from 3% to 4% at the beginning of the second cyclic block (61st cycle at 72 sec), both the predicted and measured peak stresses about double from the 60th cycle. At this point, the measured value is slightly above the predicted value. During the second cyclic block, both relax with

the measured value decreasing more rapidly to a value below the predicted value by the 105th cycle at 144 sec. With the return to 3% peak strain in the third cyclic block, both peak stress values decrease to about half their previous values with the measured value below the predicted value. Then the model predicts the increase (recovery) of measured peak stress. When the peak strain returns to 4%, the stresses about double again to nearly the same values as in the second cyclic block. They then relax until the end of that cyclic block. As the peak strain returns to 3%, the stresses drop by about half their previous values with the predicted values slightly greater than the measured values. In the final cyclic block, both predicted and measured stresses increase (recover) with the the predicted values increasing more.

The normalized peak stress values predicted from the model for C-type multiple cyclic test are presented in Table 6-6 with comparable measured results (averages and 95% confidence intervals) from Table 3-9. The pattern of response in this test type has been discussed above with reference to Figure 6-13. After the first cyclic block, the average values of measured peak stress is consistently above the predicted values in the cycles to a peak strain of 4% and below the predicted values in the cycles to a peak strain of 3%. Also, the predicted values are near the extremes or beyond the confidence intervals of the measured values. The confidence intervals for the C-type test are larger than the other types of tests.

Except for  $K_2$ , which does not affect the normalized results from the model, the numerical values of input to the model were representative of all the tendon responses for 3% peak strain. With such input, the model predicted peak stresses to be less than measured stresses in the cycles to 4% peak strain. Because the average measured stresses at 4% peak strain were greater than predicted, it is reasonable to expect that the tested specimens would relax more than predicted due to the higher stresses. This is apparent during the 4% cyclic blocks. In returning from 4% strain to 3% strain (where it has been shown that the model predicts responses very well), the average values of peak stress in tested specimens went from a value which was higher than predicted to a value that was lower than predicted. These deviations of prediction from measured response may be primarily due to the error in extrapolation of tendon characteristics from 3% to 4% strain.

The quantitative agreement between predicted and measured peak stresses in C-type test is not as exact as in the previous types tests (A and B-type). Yet, the model does predict the responses for the C-type test which are within or close to the 95% confidence intervals and the qualitative agreement is good.

## CYCLIC STRESS RELAXATION

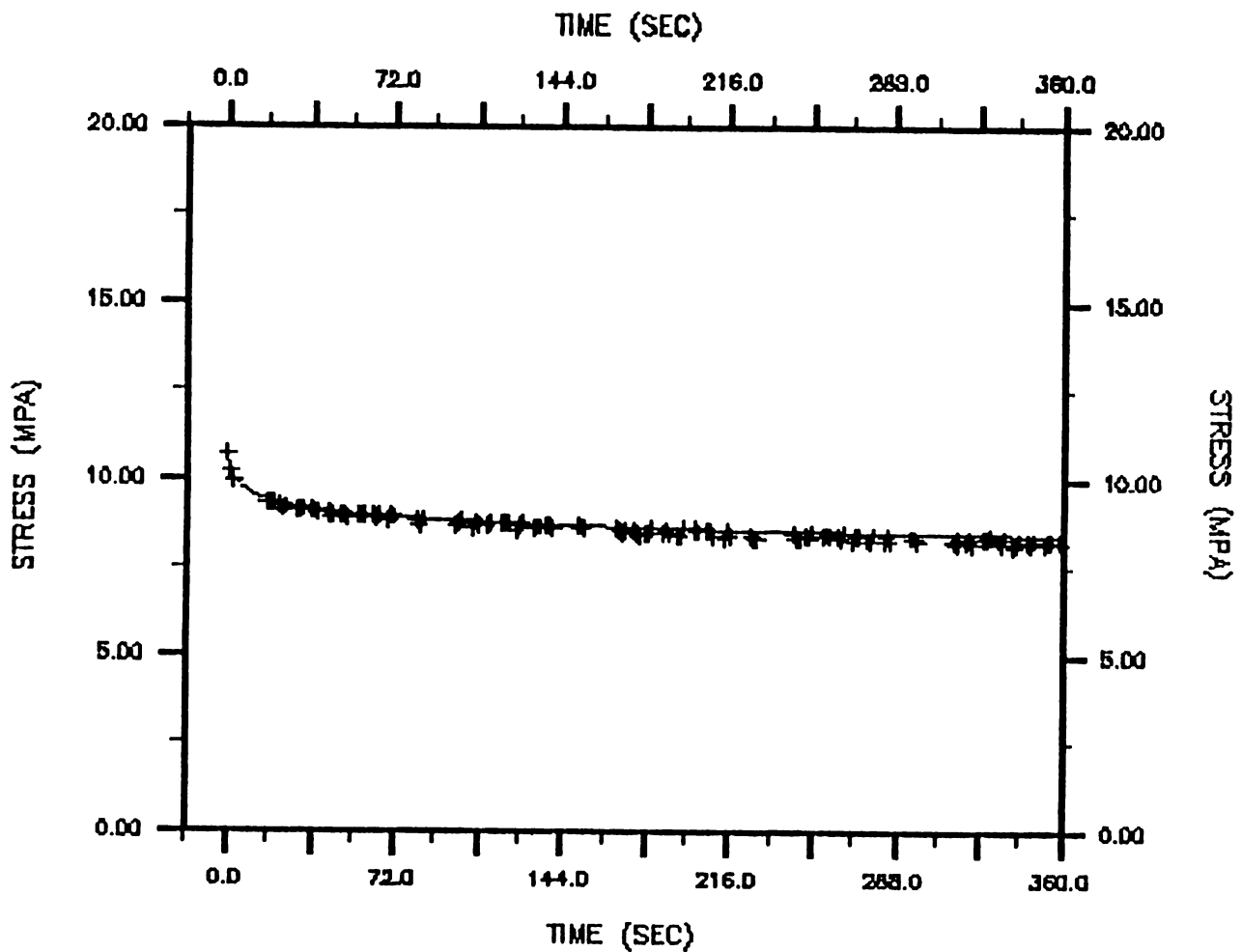


Fig. 6-1 Cyclic stress relaxation for test no. 33-6 (A-type test, see Fig. 2-1) with 5%/sec constant strain rate  
(---- : Predicted data, +++ : Measured data)

Table 6-1

Comparison of Cyclic Stress Relaxation (MPa) between Predicted and Measured Data (no. 33-6) at A-type Test (see Fig. 2-1)

| Cycle No.<br>Time    | 1     | 2     | 3     | 60<br>72s | 120<br>144s | 180<br>216s | 240<br>288s | 300<br>360s |
|----------------------|-------|-------|-------|-----------|-------------|-------------|-------------|-------------|
| Model                | 10.73 | 10.29 | 10.09 | 8.92      | 8.71        | 8.59        | 8.50        | 8.44        |
| Test<br>Data<br>33-6 | 10.73 | 10.22 | 9.96  | 8.94      | 8.68        | 8.56        | 8.42        | 8.37        |

Table 6-2

Comparison of Normalized Cyclic Stress Relaxation between Predicted and Average Measured Data at A-type Test

| Cycle No.<br>Time | 1            | 2           | 3           | 60<br>72s   | 120<br>144s | 180<br>216s | 240<br>288s | 300<br>360s |
|-------------------|--------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Model             | 100.0        | 95.9        | 94.0        | 83.1        | 81.2        | 80.1        | 79.2        | 78.7        |
| Ave.<br>95% C.I.  | 100.0<br>0.0 | 96.7<br>0.9 | 95.2<br>0.8 | 85.9<br>1.8 | 83.3<br>2.1 | 82.0<br>2.5 | 80.5<br>2.2 | 79.5<br>2.0 |

## STRESS VS. STRAIN

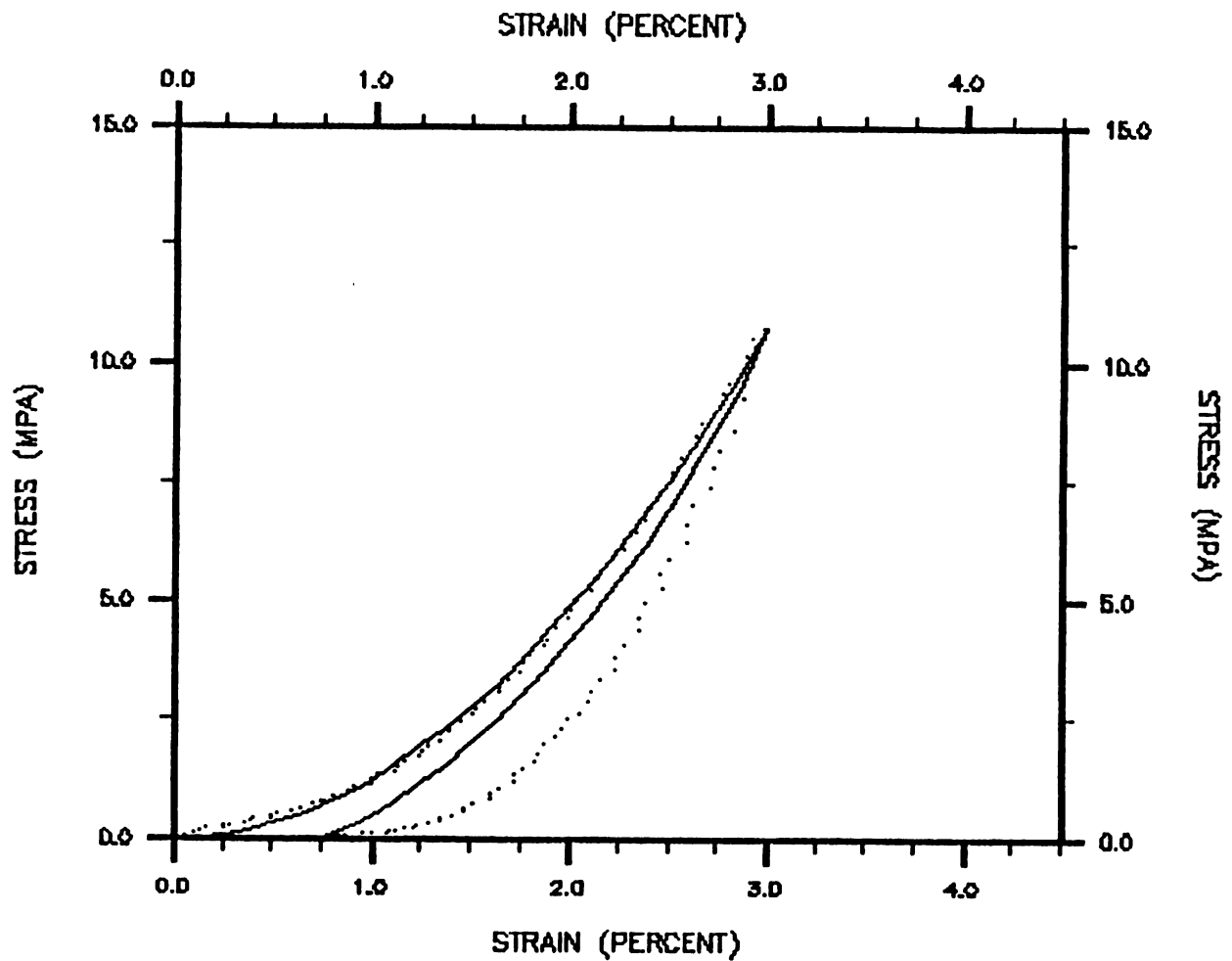


Fig. 6-2 Stress-strain plot for test no. 33-6 (1st cycle) with 5%/sec constant strain rate  
(\_\_\_\_\_ : Predicted data, ..... : Measured data)

## STRESS VS. STRAIN

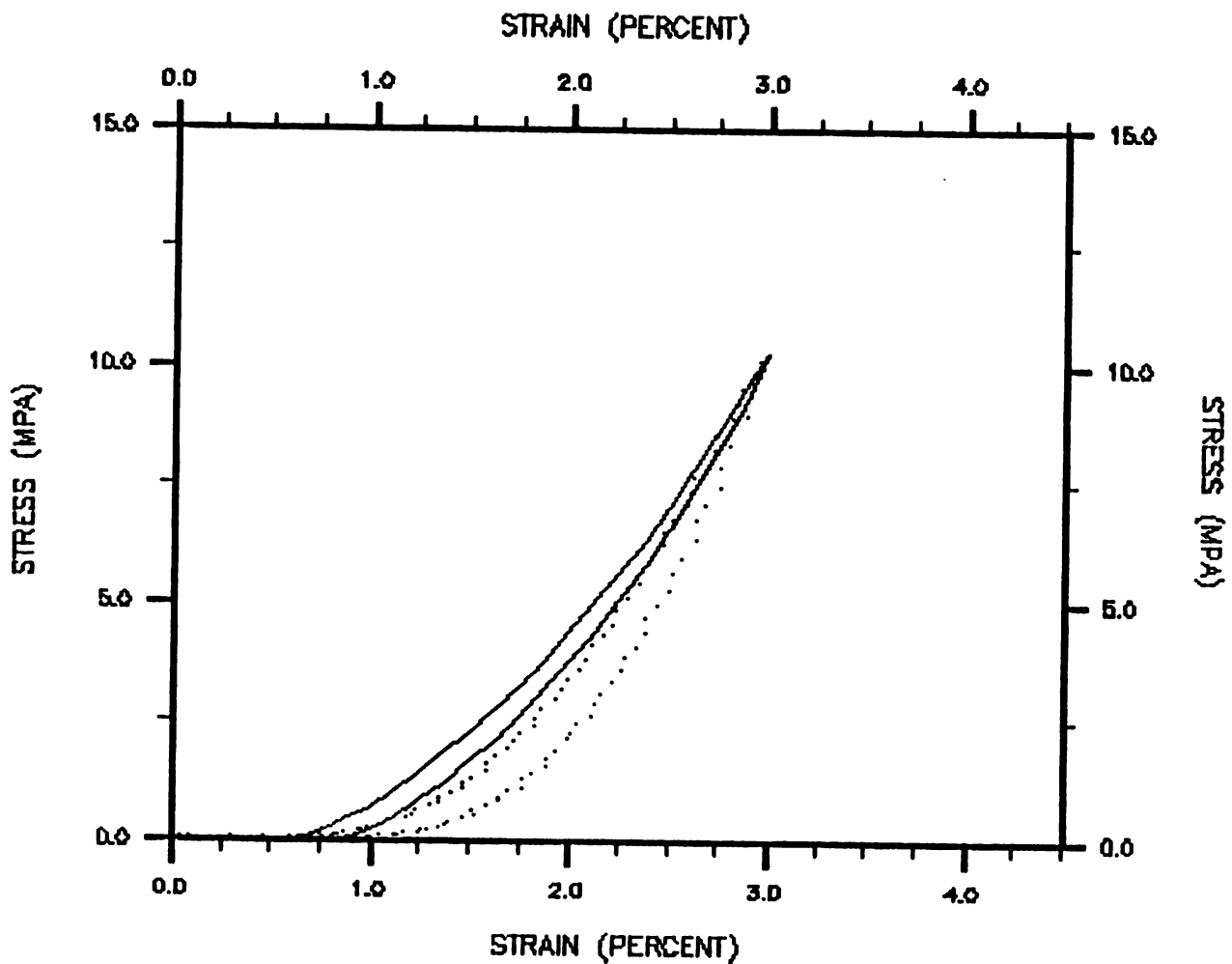


Fig. 6-3 Stress-strain plot for test no. 33-6 (2nd cycle) with 5%/sec constant strain rate  
(\_\_\_\_\_ : Predicted data, ..... : Measured data)

## STRESS VS. STRAIN

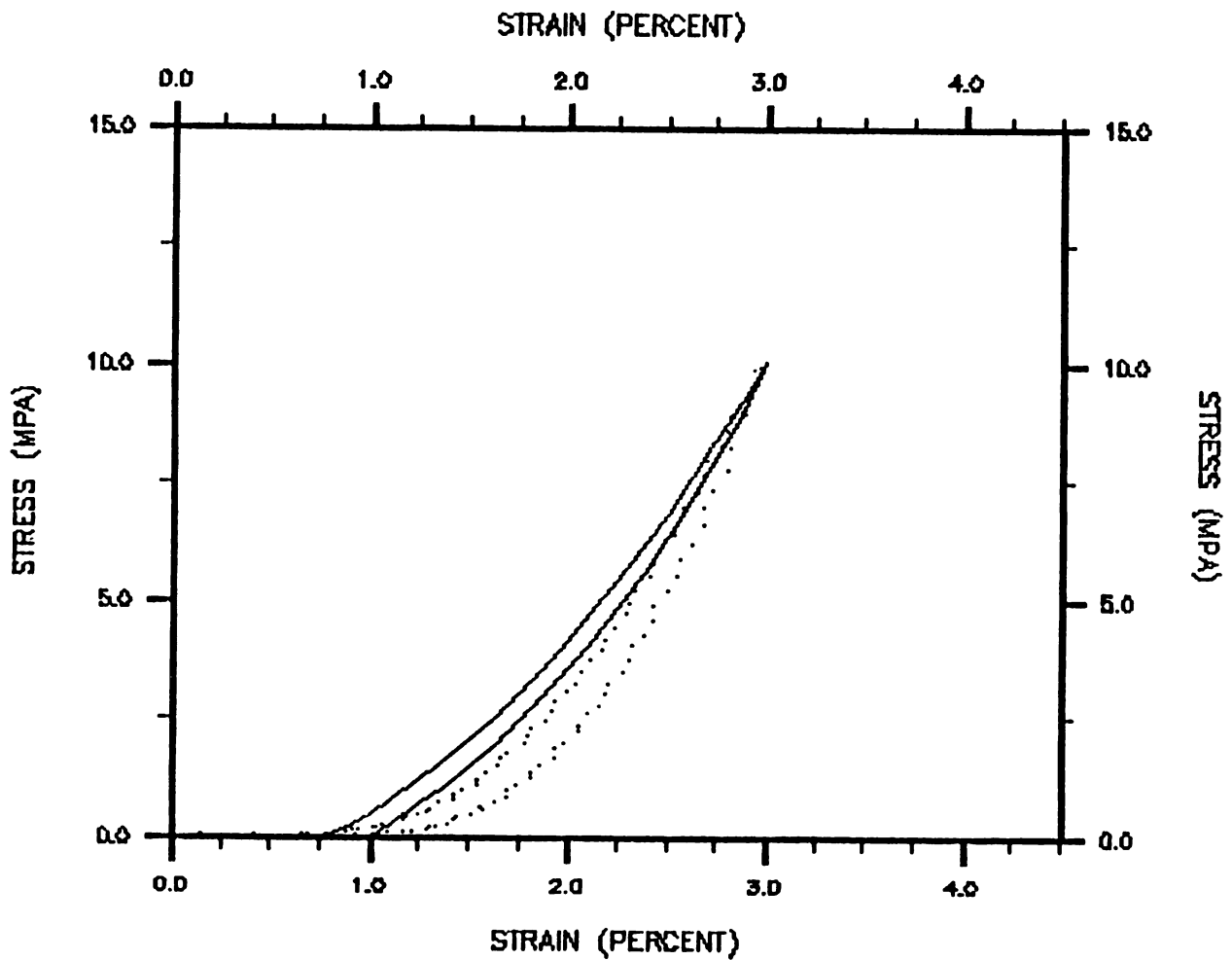


Fig. 6-4 Stress-strain plot for test no. 33-6 (3rd cycle) with 5%/sec constant strain rate  
(\_\_\_\_\_ : Predicted data, ..... : Measured data)

# STRESS VS. STRAIN

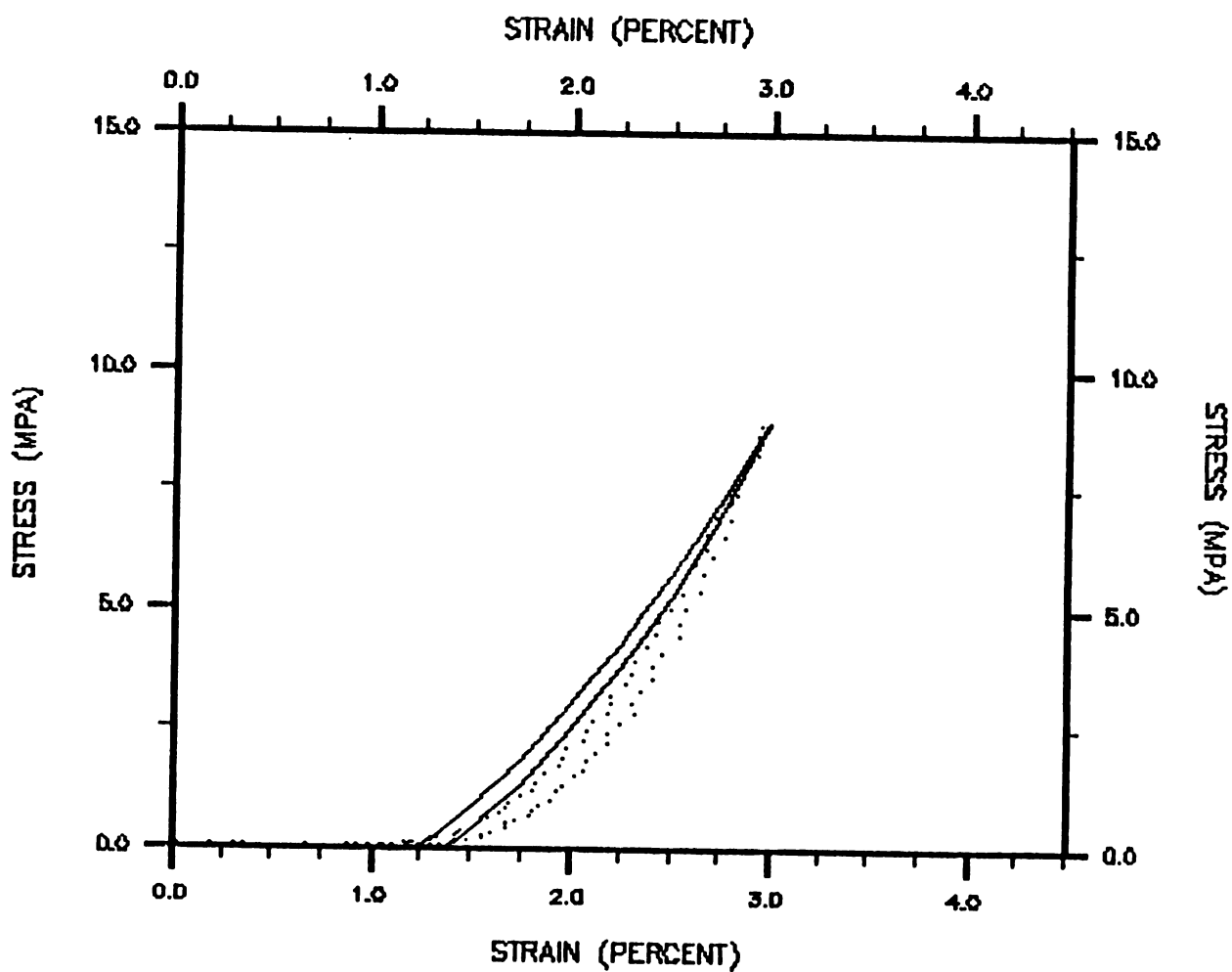


Fig. 6-5 Stress-strain plot for test no. 33-6 (60th cycle) with 5%/sec constant strain rate  
 ( — : Predicted data, .... : Measured data)

## STRESS VS. STRAIN

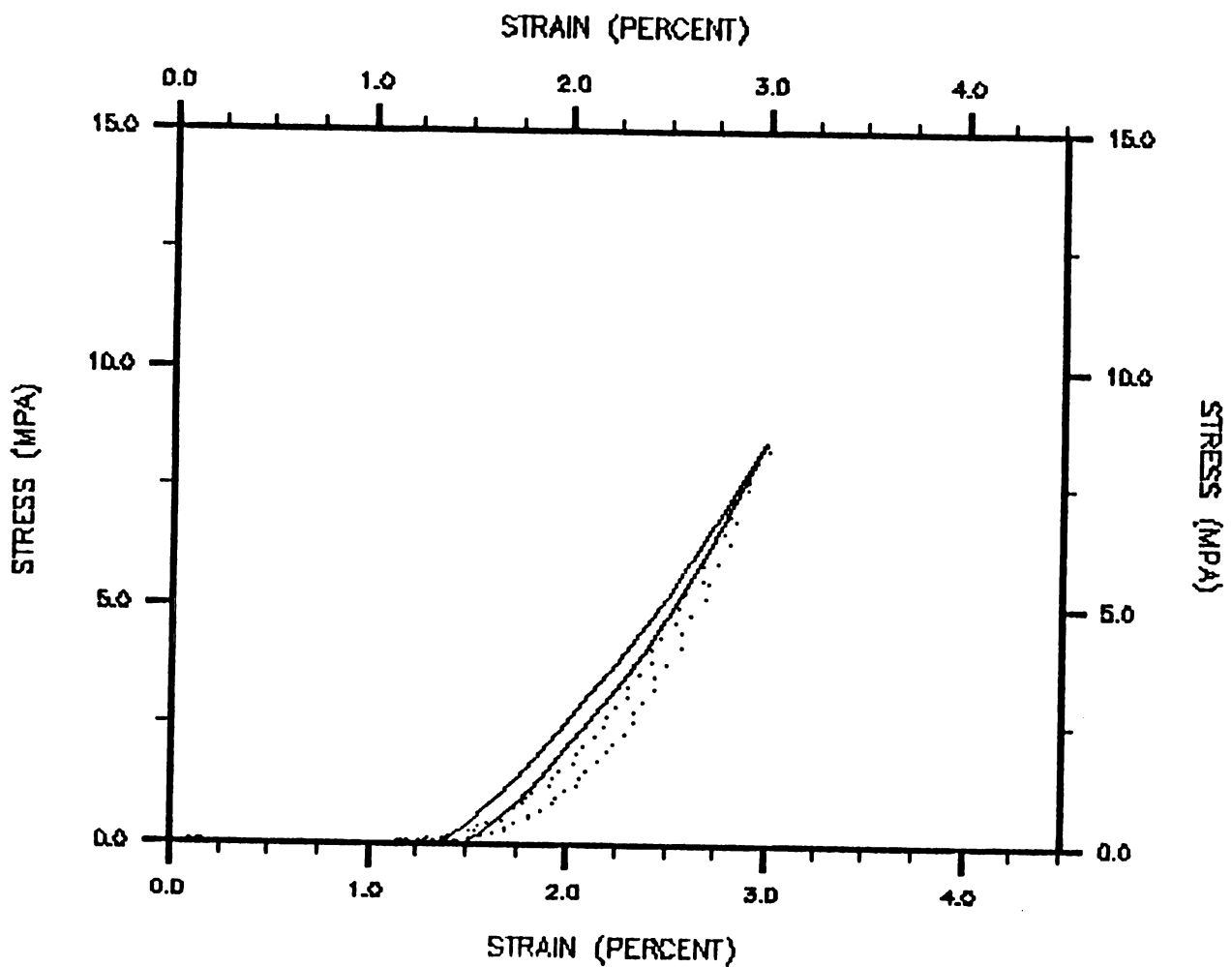


Fig. 6-6 Stress-strain plot for test no. 33-6 (300th cycle) with 5%/sec constant strain rate  
(\_\_\_\_\_ : Predicted data, ..... : Measured data)

## STRESS VS. STRAIN

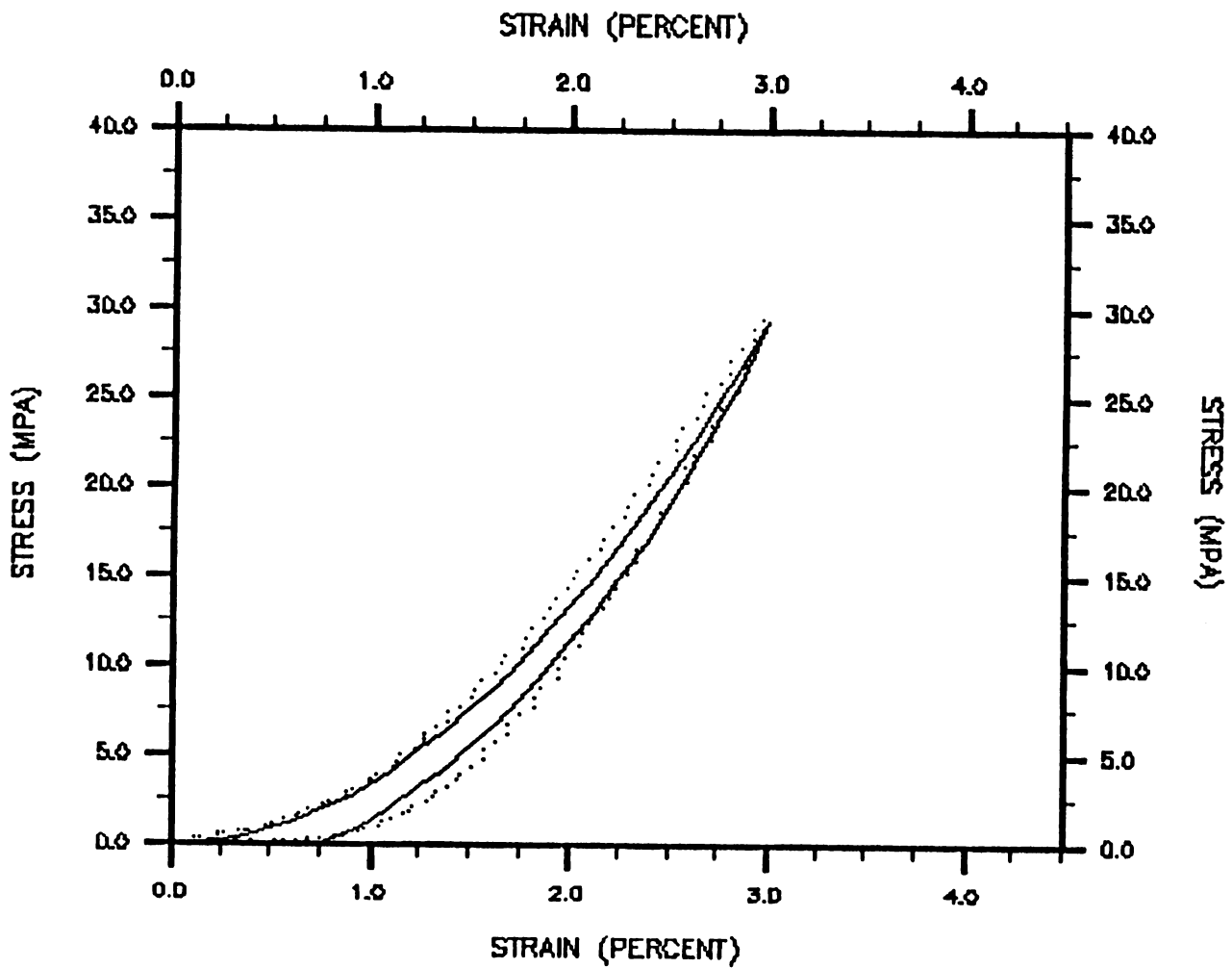


Fig. 6-7 Stress-strain plot for test no. 33-2 (1st cycle) with 5%/sec constant strain rate  
(\_\_\_\_\_ : Predicted data, ..... : Measured data)

# STRESS VS. STRAIN

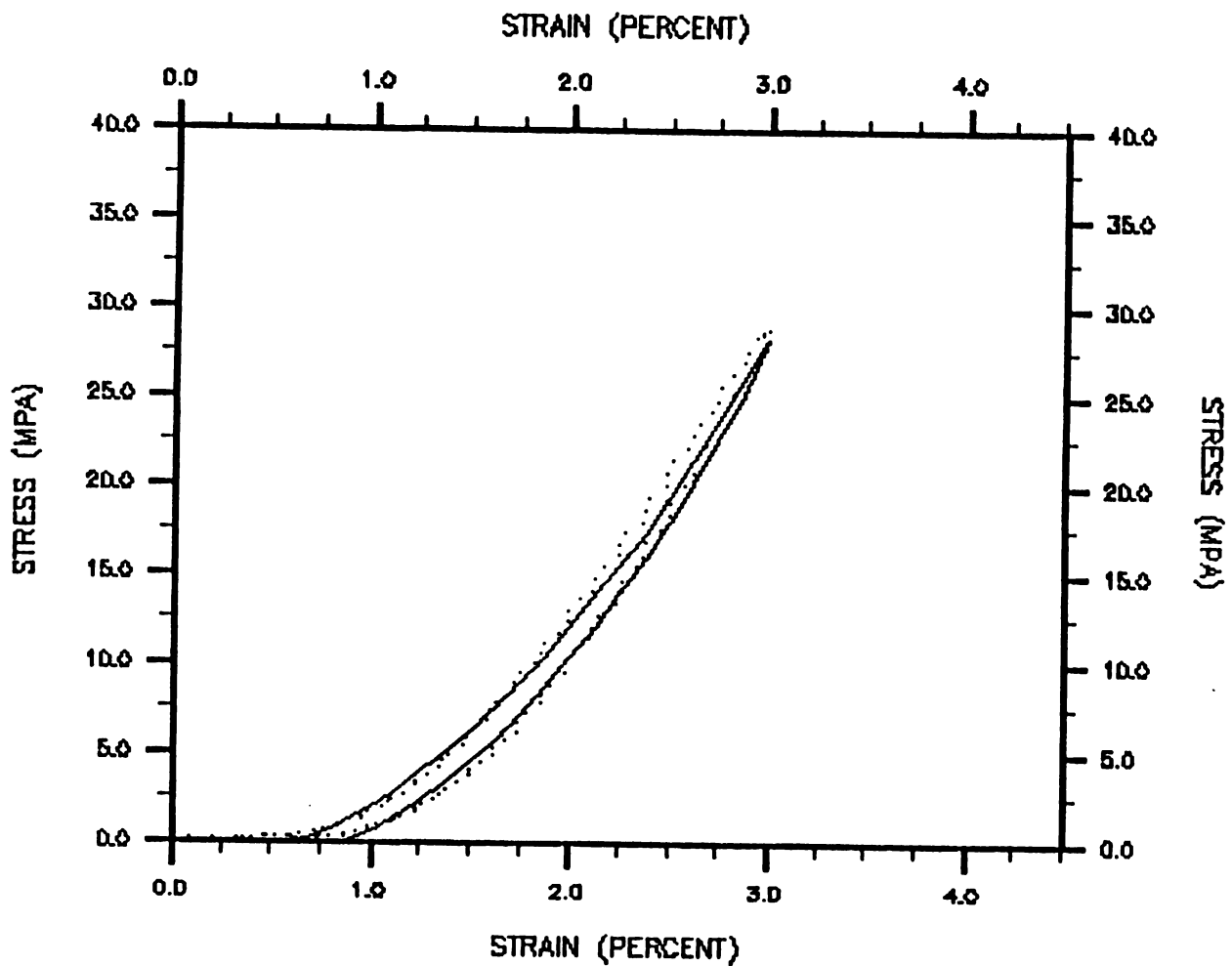


Fig. 6-8 Stress-strain plot for test no. 33-2 (2nd cycle) with 5%/sec constant strain rate  
(\_\_\_\_\_ : Predicted data, ..... : Measured data)

# STRESS VS. STRAIN

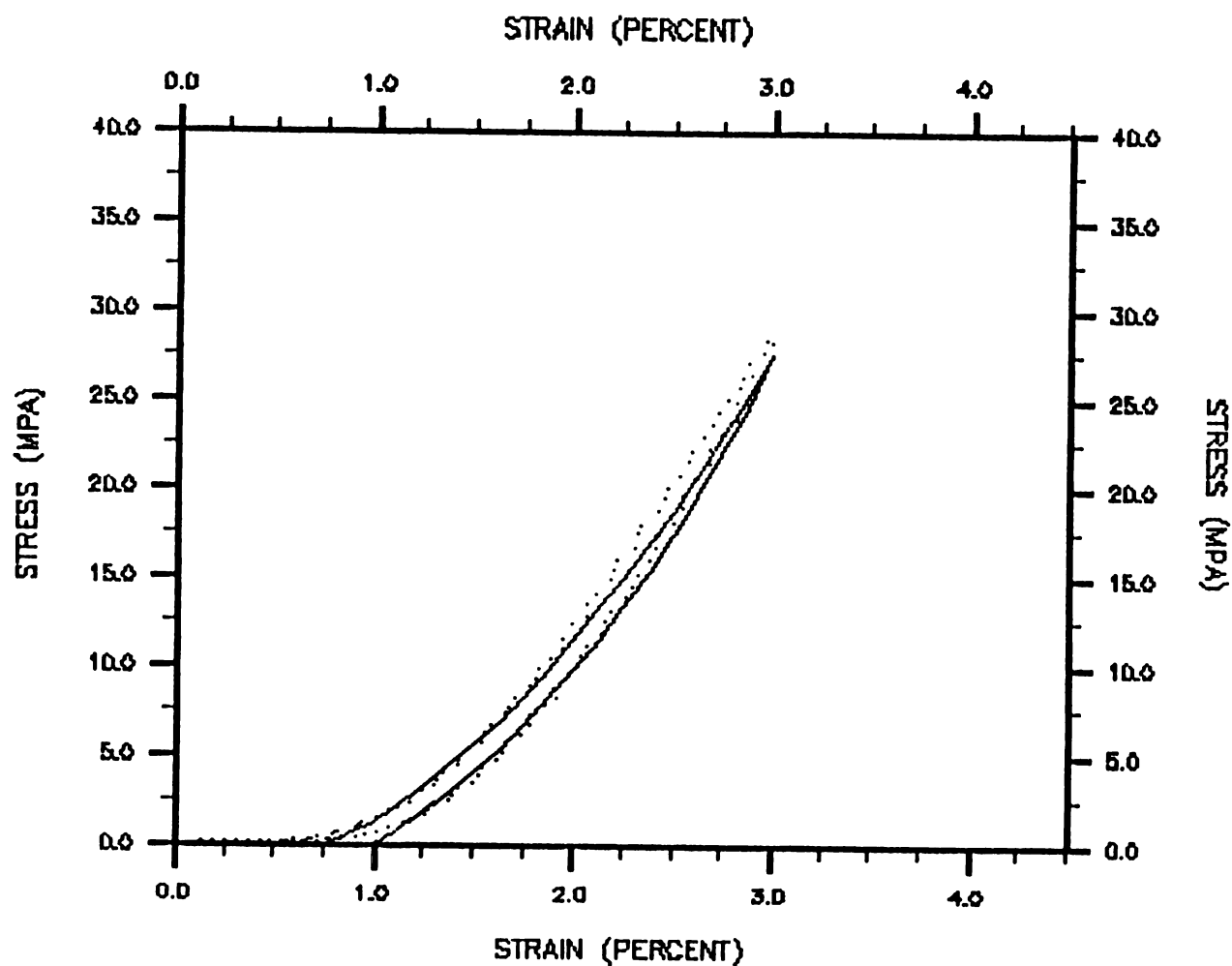


Fig. 6-9 Stress-strain plot for test no. 33-2 (3rd cycle) with 5%/sec constant strain rate  
 ( — : Predicted data, .... : Measured data)

# STRESS VS. STRAIN

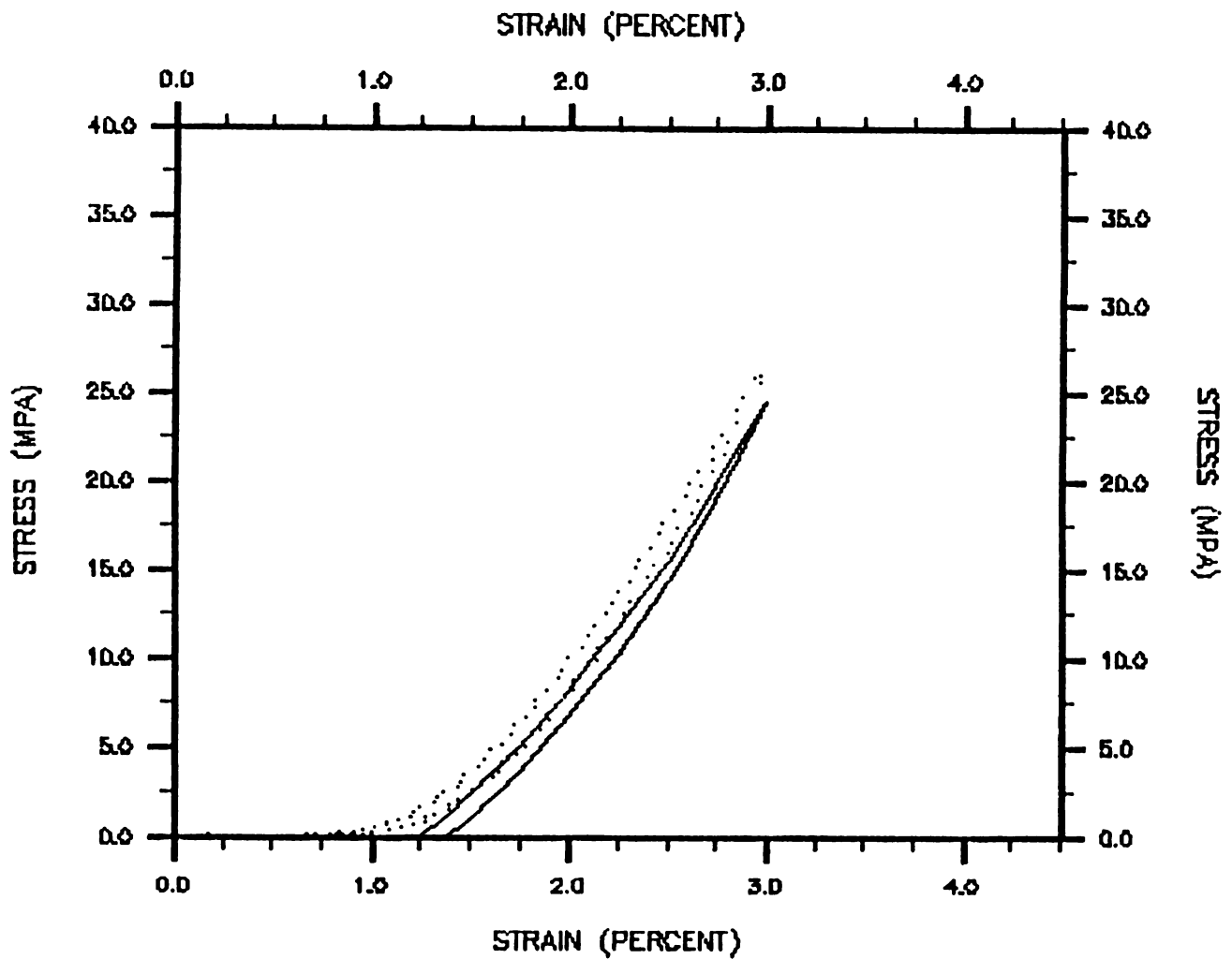


Fig. 6-10 Stress-strain plot for test no. 33-2 (60th cycle) with 5%/sec constant strain rate  
 (\_\_\_\_ : Predicted data, .... : Measured data)

# STRESS VS. STRAIN

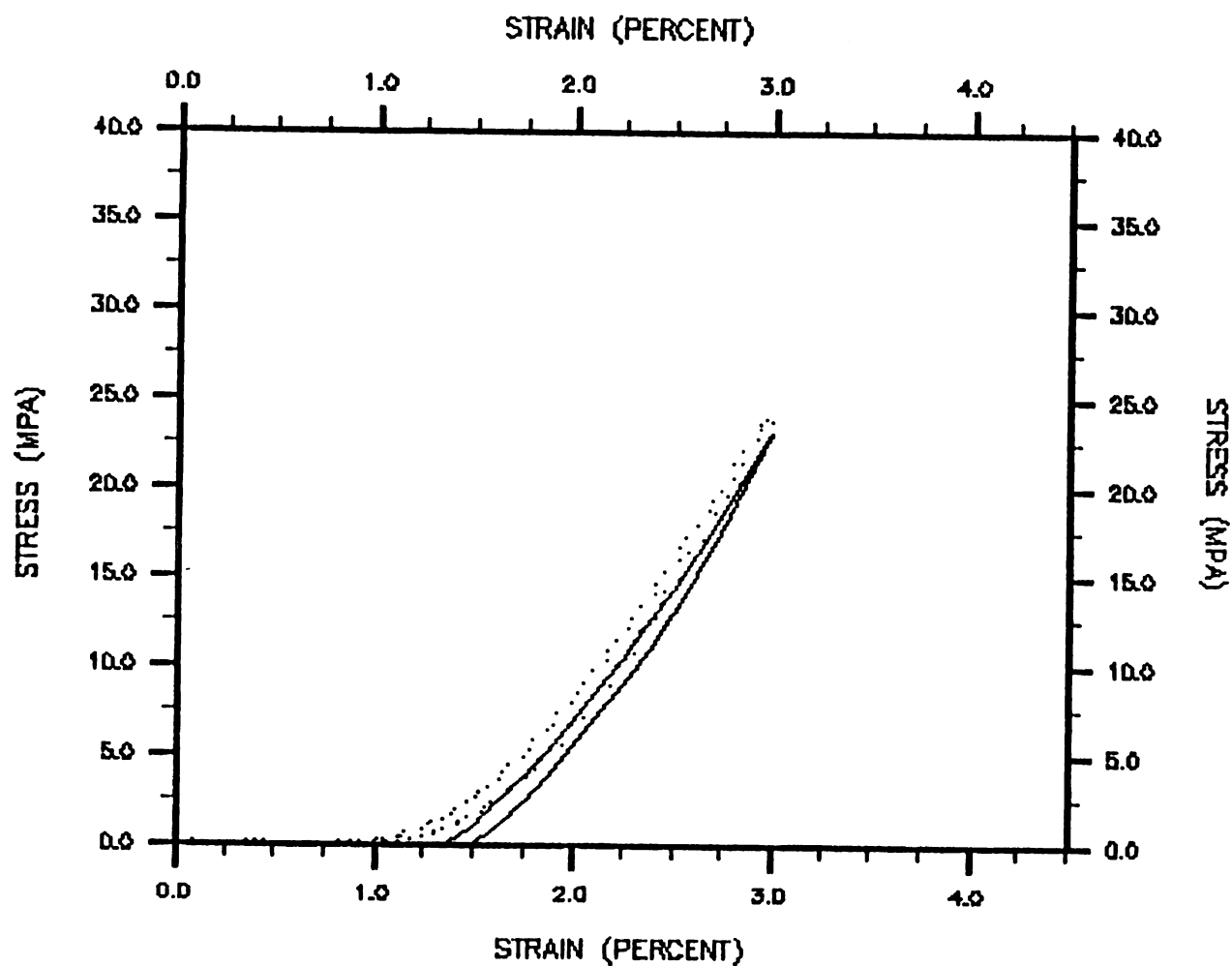


Fig. 6-11 Stress-strain plot for test no. 33-2 (300th cycle)  
 with 5%/sec constant strain rate  
 (\_\_\_\_\_ : Predicted data, ..... : Measured data)

# CYCLIC STRESS RELAXATION

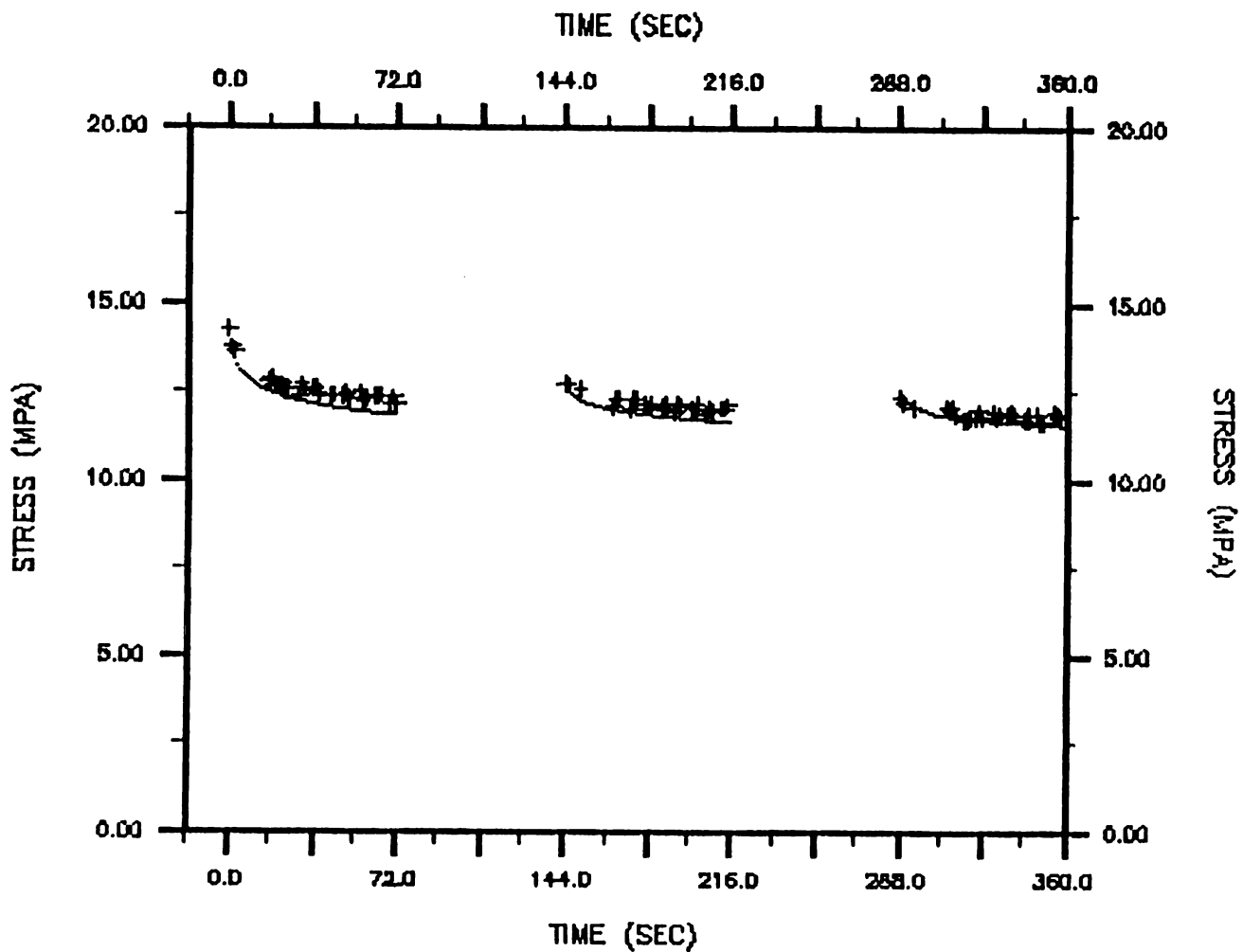


Fig. 6-12 Cyclic stress relaxation for test no. 30-3 (B-type test, see Fig. 2-1) with 5%/sec constant strain rate  
(.... : Predicted data, ++++ : Measured data)

Table 5-3

Comparison of Cyclic Stress Relaxation (MPa) between Predicted and Measured Data (no. 30-3) at B-type Test (see Fig. 2-1)

| Cycle No.<br>Time    | 1     | 2     | 3     | 60<br>72s | 61<br>144s | 120<br>216s | 121<br>288s | 180<br>360s |
|----------------------|-------|-------|-------|-----------|------------|-------------|-------------|-------------|
| Model                | 14.27 | 13.69 | 13.41 | 11.87     | 12.80      | 11.68       | 12.60       | 11.58       |
| Test<br>Data<br>30-3 | 14.27 | 13.74 | 13.62 | 12.15     | 12.74      | 12.15       | 12.37       | 11.82       |

Table 6-4

Comparison of Normalized Cyclic Stress Relaxation between Predicted and Average Measured Data at B-type Test

| Cycle No.<br>Time | 1     | 2    | 3    | 60<br>72s | 61<br>144s | 120<br>216s | 121<br>288s | 180<br>360s |
|-------------------|-------|------|------|-----------|------------|-------------|-------------|-------------|
| Model             | 100.0 | 95.9 | 94.0 | 83.2      | 89.7       | 81.9        | 88.3        | 81.1        |
| Ave.              | 100.0 | 96.2 | 94.2 | 83.2      | 86.1       | 80.9        | 83.4        | 79.0        |
| 95% C.I.          | 0.0   | 1.5  | 3.5  | 7.5       | 7.7        | 8.9         | 8.9         | 9.6         |

## CYCLIC STRESS RELAXATION

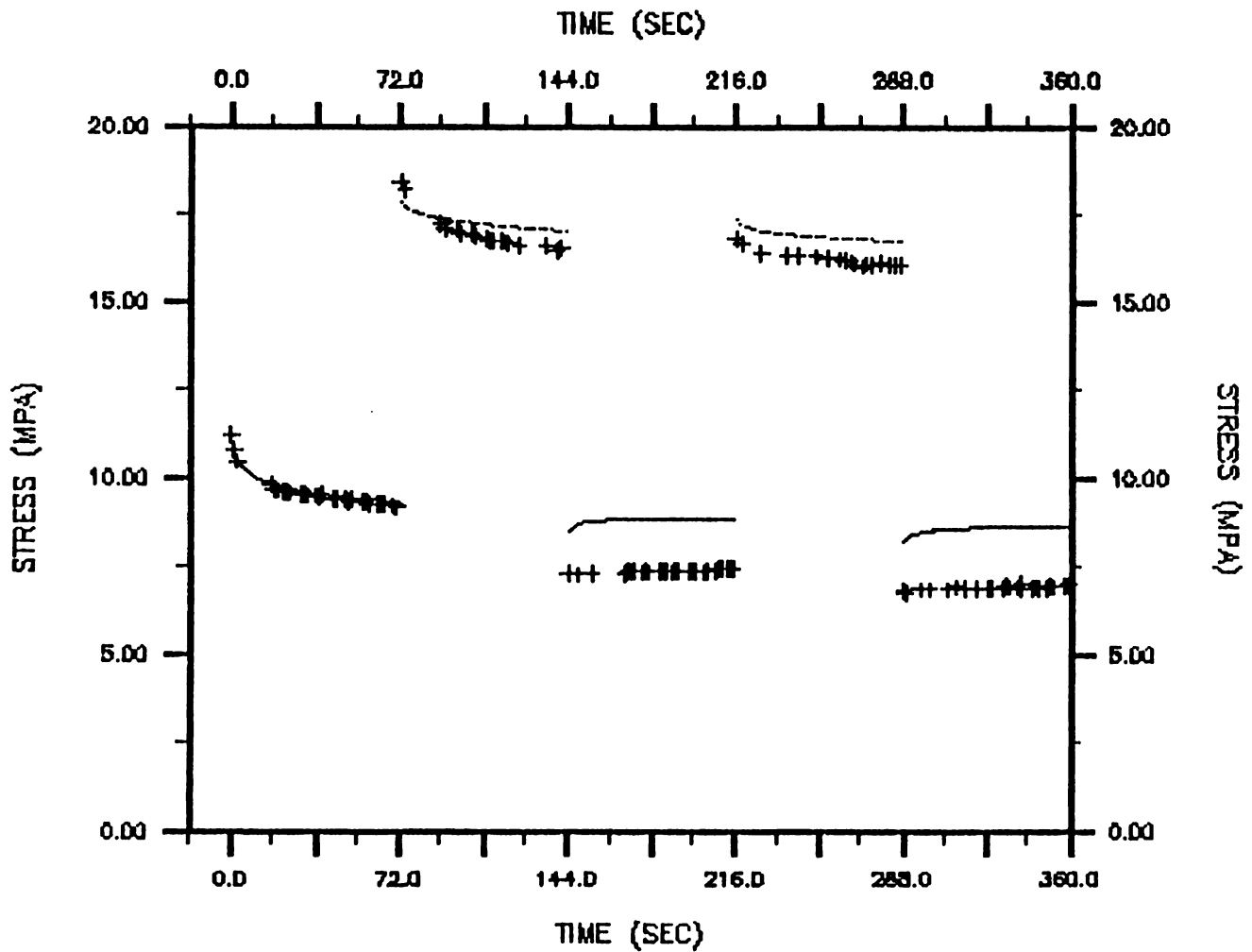


Fig. 6-13 Cyclic stress relaxation for test no. 34-1 (C-type test, see Fig. 2-1) with 5%/sec constant strain rate  
 (.... : Predicted data, +++ : Measured data)

Table 6-5

Comparison of Cyclic Stress Relaxation (MPa) between Predicted and Measured Data (no. 34-1) at C-type test (see Fig. 2-1)

|                |       |       |       |      |       |       |      |      |       |       |      |      |
|----------------|-------|-------|-------|------|-------|-------|------|------|-------|-------|------|------|
| Cyc No.        | 1     | 2     | 3     | 60   | 61    | 105   | 106  | 165  | 166   | 210   | 211  | 270  |
| Time           |       |       |       | 72s  |       | 144s  |      | 216s |       | 288s  |      | 360s |
| PKSL           | 3     | 3     | 3     | 3    | 4     | 4     | 3    | 3    | 4     | 4     | 3    | 3    |
| Model          | 11.20 | 10.75 | 10.53 | 9.32 | 17.85 | 17.04 | 8.47 | 8.84 | 17.38 | 16.76 | 8.19 | 8.64 |
| Test Data 34-1 | 11.20 | 10.76 | 10.47 | 9.15 | 18.41 | 16.56 | 7.30 | 7.43 | 16.83 | 16.05 | 6.82 | 7.01 |

Table 6-6

Comparison of Normalized Cyclic Relaxation between Predicted and Average Measured Data at C-type Test

|         |       |      |      |      |       |       |      |      |       |       |      |      |
|---------|-------|------|------|------|-------|-------|------|------|-------|-------|------|------|
| Cyc No. | 1     | 2    | 3    | 60   | 61    | 105   | 106  | 165  | 166   | 210   | 211  | 270  |
| Time    |       |      |      | 72s  |       | 144s  |      | 216s |       | 288s  |      | 360s |
| PKSL    | 3     | 3    | 3    | 3    | 4     | 4     | 3    | 3    | 4     | 4     | 3    | 3    |
| Model   | 100.0 | 95.9 | 94.0 | 83.2 | 159.4 | 152.1 | 75.6 | 78.9 | 155.2 | 149.6 | 73.1 | 77.1 |
| Ave.    | 100.0 | 94.5 | 91.7 | 77.3 | 189.1 | 162.2 | 54.8 | 56.8 | 166.0 | 156.4 | 50.0 | 51.9 |
| 95% CI  | 0.0   | 2.6  | 3.9  | 8.8  | 27.3  | 19.0  | 15.7 | 15.2 | 19.7  | 19.0  | 16.6 | 16.0 |

Cyc No.: Cycle Number

PKSL: Peak Strain Level (%)

## VII. CONCLUSIONS

The work reported here is a study to measure and model tendon responses to multiple cyclic tests including 3% constant peak strain level test (A-type test), 3% constant peak strain level test with two rest periods (B-type test), and 3-4% different peak strain level test (C-type test). The surface strains of tendons have been measured in the relaxation test by photographic analysis and during cyclic extensions with the Reticon camera.

In cyclic tests, there were decreases (relaxation) in peak stress and hysteresis, increases in slack strain, and reversals (recovery) of these changes during rest periods in the B-type tests and during lower maximum strain level (3%) cyclic block after higher maximum strain level (4%) cyclic block in the C-type tests. Considering the results of this study and those of the only other study of multiple cyclic tests with rest periods by Hubbard and Chun [23], recovery phenomena during the rest periods occurred predominantly at the beginning of the rest periods. Consistently in both studies, the effects of rest periods were small and transient compared to the effects of the cyclic extensions. The recovery with cycles at lower maximum strain level (3%) after higher maximum strain level (4%) in the C-type test has not been previously documented. This recovery seems to be a natural phenomena in tissue behavior so that collagenous structures recover during periods of decreased demand.

It was found that different sections of the same long tendons have different resistance to deformation. In general, the bone end section was stiffer than the muscle end, and the mid-portion was the least stiff (Figures 3-21 through 26). Also, it was found that anatomically paired tendons were more similar in mechanical responses than tendons from different anatomical sites. Although flexor tendons tested had much larger cross-sectional areas than the others such as peroneus or extensor tendons, the stiffnesses of the flexor tendons was much smaller than the others throughout their stress-strain responses. The differences in the stiffnesses within and between tendons have also been found by others [4,48] who have related the differences to tissue composition and morphology. The nature of these differences in the stiffness and their causes are not fully known. However, it is clear that differences in the stiffness of tendons and other connective tissues are significant to musculoskeletal performance.

In the study of surface deformations, the local surface strains near the gripped ends were greater than the local surface strains in the middle segment for both the relaxation tests (Figure 3-30) and cyclic tests (Figures 3-32 through 38). The recovery for peak load during rest periods was consistent but the changes in patterns of surface strains during recovery were not consistent (Figures 3-40 through 45, and Table 3-33). The responses observed in this study could have been affected by the gripping and deformation measurement methods. However, the responses are

generally consistent within and between groups of specimens tested in different types of cyclic tests and different strain levels.

In the constitutive modeling, the heredity integral form of a quasi-linear viscoelastic law has been used with three new features. First, a non-linear exponential reduced relaxation function was developed and employed for the time dependent part. Second, a new concept of elastic response with instant elastic recovery effect during unloading was developed and employed for the strain dependent part. Third, compressive stresses were permitted in theoretical calculations, which contributed to the capability of the model to predict the measured responses.

For the constitutive modeling, there are four coefficients ( $\alpha$ ,  $\beta$ ,  $\mu$ , and  $q$ ) in the reduced relaxation function ( $G(t) = \alpha + \beta e^{-\mu t^q}$ ) and three coefficients ( $K_2$ ,  $m$ , and  $\epsilon_e$ ) in the elastic response ( $\sigma_e = K_2[\epsilon + \epsilon_e]^m$ ), which were evaluated with experimental data. The values of the coefficients in the reduced relaxation function were the average values from regression fits to data from long-term relaxation tests (22 hours) with a constant strain of 3%. The value of 2 for  $m$  in the elastic response was selected as representative of the constant strain rate extension data to peak strains of 3% and 4%, and this value was consistent with other studies [22,28]. The value of  $\epsilon_e$  was based on the difference between average loading and unloading slack strain at the first cycle measured in 3% peak strain level tests. Unlike all the other coefficients whose values were

selected as average or representative values for all tendon specimens,  $K_2$  varied greatly between specimens and, therefore, was determined for each specimen. For anatomically paired tendons from the same animal, the differences in values of  $K_2$  were less than such differences between all specimens. Two methods for determining  $K_2$  were developed based either on constant strain rate extension data or relaxation data.

The comparisons between predicted results and measured data have been made for examples and averaged results from all types of tests including constant strain rate test and 3-different types (A, B, C) of multiple cyclic tests. The values of  $K_2$  were determined from the measured peak stress of the first extension and agreement between measured data and the calculated results from the constitutive model was very close. Thus, the coincidence of the measured and calculated peak stress in the first extension is to be expected, but the close agreement throughout the entire curve up to the peak stress does support the predictive capability of the constitutive model.

In the constant strain rate multiple cyclic test for the 3% maximum strain level test (A-type test), the predicted values of the peak stress agreed well with measured data (Figure 6-1). However, for the hysteresis loops, the agreement between predicted and measured data was not consistent (Figures 6-2 through 11). In general, the predicted hysteresis loops continued to deviate from measured data with successive cycles.

For the 3% constant maximum strain level test with two rest periods (B-type test), the model predicted recovery after each rest period and the predicted peak stresses agreed well with the measured data (Figure 6-12).

For the 3-4% different maximum strain level test (C-type test), the predicted peak stresses agreed well with the measured data in the first cyclic block at 3% peak strain level. The predicted results deviated slightly from the measured data from the second cyclic block at 4% peak strain level (Figure 6-13). Although there were some quantitative differences between the predicted and measured results after the second cyclic block, these differences are generally within the 95% confidence intervals. There were predicted and measured recoveries in the lower strain level (3%) cyclic block after the higher strain level (4%) cyclic block.

This study has shown that tendons relax and become less resistant to deformation with repeated extensions as seen in increases in slack strains and decreases in peak stresses. Also, during periods of rest or reduced strain, the tissues recover some of their previous resistance to extension as indicated by decreases in slack strain and increase in peak stress. The relaxation and recovery of connective tissue resistance are significant to musculoskeletal performance. Decreases in resistance of tissues to deformation are evident as tissues are repeatedly stretched in activities of daily living, athletic performance, and manipulative therapy. Such changes in tissue resistance are commonly transient and reversible during inactive periods.

It is a major step from studies of isolated tissues to a complete understanding of musculoskeletal performance. However, the results of the present study contribute to that understanding. Recovery phenomena in tendon responses indicate that decreases in resistance to extension are at least partially reversible. The extent and nature of this reversion was not fully evaluated in this study and remains for future work.

In the present study, substantial progress has been made in measuring and modeling viscoelastic responses of tendons. Although it was not determined whether the tendon specimens would completely recover from changes in their responses, the present model will predict complete recovery. The good agreement between measured and predicted responses implies that changes in tendons responses measured in this study might be reversible. At strain levels above the maximum of 4% used in this study, irreversible changes will occur. In metals, the onset and extent of irreversible, permanent, or plastic responses are studied as a deviation from elastic responses. Similarly, an understanding of reversible and viscoelastic responses of tissue is the necessary basis for determining the onset and character of irreversible and plastic changes in tissue responses. Thus, the methods and results of this study will be useful in future studies of reversibility and irreversibility of changes in tissue responses.



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Appendix 1

Ringer's Lactate Solution

For a 18.927 liter (5 gallon) container

1. NaCl: 170.325 g.
2. KCl: 7.949 g.
3.  $\text{CaCl}_2$  (dehydrate): 4.731 g.
4. 60% Sodium Lactate: 58.668 ml.

Appendix 2

Histology Method

(a) Fixation

Tissues were fixed during a minimum of 3 days into a 2% Gluteraldehyde on 0.2 M phosphate buffer.

(b) Cleaning, infiltration and embedding

Tissues were processed through a graded series of alcohols to toluene followed by paraplast plus. This was done overnight on an autotechnican.

Tissues were embedding in paraplast plus (mp 56°C) embedding medium (Lancer).

(c) Cutting

Blocks were cut at 7 $\mu$  on rotary microtome and sections mounted on slides. These were allowed to dry overnight at 37° before staining.

(d) Staining

Sections were stained with Hematoxylin-Eosin following standard procedures. Harris Hematoxylin and Lipp's German Eosin were used although any standard H & E solutions will give good results.

## Appendix 3

Summary of Surface Deformation (mm) from Photographic  
Results in Relaxation Test

| Test<br>no. | SEG.1 |       |      | SEG.2 |       |      | SEG.3 |       |      | TENDON |        |      | S.F. |
|-------------|-------|-------|------|-------|-------|------|-------|-------|------|--------|--------|------|------|
|             | Lo    | Lf    | Strk | Lo    | Lf    | Strk | Lo    | Lf    | Strk | Lo     | Lf     | Strk |      |
| 3-1         | 65.50 | 67.62 | 2.12 | 56.12 | 57.83 | 1.71 | 74.21 | 75.92 | 1.71 | 195.83 | 201.37 | 5.54 | 5.72 |
| 3-2         | 65.99 | 68.74 | 2.65 | 57.81 | 59.01 | 1.20 | 66.45 | 68.20 | 1.75 | 190.25 | 195.85 | 5.60 | 5.71 |
| 3-3         | 64.12 | 66.63 | 2.51 | 54.92 | 55.42 | 0.50 | 70.79 | 73.11 | 2.32 | 189.83 | 195.16 | 5.33 | 5.74 |
| 3-4         | 77.20 | 79.52 | 2.32 | 54.38 | 54.75 | 0.37 | 52.98 | 56.13 | 3.15 | 184.56 | 190.40 | 5.84 | 5.69 |
| 3-5         | 60.04 | 63.51 | 3.47 | 54.56 | 54.89 | 0.33 | 67.55 | 69.31 | 1.76 | 182.15 | 187.71 | 5.56 | 5.69 |
| 3-6         | 69.42 | 72.12 | 2.70 | 56.07 | 56.66 | 0.59 | 62.50 | 64.81 | 2.31 | 187.99 | 193.59 | 5.60 | 5.72 |
| 4-1         | 76.80 | 79.39 | 2.59 | 53.75 | 55.86 | 2.11 | 60.80 | 63.45 | 2.65 | 191.35 | 198.70 | 7.35 | 5.73 |
| 4-2         | 61.71 | 64.70 | 2.99 | 59.37 | 60.40 | 1.03 | 69.36 | 72.71 | 3.35 | 190.44 | 197.81 | 7.37 | 5.70 |
| 4-3         | 78.33 | 81.82 | 3.49 | 53.52 | 55.01 | 1.49 | 67.41 | 70.05 | 2.64 | 199.26 | 206.88 | 7.62 | 5.69 |
| 4-4         | 63.02 | 65.17 | 2.15 | 56.69 | 58.09 | 1.40 | 69.96 | 74.25 | 4.29 | 189.67 | 197.51 | 7.84 | 5.69 |
| 4-5         | 61.84 | 64.79 | 2.95 | 55.22 | 57.06 | 1.84 | 70.77 | 73.92 | 3.15 | 187.83 | 195.77 | 7.94 | 5.68 |
| 4-6         | 69.05 | 72.55 | 3.50 | 55.21 | 56.25 | 1.04 | 61.91 | 64.80 | 2.89 | 186.17 | 193.60 | 7.43 | 5.68 |

Lo - Initial Length

Lf - Final Length

Strk = Lf - Lo

S.F.: Scale Factor =  $\frac{\text{Lo of the photographic measurement}}{\text{Lo of the tendon}}$

#### Appendix 4

##### Data Acquisition and Storage

TEN360 (see Appendix 5) was the main program which runs the multiple cyclic tests on tendon. It contained many Instron driver calls which were non-Fortran. TEN360 ran the Instron automatically and asked for the data file names and other data needed to run the test. TEN360 was constructed to run a test for a total of 360 seconds in five-72 seconds sections. Sections 1, 3, and 5 were run at the first strain level asked for in the program; Sections 2 and 4, at the second strain level. The first strain level must be non-zero and both strain levels had no theoretical upper limit. For a 0% second strain level, the program caused the Instron to pause.

The test data were taken in two ways: (1) Nicolet, (2) Machine interface unit (MIU). For the Nicolet [38], the scope was set to trigger manually in the "NORM" mode and the track segment was set in the "ALL". This allowed one track of data to be stored for each test. And, the  $5\frac{1}{4}$  in. floppy disk could store eight tests data, one per track. This storage by the Nicolet allowed a more complete figure and data for the initial responses of the tendon. This stored data was transferred to the PDP-11/23 computer and translated to a usable file by using Nicolet software library which was designed to implement communication between a PDP-11 computer and a

Nicolet digital oscilloscope. Through the MIU, TEN360 took an array of 500 points at 8 ms/pt at the beginning of each section and at the end of test. TEN360 took an array of 250 points at 8 ms/pt at the end of the section except the B-type test (see Figure 2-1). In the B-type test, all data collection was an array of 500 points.

Each data group array was common to the subroutine SUB360 (see Appendix 6). TEN360 created the Rawfile, while SUB360 created the Sumfile. The Rawfile was a data file which contained the first data group, and the second data group in each 72 seconds section.

The Rawfiles stored the data as: tag, stroke, load, time. The MULPLT tag was Rn, where n began at 0 for the first data group, and ended at 9 for the very last data group of a test with non-zero strain levels, and at 5 for a test with a 0% strain level. This MULPLT tag was used for plotting the data with MULPLT [37]. The Sumfiles stored the data as: tag, time, load, stroke, energy up, energy down for the peak time. This had always the same MULPLT tag throughout the test. The Rawfile and Sumfile for each test were stored in a 8 in. floppy disk.

## Appendix 5

## PROGRAM TEN360

```

C
C*****
C      *****                NEW TENDON TEST                *****
C*****
C
C
C*****
C      ***** TO TASK BUILD USE F4POTS.OLB,                *****
C      ***** HAVE FILE 360COM.FTN AVAILABLE                *****
C      ***** SUB360, AND THE TASK BUILD OPTION                *****
C      ***** UNITS=10 AND ASQ=TTO:10                        *****
C*****
C
C
C      INCLUDE '360COM.FTN'
C*****
C      **** NON-FORTRAN OR INSTRON MACHINE DRIVER ****
C      **** SUBROUTINES CALLED FROM MAIN PROGRAM ****
C*****
C
C      EXTERNAL SUB360
C
C*****
C      ****                DECLARATION STATEMENTS                ****
C*****
C
C      DATA STROKE/4/,LUN/1/,FORMAT/4/,NO/"20116/,ADCOR/"2030/
C      DATA YES/'Y'/,STOP/8192/,NUMDAT/4/,FIFO/"2434/,QUEUE/5/
C      DATA NUMRES/5/,SMOOTH/1/,RUNAVE/"410/,IVEC/0,4/
C
C*****
C*****
C
C
C      PRINT 1
1      FORMAT(/,'***** MSU TENDON CYCLIC TEST ROUTINE *****/
+      /,/,/)
C*****
C
C
C*****
C      **** CREATE FILES FOR DATA AND TEXT TO IDENTIFY ****
C      **** DATA.MAKE LOGICAL UNIT ASSIGNMENTS ****
C*****
C
C      WRITE(6,301)
301      FORMAT(/,' ENTER NAME FOR RAW DATA FILE. ')
C      WRITE(6,302)
302      FORMAT(/,'$ENTER FILE NAME (XXXXXX.XXX) : ')
C      READ(5,306) RAWFIL
C      OPEN(UNIT=3,NAME=RAWFIL,STATUS='NEW')
C      WRITE(6,110)
110      FORMAT(/,/, ' ENTER NAME OF FILE TO HOLD SUMMARIZED DATA')
C      WRITE(6,115)
115      FORMAT(/,'$ENTER FILE NAME (XXXXXX.XXX) : ')
C      READ(5,306) SUMFIL
C      OPEN(UNIT=2,NAME=SUMFIL,STATUS='NEW')
C      PRINT 351

```

```

351  FORMAT(/, ' ENTER TWO LINES OF TEXT TO IDENTIFY THE DATA. '//
+    ' ENTER UP TO 80 CHARACTERS PER LINE. '//
+    ' THE FIRST CHARACTER MUST BE A BLANK SPACE')
    PRINT 354
    READ(5,352) (TEXTB(1,J),J=1,80)
    WRITE(2,352) (TEXTB(1,J),J=1,80)
    WRITE(3,352) (TEXTB(1,J),J=1,80)
    PRINT 354
    READ(5,352) (TEXTB(2,J),J=1,80)
    WRITE(2,352) (TEXTB(2,J),J=1,80)
    WRITE(3,352) (TEXTB(2,J),J=1,80)

C
C*****
C    **** ENTER GAUGE LENGTH OF TEST SPECIMEN ****
C    **** USED TO CALCULATE ACTUAL DEFLECTION ****
C*****
C
200  PRINT 6
6    FORMAT(/, ' ENTER THE GAUGE LENGTH FOR THIS TEST '//
+    ' , '$IN MILLIMETERS: (XX.XXXX): ')
    GAUGE = 00.0000
    ACCEPT 9, GAUGE
    PRINT 7, GAUGE
7    FORMAT(/, '$RESPONSE = ', F9.4, ' CORRECT? (Y/N): ')
    READ(5,2) ANS
    IF(ANS.NE.YES) GOTO 200
201  PRINT 202
202  FORMAT(/, '$ENTER THE LOAD RANGE, 0-10%, 1-20% : ')
    ACCEPT 100, LDRNG
    PRINT 203, LDRNG
203  FORMAT(/, '$RESPONSE = ', I5, ' CORRECT? (Y/N): ')
    READ(5,2) ANS
    IF(ANS.NE.YES) GO TO 201
    IF(LDRNG.EQ.0) THEN
        E=-1.00
        F=0.13616E-02
    ELSE
        E=-1.00
        F=0.27232E-02
    ENDIF

C
C*****
C    **** ENTER STRAIN LEVELS FOR TEST ****
C    **** FIRST ONE MUST BE > 0% ****
C    **** SECOND ONE MAY BE 0% OR GREATER ****
C    **** A 0% STRAIN PRODUCES A TIMED PAUSE ****
C*****
C
415  PRINT 420
420  FORMAT(/, ' ENTER VALUE FOR FIRST STRAIN LEVEL '//
+    ' '$IN PERCENT (1% TO MAX OF 6%): (XX): ')
    ACCEPT 99, IPERST(1)
    PRINT 425, IPERST(1)
425  FORMAT(/, '$RESPONSE = ', I5, ' %', ' CORRECT? (Y/N): ')
    READ(5,2) ANS
    IF(ANS.NE.YES) GOTO 415
440  PRINT 445
445  FORMAT(/, ' ENTER VALUE FOR SECOND STRAIN LEVEL '//
+    ' '$IN PERCENT (0% TO MAX OF 6%): (XX): '//
+    ' $FOR CONSTANT STRAIN TEST ENTER 99 ')

```

```

ACCEPT 99, IPERST(2)
PRINT 450, IPERST(2)
450  FORMAT(/, '$RESPONSE =      ', 15, ' %', '  CORRECT?  (Y/N):  ')
      READ(5,2) ANS
      IF(ANS.NE.YES) GOTO 440
      WRITE(3,1000)
C
C*****
C      ***  WAITS FOR A 'Y' RESPONSE TO START TEST  ***
C*****
C
940  PRINT 12
12   FORMAT(/, ' ARE YOU READY FOR THE TEST TO BEGIN?'/
      + '$ENTER Y TO BEGIN',/,/)
      READ(5,2) START
      IF(START.NE.YES) GOTO 940
1000 FORMAT('0', 5X, 'STROKE', 6X, 'LOAD', 6X, 'TIME', /)
C
C*****
C      ****   CLEAR VARIABLES USED IN PROGRAM   ****
C*****
C
      IRATE=0
      IWW=0
      IFILT=0
C
C*****
C      ****   SET CONSTANTS USED FOR WINDOW   ****
C      ****   WIDTH, FILTER AND DATA RATE   ****
C*****
C
      IWW=19
      IFILT=2
      IRATE=8
      STRTIM=72.0
C
C*****
C      ****   SET PARAMETERS FOR MACHINE CAL.   ****
C      ****   DATA , I/O, BUFFERING   ****
C      ****   AND RATE AT WHICH DATA IS TAKEN   ****
C*****
C
      CALL ASNLUN(1, 'IN', 0, IDS)
      CALL QIO("12, 1, , , , 10SB)
      CALL SETCAL(LUN, 10SB, STROKE, 162, 16384, -105.00, 0.18755E-03)
      CALL SETCAL(LUN, 10SB, LOAD, 0, 16384, E, F)
500  CONTINUE
      CALL SETVEC(LUN, 10SB, 2, IVEC)
      CALL DATAHA(LUN, 10SB, SMOOTH, RUNAVE, 1FILT)
      CALL DATAHA(LUN, 10SB, FORMAT, ADCOR)
      CALL DATAHA(LUN, 10SB, QUEUE, FIFO)
      CALL DATARA(LUN, 10SB, IRATE)
C
C*****
C      ****   CONVERT INTEGER VALUES TO   ****
C      ****   REAL VALUES NEEDED FOR MACHINE   ****
C      ****   CONTROL CALCULATIONS   ****
C*****
C
      RATE = 0.0

```

```

      RATE = IRATE/1000.0
      PERSTR(1) = IPERST(1)/100.0
      IF(IPERST(2).EQ.99)GOTO 220
      IF(IPERST(2).EQ.0)PERSTR(2) = 0.0
      IF(IPERST(2).EQ.0) GOTO 220
      PERSTR(2) = IPERST(2)/100.0
220    TSTVAL(1)=GAUGE * PERSTR(1)
      TSTVAL(2)=0.05/(PERSTR(1)*2)
      IF(IPERST(2).EQ.0.OR.IPERST(2).EQ.99) GOTO 230
      TSTVAL(3)=GAUGE*PERSTR(2)
      TSTVAL(4)=0.05/(PERSTR(2)*2)

C
C*****
C      ****          START MASTER TEST TIMER          ****
C      ****          AND SET ARRAY COUNTER TO ZERO      ****
C*****
C
230    T1 = SECNDS(0.0)
      MUL = 0

C
C      1
C
C*****
C      ****  SET VALUES UP FOR STRAIN LEVEL ONE  ****
C*****
C
700    CONTINUE
      CYCTIM(1) = 0.0
      CYCDES(1)=0.0
      CYCDES(2)=0.0
      STKPK9 = 0.0
      CYCDES(1)=TSTVAL(2)
      CYCDES(2)=TSTVAL(1)
      STKPK9 = TSTVAL(1) * (0.9)
      GOTO 900

C
C*****
C      ****  SET VALUES FOR STRAIN LEVEL TWO  ****
C*****
C
800    CONTINUE
C
C      *****
C      ****  IF LEVEL TWO EQUALS ZERO JUMP TO  ****
C      ****  PAUSE LOOP PORTION OF PROGRAM      ****
C      *****
C
      IF(IPERST(2).EQ.99)GOTO 900
      IF(IPERST(2).EQ.0)CYCDES(1) = 0.0
      IF(IPERST(2).EQ.0) GOTO 240

C
C
C      *****
C
      CYCTIM(1) = 0.0
      CYCDES(1)=0.0
      CYCDES(2)=0.0
      STKPK9 = 0.0
      CYCDES(1)=TSTVAL(4)
      CYCDES(2)=TSTVAL(3)
      STKPK9 = TSTVAL(3)*(0.9)

```

```

C
C*****
C      ****      STORE DATA ON NICOLET      ****
C      ****      ONLY AT VERY START OF TEST  ****
C*****
C
900      CONTINUE
      NPRINT = 0
C
C*****
C      ****      TEST MACHINE IS STARTED HERE      ****
C      ****      USING THE VALUES AS SET ABOVE      ****
C      ****      TO DETERMINE DEFLECTION ECT.      ****
C*****
C
      CALL STARTE(LUN, IOSB)
      IF(IOSB(1).NE.1) GOTO 610
      CALL MODECH(LUN, IOSB, STROKE, 1)
C
C      *****
C      **** EACH STRAIN LEVEL TIMER STARTS HERE ****
C      *****
C
      T2 = SECNDS(0.0)
C
C      *****
C
C
C
C
      CALL ANLGEN(LUN, IOSB, B, CYCDES, STROKE, 1, 0)
      IF(IOSB(1).NE.1) GOTO 610
600      CONTINUE
      XTIME = SECNDS(T2)
      TTIME = SECNDS(T1)
      NPRINT = NPRINT+1
      IF(SECNDS(T1).GE.360.0)GOTO 590
      CALL DATAIN(LUN, IOSB, DATA2, 2000, IPOINT, 0, 1, SUB360)
      CALL WAITCA(LUN, IOSB, NUMDAT)
C      IF(NPRINT.EQ.1)PRINT *, 'PRE WRIT= ', SECNDS(T1)
      IF(NPRINT.EQ.1)WRITE(3,9004)((MUL, (DATA(J, I), J=1, 3)), I=1, 500)
C      IF(NPRINT.EQ.1)PRINT *, 'POST WRIT= ', SECNDS(T1)
      IF(NPRINT.EQ.1) MUL = MUL + 1
      IF(IOSB(1).NE.1) PRINT *, 'DATAIN ERR= ', IOSB(1)
      IF(IOSB(1).NE.1) GOTO 610
      IF(SECNDS(T1).LT.STRTIM) GOTO 600
      IF(IPERST(2).EQ.99)GOTO 590
      CALL STOPTE(LUN, IOSB)
      IF(IOSB(1).NE.1) PRINT *, 'STOPTEST ERR= ', IOSB(1)
      IF(IOSB(1).NE.1) GOTO 610
      CALL RESTOR(LUN, IOSB, STROKE)
      IF(IOSB(1).EQ.1.OR.IOSB(1).EQ.-130)THEN
      GOTO 241
      ELSE
      PRINT *, 'RESTORE ERR= ', IOSB(1)
      ENDIF
241      CONTINUE
      CALL MARK(B, 2, 2)
      CALL WAITFR(B)
590      IF(SECNDS(T1).LT.350.0)THEN
      LWRTIT=250

```

```

ELSE
  LWRT=500
ENDIF
IF(IPERST(2).EQ.0)LWRT=500
WRITE(3,9004) ((MUL, (DATA(J, I), J=1, 3)), I=1, LWRT)
MUL = MUL + 1
IF(SECNDS(T1).GE.360.0)GOTO 610
IF(STRTIM.LT.360.0)STRTIM=STRTIM+72.0
IF(IPERST(2).EQ.99)T2=SECNDS(0.0)
IF(IPERST(2).EQ.99)NPRINT=0
IF(IPERST(2).EQ.99)GOTO 600

C
C*****
C      ****      ZERO STRAIN PAUSE LOOP      ****
C*****
C
240      CONTINUE
        IF(IPERST(2).EQ.0)GOTO 242
        IF(CYCDES(1).NE.0.0) GOTO 250
242      CONTINUE
        IF(IPERST(2).EQ.0) T2 = SECNDS(0.0)
245      CONTINUE
        IF(SECNDS(T2).LT.62.0)GOTO 245
        IF(SECNDS(T1).LT.360.0)STRTIM=STRTIM+72.0

C
C
C*****
C      ****      END OF TEST CONTROL TIME      ****
C*****
C
250      IF(SECNDS(T1).GE.360.)GO TO 610
C
C*****
C      *** TOGGLE BETWEEN LEVEL ONE & LEVEL TWO ***
C*****
C
        IF(IPERST(2).EQ.0)GOTO 900
        IF(CYCDES(1).EQ.TSTVAL(2)) GOTO 800
        IF(CYCDES(1).NE.TSTVAL(2)) GOTO 700

C
C*****
C      ****      ORDERLY SHUT-DOWN OF TEST MACHINE      ****
C*****
C
610      CALL RESTOR(LUN, IOSB, STROKE)
        CALL STOPTE(LUN, IOSB)
        PRINT 310
310      FORMAT(/, '^', 'END OF TEST')
C
C*****
C      ****      FORMAT STATEMENTS      ****
C*****
C
2          FORMAT(1A1)
4          FORMAT(F9.2)
9          FORMAT(F9.4)
99         FORMAT(I5)
100        FORMAT(I5)
306        FORMAT(A11)
352        FORMAT(80A1)

```

```
354      FORMAT('$TEXT : ')
9004      FORMAT('R', 11, 2F10. 4, F10. 3)
C
C*****
C      ****              END OF THIS PROGRAM      ****
C*****
C
C
C      END
```

## Appendix 6

## SUBROUTINE SUB360

```

*****
**
**   THIS SUBROUTINE WILL ANALYZE EACH DATA GROUP FROM
**   THE MAIN PROGRAM TENDON. EACH DATA GROUP CONSISTS
**   OF 500 POINTS TAKEN AT 8 MS/PT., WITH A RUNNING
**   AVERAGE OVER 2 PTS. IT WILL CREATE THE SUMMARY FILE
**   BY LOCATING AND CALCULATING THE FOLLOWING PARAMETERS
**   FOR EACH DATA GROUP: THE TIME-LOAD-STROKE AT THE
**   LOAD PEAK, THE LOADING AND UNLOADING ENERGIES.
**
**   THE SUBROUTINE WILL WRITE THE ABOVE VALUES TO
**   THE SUMMARY FILE IN THE FOLLOWING FASHION:
**   1) R1-TLP-LP-SLP-ENGUP-ENGDOWN
**   WHERE:
**       TLP: TIME OF THE LOAD PEAK
**       SLP: THE STROKE AT THE LOAD PEAK
**   *** ENGUP: THE ENERGY UP
**   * * ENGDOWN: THE ENERGY DOWN
**       R1: THE MULPLT TAG
**
**   THE FORMATS FOR THE ABOVE PARAMETERS ARE ALL
**   IDENTICAL (SEE FORMATS 9000-9002).
**
*****

```

```

*****
**
**   VARIABLES COMMON TO BOTH TENDON AND TENSUB
**   AND OTHER VARIABLE DECLARATIONS.
**
*****

```

```

INCLUDE '360COM.FTN'

```

```

*****
**
**   THE RAW DATA FROM TENDON COMES IN INTEGER FORM
**   AND IS UNCONVERTED TO REAL LIFE VALUES (N AND MM).
**   THIS CONVERSION TAKES PLACE HERE BY GENERATING A
**   CONVERTED VALUE ARRAY, WITH CONVERSION FACTORS FROM
**   TENDON. FOR THE CONVERTED ARRAY, CALLED DATA, THE
**   ELEMENTS ARE: DATA(1,-)=STROKE, DATA(2,-)=LOAD,
**   AND DATA(3,-)=TIME.
**
*****

```

```

DO 10 I=1,500
A=DATA2(2,I)
B=(A+(-105.00))*(0.18755E-03)
DATA(1,I)=B
C=DATA2(1,I)
D=(C+E)*(F)

```

```

DATA(2,1)=D
DATA(3,1)=(TTIME+(RATE*1))
10 CONTINUE
C
C
C *****
C **                                     **
C **           PRESETS                 **
C **                                     **
C *****
C
C
C MAXCHK=1
C MINCHK=1
C IBEG=10
C PKTIM=0.0
C PRINT=1.0
C ITYPL=1
C ITYPUL=1
C TMLDPK=0.0
C LDPK=0.0
C STLDPK=0.0
C ENG=0.0
C ENGSUM=0.0
C ENGUP=0.0
C ENGDOWN=0.0
C
C
C
C *****
C **                                     **
C **           MAIN LOOP START         **
C **                                     **
C *****
C
C DD 50 M=1,500
C
C ***** THIS WRITE WILL ENGAGE AT THE END OF THE
C ***** ARRAY IF THE LAST PEAK ENCOUNTERED IS
C ***** A MINIMUM:
C
C IF((M.EQ.500).AND.(MAXCHK.EQ.0))
C 2WRITE(2,9000) TMLDPK,LDPK,STLDPK,ENGUP,ENGDOWN
C
C *****
C ** ENERGY CALCULATION **
C ** (RECTANGULAR RULE) **
C *****
C
C ENG=((DATA(2,M+1)+DATA(2,M))/2.)*(DATA(1,M+1)-
C 2DATA(1,M))
C ENGSUM=ENGSUM+ENG
C
C *****
C

```

```

C *****
C **
C **
C **
C **
C *****
C
C IF(MINCHK.EQ.0) GO TO 16
C MIN=1
C
C ***** THIS FIRST CHECK IS USED FOR THE *****
C ***** FIRST MINIMUM IN A 72S BLOCK *****
C ***** ONLY. *****
C
C IF(XTIME.LT.0.3)GO TO 12
C GO TO 14
12 DO 13 I=1,20
C IF(DATA(1,M).LT.DATA(1,M+1)) GO TO 13
C MIN=0
13 CONTINUE
C IF(MIN.EQ.1) GO TO 25
C GO TO 16
C
C ***** THIS NEXT MINIMUM CHECK IS USED *****
C ***** FOR THE REST OF THE MINIMUMS. *****
C
C IF((M.LE.20).OR.(M.GE.(500-20))) GO TO 50
C DO 15 I=1,20
C IF((DATA(1,M).LE.DATA(1,M+1)).AND.(DATA(1,M)
C 2.LT.DATA(1,M-1))) GO TO 15
C MIN=0
15 CONTINUE
C IF(MIN.EQ.1) GO TO 25
C
C *****
C **
C **
C **
C **
C *****
C
C IF(MAXCHK.EQ.0) GO TO 19
C IF((M.LE.20).OR.(M.GE.(500-20))) GO TO 50
C MAX=1
C DO 17 I=1,20
C IF((DATA(2,M).GE.DATA(2,M+1)).AND.(DATA(2,M)
C 2.GT.DATA(2,M-1)).AND.(DATA(1,M).GT.STKPK9)) GO TO 17
C MAX=0
17 CONTINUE
C IF(MAX.EQ.1) GO TO 30
C
C *****
19 GOTO 50
C *****
C
C

```

```

C
C *****
C **  MINIMUM WRITES AND RESETS. HERE THE **
C **  VARIABLE  MAXCHK IS THE CHECK FOR A **
C **  PREVIOUS MAXIMUM. THE WRITES WILL **
C **  ENGAGE ONLY IF THERE WAS A PREVIOUS **
C **  PREVIOUS MAXIMUM **
C **
C *****
C
C
C
25  IF(MAXCHK.EQ.0)GO TO 27
    GO TO 28
27  CONTINUE
    ENGDOWN=ENGDSUM
    WRITE(2,9000) TMLDPK,LDPK,STLDPK,ENGUP,ENGDOWN
    ITYPUL=0
28  ENGSUM=0.0
    ENG=0.0
    PKTIM=0.0
    MINCHK=0
    MAXCHK=1
    TMLDPK=0.0
    LDPK=0.0
    STLDPK=0.0
    ENGUP=0.0
    ENGDOWN=0.0
    GO TO 50

C
C
C
C *****
C **
C **  MAXIMUM WRITES AND RESETS SECTION. HERE MINCHK**
C **  HAS A SIMILAR FUNCTION TO MAXCHK. IT WILL **
C **  CAUSE A WRITE ONLY IF THERE WAS A PREVIOUS **
C **  MINIMUM. **
C **
C *****
C
C
C
30  TMLDPK=DATA(3,M)
    LDPK=DATA(2,M)
    STLDPK=DATA(1,M)
    PRINT=0.0
    IF(MINCHK.EQ.0)GO TO 35
    GO TO 40
35  ENGUP=ENGDSUM
    ITYPL=0
40  ENGSUM=0.0
    ENG=0.0
    PKTIM=DATA(3,M)
    MINCHK=1
    MAXCHK=0
50  CONTINUE

C
C
C
C *****

```

```

C      **
C      **          MAIN LOOP END          **
C      **
C      ****
C
C
C
C
C
C      ****
C      **
C      **          FORMAT STATEMENTS      **
C      **
C      ****
C
9000  FORMAT( 'R1 ', F10. 3, 4F10. 4 )
      RETURN
      END

```

```

C
C*****
C      *** INCLUDE FILE FOR TEN360 & SUB360      ****
C*****
C
      INTEGER STROKE, LUN, FORMAT, IRATE, IOSB(2), ADCOR, NO, STOP
      INTEGER IPOINT(4), FIFO, QUEUE, IPERST(2), IFILT, LDRNG
      INTEGER SMOOTH, RUNAVE, IVEC(2), KNT2, MIN, MAX, KK
      INTEGER M, IWW, K2, K3, N, I, MAXCHK, MINCHK, KNT1

C
      LOGICAL*1 TEXTB(2, 80), YES, ANS, START, BEL
      CHARACTER*11 SUMFIL, RAWFIL

C
      REAL*4 DATA(3, 500), A, B, C, D, E, F, STF, STFER, TMLDPK, STRTIM
      2, SUMLD, SUMLD2, SUMST, SUMST2, STFMAX, SUMLS, RATE, LDPK, PRINT
      2, SY, SX, SYX, PKTIM, STERMX, STLDPK, ENG, ENGSUM, ENGUP, ENGDOWN
      2, STFMXT, STKPK9, SPEC, SPEC2

C
      DIMENSION CYCDES(2), TSTVAL(4), PERSTR(2), CYCTIM(2)

C
      COMMON /COMDA2/ DATA2, XTIME, TTIME, IFILT, TMLDPK, LDPK, STLDPK

C
      COMMON /COMDA3/ M, IWW, K2, K3, N, I, MAXCHK, MINCHK, KNT1, KNT2, PRINT
      2, MIN, MAX, DATA, A, B, C, D, E, F, STF, STFER, SUMLD, SUMLD2
      2, SUMST, SUMST2, STFMAX, SUMLS, RATE, SY, SX, SYX
      2, PKTIM, STERMX, STFMXT, STKPK9

C
      INTEGER*2 DATA2(2, 500)

C
C
C*****
C      ***      END OF INCLUDE FILE      ***
C*****

```

## Appendix 7

```

PROGRAM NEWCAM
C
C      ** THIS INCLUDE REPLACES MANY COMMON BLOCKS **
C
C      INCLUDE 'COMMON.FTN'
C
C*****
C      ***** NEW CAMERA TEST *****
C*****
C
C*****
C      ***** COMPILE W/ 'COMMON.FTN' PRESENT *****
C      ***** TO TASK BUILD USE F4POTS.OLB, *****
C      ***** NICLB.OLB *****
C      ***** PRECAM, CAMDAT, NICSET *****
C      ***** CONTRL, STORE, DATRIT *****
C      ***** AND THE TASK BUILD OPTION *****
C      ***** COMMON=RETCOM:RW *****
C      ***** UNITS=10, ASQ=TI:6, ASQ=TTO:10 *****
C*****
C
C      INTEGER STROKE, LUN, FORMAT, IRATE, IOSB(2), ADCOR, NO, STOP
C      INTEGER IPOINT(4), FIFO, QUEUE, IPERST(2), IFILT, LDRNG
C      INTEGER SMOOTH, RUNAVE, IVEC(2), IBEL, ITUP, IZB, ONESET
C
C      LOGICAL*1 TEXTB(2,80), YES, ANS, START, BEL
C      CHARACTER*11 BUMFIL, RAWFIL
C
C      REAL*4 STKPK9, XTIME
C
C      REAL SETIME, STRTIM
C
C      DIMENSION CYCDES(2), TSTVAL(4), PERSTR(2), CYCTIM(2), VALS(2,2)
C
C*****
C      **** NON-FORTRAN OR INSTRON MACHINE DRIVER ****
C      **** SUBROUTINES CALLED FROM MAIN PROGRAM ****
C*****
C
C      EXTERNAL PRECAM, CAMDAT, FILRIT, DATRIT
C      EXTERNAL NICSET, STORE, CONTRL
C
C*****
C      **** DECLARATION STATEMENTS ****
C*****
C
C      DATA STROKE/4/, LUN/1/, FORMAT/4/, NO/"20116/", ADCOR/1048/
C      DATA YES/'Y'/, STOP/8192/, NUMDAT/4/, FIFO/1308/, QUEUE/5/
C      DATA NUMRES/5/, SMOOTH/1/, RUNAVE/264/, IVEC/0,4/, BEL/"007/
C      DATA RAMPS/"1010/, LOAD/0/, NONE/260/, ONESET/1312/

```

```

DATA PHYREA/1036/
C
C*****
C*****
C
C
      PRINT 1
1      FORMAT(/, '*****          MSU TENDON CYCLIC TEST ROUTINE          ***
      +   /, /, /)
C*****
C*****
C
      CALL NICSET
C
C*****
C      **** CREATE FILES FOR DATA AND TEXT TO IDENTIFY ****
C      **** DATA.MAKE LOGICAL UNIT ASSIGNMENTS ****
C*****
C
      WRITE(6,110)
110     FORMAT(/, /, ' ENTER NAME OF FILE TO HOLD CAMERA DATA')
      WRITE(6,115)
115     FORMAT(/, '$ENTER FILE NAME (XXXXXX.XXX) : ')
      READ(5,306) SUMFIL
      OPEN(UNIT=2, NAME=SUMFIL, STATUS='NEW')
      PRINT 351
351     FORMAT(/, ' ENTER TWO LINES OF TEXT TO IDENTIFY THE DATA. '//
      +   ' ENTER UP TO 80 CHARACTERS PER LINE. '//
      +   ' THE FIRST CHARACTER MUST BE A BLANK SPACE')
      PRINT 354
      READ(5,352) (TEXTB(1,J), J=1,80)
      WRITE(2,352) (TEXTB(1,J), J=1,80)
      WRITE(3,352) (TEXTB(1,J), J=1,80)
      PRINT 354
      READ(5,352) (TEXTB(2,J), J=1,80)
      WRITE(2,352) (TEXTB(2,J), J=1,80)
      WRITE(3,352) (TEXTB(2,J), J=1,80)
C
C*****
C      **** ENTER GAUGE LENGTH OF TEST SPECIMEN ****
C      **** USED TO CALCULATE ACTUAL DEFLECTION ****
C*****
C
200     PRINT 6
6       FORMAT(/, ' ENTER THE GAUGE LENGTH FOR THIS TEST'//
      +   /, '$IN MILLIMETERS: (XX.XXXX): ')
      GAUGE = 00.0000
      ACCEPT 9, GAUGE
      PRINT 7, GAUGE
7       FORMAT(/, '$RESPONSE = ', F9.4, ' CORRECT? (Y/N): ')
      READ(5,2) ANS
      IF(ANS.NE.YES) GOTO 200
201     PRINT 202
202     FORMAT(/, '$ENTER THE STRAIN RATE; 0 = 5%, 1 = 2% : ')
      ACCEPT 100, LDRNG
      PRINT 203, LDRNG
203     FORMAT(/, '$RESPONSE = ', I5, ' CORRECT? (Y/N): ')
      READ(5,2) ANS
      IF(ANS.NE.YES) GO TO 201
      IF(LDRNG.EQ.0)THEN

```

```

E=0.05
ELSE
E=0.02
ENDIF

C
C*****
C      ****      ENTER STRAIN LEVELS FOR TEST      ****
C      ****      FIRST ONE MUST BE > 0%      ****
C      ****      SECOND ONE MAY BE 0% OR GREATER      ****
C      ****      A 0% STRAIN PRODUCES A TIMED PAUSE      ****
C*****
C
415      PRINT 420
420      FORMAT(/, ' ENTER VALUE FOR FIRST STRAIN LEVEL' /
+      '$IN PERCENT (1% TO MAX OF 6%): (XX): ')
      ACCEPT 99, IPERST(1)
      PRINT 425, IPERST(1)
425      FORMAT(/, '$RESPONSE = ', 15, ' %', ' CORRECT? (Y/N): ')
      READ(5, 2) ANS
      IF(ANS.NE.YES) GOTO 415
440      PRINT 445
445      FORMAT(/, ' ENTER VALUE FOR TIMED REST PERIOD' /
+      '$AS INTEGER ( 0 = NO PAUSE-END TEST): (XX): ')
      ACCEPT 99, IPERST(2)
      PRINT 450, IPERST(2)
450      FORMAT(/, '$RESPONSE = ', 15, ' %', ' CORRECT? (Y/N): ')
      READ(5, 2) ANS
      IF(ANS.NE.YES) GOTO 440
C      *****
C      ***      GET ZERO STRAIN CAMERA DATA      ****
C      *****
      ICNT=0
      CALL PRECAM
      CALL MARK(8, 40, 1)
      CALL WAITFR(8)
      CALL FILRIT
C
C*****
C      ***      WAITS FOR A 'Y' RESPONSE TO START TEST      ***
C*****
C
      LOOP=0
940      PRINT 12
12      FORMAT(/, ' ARE YOU READY FOR THE TEST TO BEGIN?' /
+      '$ENTER Y TO BEGIN', /, /)
      READ(5, 2) START
      IF(START.NE.YES) GOTO 940
C
C*****
C      ****      CLEAR VARIABLES USED IN PROGRAM      ****
C*****
C
      IRATE=0
      IWW=0
      IFILT=0
C
C*****
C      ****      SET CONSTANTS USED FOR WINDOW      ****
C      ****      WIDTH, FILTER AND DATA RATE      ****
C*****

```

```

C
      IWW=19
      IFILT=2
      IRATE=6
      IZS=0
C
C*****
C      ****   SET PARAMETERS FOR MACHINE CAL.   ****
C      ****   DATA , I/O, BUFFERING           ****
C      ****   AND RATE AT WHICH DATA IS TAKEN   ****
C*****
C
      CALL ASNLUN(1, 'IN', 0, IDS)
      CALL GIO("12,1,,,, IOSB)
      CALL SETCAL(LUN, IOSB, STROKE, 162, 16384, -105.00, 0.18755E-03)
      IF(IOSB(1).NE.1)PRINT *, 'SETCAL ERR1= ', IOSB(1)
C      CALL SETCAL(LUN, IOSB, LOAD, 0, 16384, E, F)
C      IF(IOSB(1).NE.1)PRINT *, 'SETCAL ERR2= ', IOSB(1)
500    CONTINUE
      CALL SETVEC(LUN, IOSB, 2, IVEC)
      IF(IOSB(1).NE.1)PRINT *, 'SETVEC ERR= ', IOSB(1)
C      CALL DATAHA(LUN, IOSB, SMOOTH, NONE, IFILT)
C      IF(IOSB(1).NE.1)PRINT *, 'DATAHA I ERR= ', IOSB(1)
      CALL DATAHA(LUN, IOSB, FORMAT, ADCOR)
      IF(IOSB(1).NE.1)PRINT *, 'DATAHA II ERR= ', IOSB(1)
      CALL DATAHA(LUN, IOSB, QUEUE, FIFO)
      IF(IOSB(1).NE.1)PRINT *, 'DATAHA III ERR= ', IOSB(1)
      CALL DATARA(LUN, IOSB, IRATE)
      IF(IOSB(1).NE.1)PRINT *, 'DATARATE ERR= ', IOSB(1)
C
C*****
C      ****   CONVERT INTEGER VALUES TO         ****
C      ****   REAL VALUES NEEDED FOR MACHINE     ****
C      ****   CONTROL CALCULATIONS                ****
C*****
C
      IZS=1
      RATE = 0.0
      RATE = IRATE/1000.0
      PERSTR(1) = IPERST(1)/100.0
      IF(IPERST(2).EQ.0)PERSTR(2) = 0.0
      IF(IPERST(2).EQ.0) GOTO 220
      PERSTR(2) = IPERST(2)*1.0
220    TSTVAL(1)=GAUGE * PERSTR(1)
      TSTVAL(2)=E/(PERSTR(1)*2)
      IF(IPERST(2).EQ.99)GOTO 230
      IF(IPERST(2).EQ.0) GOTO 230
      TSTVAL(3)=GAUGE*PERSTR(2)
      TSTVAL(4)=E/(PERSTR(2)*2)
C
C*****
C      ****   START MASTER TEST TIMER             ****
C      ****   AND SET ARRAY COUNTER TO ZERO       ****
C*****
C
230    T1=SECNDS(0.0)
C
C
C*****
C      ****   SET VALUES UP FOR STRAIN LEVEL ONE ****

```

```

C*****
C
700    CONTINUE
      CYCTIM(1) = 0.0
      CYCDES(1)=0.0
      CYCDES(2)=0.0
      STKPK9 = 0.0
      CYCDES(1)=TSTVAL(2)
      CYCDES(2)=TSTVAL(1)
      STKPK9 = TSTVAL(1) * (0.9)
      GOTO 900

C
C*****
C      **** SET VALUES FOR STRAIN LEVEL TWO ****
C*****
C
800    CONTINUE
C
C
C*****
C
C*****
C
900    CONTINUE
C
      WRITE(10) BEL
      CALL CONTRL(3)
      CALL STORE(0)
      CALL MARK(8,10,1)
      CALL WAITFR(8)
      T2=SECNDS(0.0)

C*****
C      **** TEST MACHINE IS STARTED HERE ****
C      **** USING THE VALUES AS SET ABOVE ****
C      **** TO DETERMINE DEFLECTION ECT. ****
C*****
C
      CALL STARTE(LUN,IOSB)
      IF(IOSB(1).NE.1)PRINT *, 'STARTEST ERR= ', IOSB(1)
      IF(IOSB(1).NE.1) GOTO 610
      CALL MODECH(LUN,IOSB,STROKE,1)
      IF(IOSB(1).NE.5)PRINT *, 'MODECHANGE ERR= ', IOSB(1)

C
      LOOP=LOOP+1
      CALL ANLGEN(LUN,IOSB,8,CYCDES,STROKE,1,0)
      IF(IOSB(1).NE.1)PRINT *, 'ANLGEN ERR= ', IOSB(1)
      IF(IOSB(1).NE.1) GOTO 610
600    CONTINUE
599    CTIME=SECNDS(T1)
      CALL CAMDAT

C
      CALL MARK(8,4,1)
      CALL WAITFR(8)

C
      IF(SECNDS(T2).LT.20.0)GOTO 600

C
      CALL STOPTE(LUN,IOSB)
      IF(IOSB(1).NE.1)PRINT *, 'STOPTEST ERR= ', IOSB(1)
      IF(IOSB(1).NE.1) GOTO 610
      CALL RESTOR(LUN,IOSB,STROKE)

```

```

      IF(IOSB(1).NE.1)PRINT *, 'RESTOR ERR= ', IOSB(1)
      CALL MARK(8,2,2)
      CALL WAITFR(8)
C
C
C*****
C      ****      ZERO STRAIN PAUSE LOOP      ****
C*****
C
240      CONTINUE
      IF(IPERST(2).EQ.0)GOTO 610
      IF(LOOP.OT.1)GOTO 610
      T3=SECNDS(0.0)
241      CONTINUE
      IF(SECNDS(T3).LT.PERSTR(2))GOTO 241
      CALL DATRIT
      ICNT=0
      WRITE(10) BEL
      WRITE(10) BEL
      GOTO 900
C
C*****
C      ****      END OF TEST CONTROL TIME      ****
C*****
C
250      IF(SECNDS(T1).GE.20.0)GO TO 610
C
C
C*****
C      ****      ORDERLY SHUT-DOWN OF TEST MACHINE      ****
C*****
C
610      CALL DATRIT
      CALL RESTOR(LUN, IOSB, STROKE)
      IF(IOSB(1).EQ.1.OR. IOSB(1).EQ.3) THEN
      GOTO 300
      ELSE
      PRINT *, 'FINAL SHUT-DOWN ERR= ', IOSB(1)
      END IF
300      CALL STOPTE(LUN, IOSB)
      IF(IOSB(1).NE.1)PRINT *, 'FINAL STOPTEST ERR= ', IOSB(1)
      PRINT 310
310      FORMAT(/, '^', 'END OF TEST')
C
C*****
C      ****      FORMAT STATEMENTS      ****
C*****
C
2          FORMAT(1A1)
4          FORMAT(F9.2)
9          FORMAT(F9.4)
99         FORMAT(I5)
100        FORMAT(I5)
306        FORMAT(A11)
352        FORMAT(80A1)
354        FORMAT('$TEXT : ')
C
C*****
C      ****      END OF THIS PROGRAM      ****
C*****
C
      END

```

```

SUBROUTINE PRECAM
C
C   INCLUDE 'COMMON.FTN'
C
C   SET BOARD FOR FIRST INTIAL SCAN (NO EXT. STROBE)
C
C   ICAMRA (256)=262
C
C   LOOP UNTIL OUTPUT BUFFER FULL
C
10  CONTINUE
    ITEST=ICAMRA(256).AND.1
    IF(ITEST.NE.1) GOTO 10
C
C   TAKE INITIAL SCAN
C
    KOUNT=ICAMRA(1).AND.4095
    ITOT=0
    IEND=KOUNT
    JEND=(IEND+1)/2
    DO 20 N=3, IEND
        IVAL(N)=ICAMRA(N).AND.4095
        ITOT=ITOT+IVAL(N)
    20 CONTINUE
C
C   CALCULATE UNCERTAINTIES
C
    DO 30 N=2, JEND
        K=2*N-1
        ERROR(N)=2./IVAL(K)*100.
    30 CONTINUE
        ERROR(JEND+1)=2./ITOT*100.
C
C   RETURN
    END

```

```

SUBROUTINE CAMDAT
C
C   INCLUDE 'COMMON.FTN'
C
C
C   SET BOARD, STROBE, START TIMER
C
C   ICAMRA(256)=262
C
C   CHECK OUTPUT BUFFER
C
50  CONTINUE
    ITEST=ICAMRA(256).AND.1
    IF(ITEST.NE.1) GOTO 50
C
C   ICNT=ICNT+1
C
C   KNTTST=ICAMRA(1).AND.4095
    IF(KNTTST.NE.KOUNT)PRINT *, '** TRANSITION COUNT CHANGE **'
C
C   CALCULATE TIME AND STRAINS *****
C
C   ***** TIME *****
C
C   CDATA(1, ICNT)=0.00208333*IISHFT((ICAMRA(5).AND."70000"),-12)
    2+.01666667*ANINT(CTIME/.01666667)
C
C   ***** STRAIN *****
C
C   KTOT=0
    DO 60 N=3, IEND
      JVAL(N)=ICAMRA(N).AND.4095
      KTOT=KTOT+JVAL(N)
60  CONTINUE
    DO 70 N=2, JEND
      K=2*N-1
      CDATA(N, ICNT)=100.*(JVAL(K)-IVAL(K))/IVAL(K)
70  CONTINUE
    CDATA(JEND+1, ICNT)=100.*(KTOT-ITOT)/ITOT
C
C   *** END OF TIME/STRAIN CALCULATION ***
C
C   RETURN
C   END

```

```

SUBROUTINE FILRIT
C
  INCLUDE 'COMMON.FTN'
C
  OUTPUT CAMERA DATA
C
  WRITE (2,9030)
9030  FORMAT(/,5X,'UNCERTAINTY',/,5X,'-----',/)
      DO 80 N=2,JEND
      WRITE (2,9040) LABEL, SEQ(N-1), ERROR(N)
9040  FORMAT(5X,A5,A3,'= (+/-) ',F10.3)
      80  CONTINUE
      WRITE(2,9050)ERROR(JEND+1)
9050  FORMAT(5X,'TOTAL = (+/-) ',F10.3,/)
      WRITE(2,9060) (LABEL, SEQ(J), J=1, JEND-1)
9060  FORMAT(8X,'TIME',4X,<JEND-1>(A5,A1,4X), ' TOTAL',/)
C
  RETURN
  END

```

```

SUBROUTINE DATRIT
C
  INCLUDE 'COMMON.FTN'
C
  OUTPUT CAMERA DATA
C
  8999  CONTINUE
9080  FORMAT('R1',F10.3,<JEND-1>F10.2,F10.3)
      WRITE(2,9080)((CDATA(J,I), J=1, JEND+1), I=1, ICNT)
C
  OUTPUT LOAD - STROKE DATA
C
  ICNT=0
  RETURN
  END

```

PIP NEWCAM, TSK, \*/DE  
PIP \*. \*/PU  
F77 NEWCAM, NEWCAM/-SP=NEWCAM  
F77 PRECAM, PRECAM/-SP=PRECAM  
F77 FILRIT, FILRIT/-SP=FILRIT  
F77 CAMDAT, CAMDAT/-SP=CAMDAT  
F77 DATRIT, DATRIT/-SP=DATRIT  
PIP \*. \*/PU  
TKB @NEWCAM  
PIP \*. \*/PU  
PIP /FR

NEWCAM/-CP=NEWCAM, PRECAM, FILRIT, CAMDAT, DATRIT, DLO: [1, 1]F4POTS. OLB/LB  
NICSET, CONTRL, STORE, DYO: [10, 12]NICLB. OLB/LB  
/  
COMMON=RETCOM: RW  
UNITS=10  
ASQ=TI: 6  
ASQ=TTO: 10  
PRI=56  
//

## Appendix 8

## PROGRAM CYCQVL

```

C
C
C *****
C *      THIS PROGRAM SHOWS THE QUASI LINEAR
C * VISCOELASTIC LAW FOR THE MULTIPLE CYCLIC TESTS.
C * FROM THIS PROGRAM, WE CAN COMPARE THEORETICAL
C * MODEL WITH EXPERIMENTAL DATA WITH ANY CONSTANT
C * STRAIN RATE IN THE 5-CYCLIC TEST PERIODS.
C * EXAMPLE(1): 3-4-3-4-3 TEST
C * EXAMPLE(2): 3-0-3-0-3 TEST
C * EXAMPLE(3): 3-3-3-3-3 TEST
C * EXAMPLE(4): 5-3-5-3-5 TEST
C * ETC.
C *      TWO TYPES OF DATAS ARE COLLECTED.
C *      1. RAWDATA(RAWFILE)
C *      2. SUMDATA(SUMFILE)
C *****
C
C ***** THE MEANING OF VARIABLES *****
C *      I=TOTAL DATA POINTS AT CURRENT TIME(T), START FROM 0.
C *      I*=DATA POINTS AT EACH CYCLIC TEST PERIOD.
C *      ID,ID*=ADJUSTED DATA POINTS AT EACH HALF CYCLE,
C *      START FROM 0 AT EACH HALF CYCLE.
C *      II*=PARAMETER TO MAKE 'I*'.
C *      IN,IN*=HALF CYCLE NUMBERS AT CURRENT TIME(T).
C *      INK*=PARAMETER TO MAKE 'ID*','SLTK*','STK*','CCHA',
C *      'CCHB'.
C *      IT=HALF CYCLE NUMBER FROM BEGINNING TO 'IN' FOR
C *      INTEGRATION AT DO-LOOP.
C *      JT=THE SAME MEANING OF 'JN' ABOUT 'IT'.
C *      JN=IDENTIFICATION OF ODD(=0) OR EVEN(=-1) HALF CYCLE.
C *      KT=JT+1
C *      NP,NP*=NUMBER OF DATA POINTS PER EACH HALF CYCLE.
C *      NDT=NUMBER OF TOTAL DATA POINTS DURING WHOLE TESTS.
C *      NTP(*)=TOTAL HALF CYCLE NUMBER IN EACH CYCLIC TEST
C *      PERIOD.
C *      NCTP(*)=THE SUM OF 'NTP(*)'.
C *      CTP*=TIME OF CYCLIC TEST PERIOD AT EACH STRAIN LEVEL.
C *      DELT=TIME BETWEEN EACH DATA POINT(SEC).
C *      PSLTK,CCHA=X-INTERCEPTS FOR INPUT(STRAIN) EQUATION
C *      AT LOADING.
C *      PSTK,CCHB=X-INTERCEPTS FOR INPUT(STRAIN) EQUATION
C *      AT UNLOADING.
C *      R(*),RA,RR=STRAIN RATES(EX. 5PERCENT/SEC=0.05/SEC).
C *      ROMBRG=FUNCTION NAME FOR ROMBERG INTEGRATION.
C *      SCTP*=SUM OF 'CTP*'.
C *      SLTK*=PARAMETER TO MAKE 'PSLTK' AT EACH CYCLIC TEST
C *      PERIOD.
C *      STK*=PARAMETER TO MAKE 'PSTK' AT EACH CYCLIC TEST
C *      PERIOD.
C *      STN*=STRAIN LEVEL AT EACH CYCLIC TEST PERIOD.
C *      (EX. 3PERCENT=0.03) =MAXIMUM STRAIN
C *      STRESS=STRESS AT CURRENT TIME(=CUMMULATIVE STRESS).
C *      STRN=STRAIN AT CURRENT TIME.
C *      T=TIME AT EACH DATA POINT(CURRENT TIME)
C *      TK(*),TKA,TKK=HALF CYCLING TIME AT EACH STRAIN LEVEL.
C *      XL=LOWER LIMIT FOR INTEGRATION.
C *      XU=UPPER LIMIT FOR INTEGRATION.
C *      A,B=CONSTANTS AT REDUCED RELAXATION FUNCTION.
C *      U=CONST. FOR RETARDATION AT REDU RELAX FUNCTION .
C *      Q=POWER VALUE OF TIME AT REDU RELAX FUNCTION.

```

```
*      CK=SCALE FACTOR(SLOPE) AT STRESS-STRAIN RELATIONSHIP.  
*      M=POWER VALUE AT STRESS-STRAIN RELATIONSHIP.  
*      MM1=M-1  
*      EK=INSTANT ELASTIC RECOVERY STRAIN DURING UNLOADING  
*      AT STRESS-STRAIN RELATIONSHIP.  
*****  
  
REAL DELT,RA,STN1,STN2,STN3,  
2STN4,STN5,CTP1,CTP2,CTP3,CTP4,CTP5,  
2TKA,STRN,XL,XU,BB1,A,B,U,Q,EK,CK  
2,SCTP1,SCTP2,SCTP3,SCTP4,SCTP5,STK1,STK2,STK3  
2,STK4,STK5,SLTK1,SLTK2,SLTK3,SLTK4,SLTK5,PSLTk,PSTK  
2,CCHA,CCHB,ZDELT1  
  
INTEGER I,I1,I2,I3,I4,I5,I11,I12,I13,I14,I15,IN,  
2IN1,IN2,IN3,IN4,IN5,ID,ID1,ID2,ID3,ID4,ID5,IAN5,  
2JN,NP,NP1,NP2,NP3,NP4,NP5,NDT,INK2,INK3,INK4,INK5  
2,M,MUL,IT  
  
DOUBLE PRECISION T,STRESS,ROMBRG  
  
COMMON T,CTP2,CTP4,IT,IN,NCTP(5),ITAY(5),TK(5),R(5)  
  
DIMENSION NTP(5)  
  
LOGICAL*1 RAWFIL(11)  
LOGICAL*1 SUMFIL(11)  
  
TYPE 8500  
TYPE 8600  
TYPE 8610  
TYPE 9000  
  
TYPE 9010  
ACCEPT 9020,(RAWFIL(I),I=1,11)  
OPEN(UNIT=3,FILE=RAWFIL,STATUS='NEW')  
TYPE 9030  
ACCEPT 9020,(SUMFIL(I),I=1,11)  
OPEN(UNIT=4,FILE=SUMFIL,STATUS='NEW')  
  
TYPE 9040  
ACCEPT 9050,STN1  
TYPE 9060  
ACCEPT 9050,STN2  
TYPE 9070  
ACCEPT 9050,STN3  
TYPE 9080  
ACCEPT 9050,STN4  
TYPE 9090  
ACCEPT 9050,STN5  
  
TYPE 9100  
ACCEPT 9050,R(1)  
TYPE 9110  
ACCEPT 9050,R(2)  
TYPE 9120  
ACCEPT 9050,R(3)  
TYPE 9130  
ACCEPT 9050,R(4)  
TYPE 9140  
ACCEPT 9050,R(5)
```

```

C      TYPE 9150
      ACCEPT 9050,CTP1
      TYPE 9160
      ACCEPT 9050,CTP2
      TYPE 9170
      ACCEPT 9050,CTP3
      TYPE 9180
      ACCEPT 9050,CTP4
      TYPE 9190
      ACCEPT 9050,CTP5

C      TYPE 9200
      ACCEPT 9050,DELT

C
C
C      ***** MAIN STRUCTURE *****
C
C      ***** PRESETTING *****
C
      SCTP1=CTP1
      SCTP2=SCTP1+CTP2
      SCTP3=SCTP2+CTP3
      SCTP4=SCTP3+CTP4
      SCTP5=SCTP4+CTP5
      NDT=INT(SCTP5/DELT+0.5)

C
      NP1=INT(STN1/(R(1)*DELT)+0.5)
      IF((STN2.EQ.0.0).OR.(R(2).EQ.0.0))THEN
        NP2=0
      ELSE
        NP2=INT(STN2/(R(2)*DELT)+0.5)
      ENDIF
      NP3=INT(STN3/(R(3)*DELT)+0.5)
      IF((STN4.EQ.0.0).OR.(R(4).EQ.0.0))THEN
        NP4=0
      ELSE
        NP4=INT(STN4/(R(4)*DELT)+0.5)
      ENDIF
      NP5=INT(STN5/(R(5)*DELT)+0.5)

C
      TK(1)=NP1*DELT
      TK(2)=NP2*DELT
      TK(3)=NP3*DELT
      TK(4)=NP4*DELT
      TK(5)=NP5*DELT

C
      NTP(1)=INT(CTP1/TK(1)+0.5)
      IF(NP2.EQ.0)THEN
        NTP(2)=0
      ELSE
        NTP(2)=INT(CTP2/TK(2)+0.5)
      ENDIF
      NTP(3)=INT(CTP3/TK(3)+0.5)
      IF(NP4.EQ.0)THEN
        NTP(4)=0
      ELSE
        NTP(4)=INT(CTP4/TK(4)+0.5)
      ENDIF
      NTP(5)=INT(CTP5/TK(5)+0.5)

C
      NCTP(1)=NTP(1)
      NCTP(2)=NCTP(1)+NTP(2)
      NCTP(3)=NCTP(2)+NTP(3)
      NCTP(4)=NCTP(3)+NTP(4)
      NCTP(5)=NCTP(4)+NTP(5)

```

```

C      II1=INT(SCTP1/DELT+0.5)
      II2=INT(SCTP2/DELT+0.5)
      II3=INT(SCTP3/DELT+0.5)
      II4=INT(SCTP4/DELT+0.5)
      II5=INT(SCTP5/DELT+0.5)

C
C
C      *****  INITIALIZING  *****

      I=0
      ID=0
      STK1=0.0
      STK2=0.0
      STK3=0.0
      STK4=0.0
      STK5=0.0
      SLTK1=0.0
      SLTK2=0.0
      SLTK3=0.0
      SLTK4=0.0
      SLTK5=0.0
      A=0.270
      B=0.730
      U=0.590
      Q=0.129
      M=2
      MM1=M-1
      CK=44406.820
      ZDELT1=0.5*DELT

C
C
C      *****  LOOPING START (CALCULATION)  *****

1000  T=I*DELT
      IF(T.GE.0.0.AND.T.LT.(SCTP1-ZDELT1))THEN
          I1=I
          IN1=1+INT(I1/NP1)
          IN=IN1
          ID1=I1-(IN1-1)*NP1
          ID=ID1
          NP=NP1
          TKA=TK(1)
          RA=R(1)
          STK1=IN1*TK(1)
          SLTK1=(IN1-1)*TK(1)
      ELSEIF(T.GE.(SCTP1-ZDELT1).AND.T.LT.(SCTP2-ZDELT1))THEN
          IF(NP2.EQ.0)THEN
              I=I+INT(CTP2/DELT+0.5)
              IN2=IN1
              GO TO 1000
          ENDIF
          I2=I-II1
          IN2=IN1+1+INT(I2/NP2)
          INK2=IN2-IN1
          IN=IN2
          ID2=I2-(INK2-1)*NP2
          ID=ID2
          NP=NP2
          TKA=TK(2)
          RA=R(2)
          STK2=INK2*TK(2)
          SLTK2=TK(1)+(INK2-1)*TK(2)
      ELSEIF(T.GE.(SCTP2-ZDELT1).AND.T.LT.(SCTP3-ZDELT1))THEN
          I3=I-II2
          IN3=IN2+1+INT(I3/NP3)
          INK3=IN3-IN2

```

```

IN=IN3
ID3=I3-(INK3-1)*NP3
ID=ID3
NP=NP3
TKA=TK(3)
RA=R(3)
STK3=INK3*TK(3)
SLTK3=TK(2)+(INK3-1)*TK(3)

C
IF(NP2.EQ.0)THEN
  CCHA=SCTP2+(INK3-1)*TK(3)
  CCHB=SCTP2+INK3*TK(3)
ENDIF
ELSEIF(T.GE.(SCTP3-ZDELT1).AND.T.LT.(SCTP4-ZDELT1))THEN
  IF(NP4.EQ.0)THEN
    I=I+INT(CTP4/DELT+0.5)
    IN4=IN3
    GO TO 1000
  ENDIF
  I4=I-I13
  IN4=IN3+1+INT(I4/NP4)
  INK4=IN4-IN3
  IN=IN4
  ID4=I4-(INK4-1)*NP4
  ID=ID4
  NP=NP4
  TKA=TK(4)
  RA=R(4)
  STK4=INK4*TK(4)
  SLTK4=TK(3)+(INK4-1)*TK(4)
ELSEIF(T.GE.(SCTP4-ZDELT1).AND.T.LE.(SCTP5+ZDELT1))THEN
  I5=I-I14
  IN5=IN4+1+INT(I5/NP5)
  INK5=IN5-IN4
  IN=IN5
  ID5=I5-(INK5-1)*NP5
  ID=ID5
  NP=NP5
  TKA=TK(5)
  RA=R(5)
  STK5=INK5*TK(5)
  SLTK5=TK(4)+(INK5-1)*TK(5)

C
IF(NP4.EQ.0)THEN
  CCHA=SCTP4+(INK5-1)*TK(5)
  CCHB=SCTP4+INK5*TK(5)
ENDIF
ENDIF

C
C
JN=IN-INT(IN/2.0+0.3)*2-1

C
C
C
C
*****
***** GETTING THE RAWDATA *****
*****
***** GETTING THE STRAIN *****

IF(((T.GE.(SCTP2-ZDELT1).AND.T.LE.(SCTP3+ZDELT1))
2.AND.(NP2.EQ.0)).OR.
2((T.GE.(SCTP4-ZDELT1).AND.T.LE.(SCTP5+ZDELT1))
2.AND.(NP4.EQ.0))) THEN
  IF(JN.EQ.0)THEN
    STRN=RA*(T-CCHA)

```

```

      ELSE
        STRN=-RA*(T-CCHB)
      ENDIF
C
      GO TO 1100
    ENDIF
C
    PSLTK=SLTK1+SLTK2+SLTK3+SLTK4+SLTK5
    PSTK=STK1+STK2+STK3+STK4+STK5
C
    IF(JN.EQ.0)THEN
      STRN=RA*(T-PSLTK)
    ELSE
      STRN=-RA*(T-PSTK)
    ENDIF
C
    ***** GET THE STRESS *****
1100  STRESS=0.0
C
    DO 1500 IT=1,IN
      STRESS=STRESS+ROMBRG(A,B,Q,U,MM1,M,CK)
1500  CONTINUE
C
    ***** WRITE THE RAW(TOTAL)DATA *****
C
    IF(T.LE.(12.0+ZDELT1))THEN
      MUL=0
      WRITE(3,9300)MUL,STRN,STRESS,T
    ELSEIF(T.GE.(SCTP1-(4.8+ZDELT1)).AND.T.LE.(SCTP1-ZDELT1))THEN
      MUL=1
      WRITE(3,9300)MUL,STRN,STRESS,T
    ELSEIF(T.GT.(SCTP1-ZDELT1).AND.T.LE.(SCTP1+9.6+ZDELT1))THEN
      IF(NP2.EQ.0)THEN
        GO TO 1550
      ELSE
        MUL=2
        WRITE(3,9300)MUL,STRN,STRESS,T
      ENDIF
    ELSEIF(T.GE.(SCTP2-(4.8+ZDELT1)).AND.T.LE.(SCTP2-ZDELT1))THEN
      IF(NP2.EQ.0)THEN
        GO TO 1550
      ELSE
        MUL=3
        WRITE(3,9300)MUL,STRN,STRESS,T
      ENDIF
    ELSEIF(T.GT.(SCTP2-ZDELT1).AND.T.LE.(SCTP2+9.6+ZDELT1))THEN
      IF(NP2.EQ.0)THEN
        MUL=2
      ELSE
        MUL=4
      ENDIF
      WRITE(3,9300)MUL,STRN,STRESS,T
    ELSEIF(T.GE.(SCTP3-(4.8+ZDELT1)).AND.T.LE.(SCTP3-ZDELT1))THEN
      IF(NP2.EQ.0)THEN
        MUL=3
      ELSE
        MUL=5
      ENDIF
      WRITE(3,9300)MUL,STRN,STRESS,T
    ELSEIF(T.GT.(SCTP3-ZDELT1).AND.T.LE.(SCTP3+9.6+ZDELT1))THEN
      IF(NP4.EQ.0)THEN
        GO TO 1550
      ELSE
        MUL=6
        WRITE(3,9300)MUL,STRN,STRESS,T
      ENDIF
    ELSEIF(T.GE.(SCTP4-(4.8+ZDELT1)).AND.T.LE.(SCTP4-ZDELT1))THEN

```

```

      IF(NP4.EQ.0)THEN
        GO TO 1550
      ELSE
        MUL=7
        WRITE(3,9300)MUL,STRN,STRESS,T
      ENDIF
    ELSEIF(T.GT.(SCTP4-ZDELT1).AND.T.LE.(SCTP4+9.6+ZDELT1))THEN
      IF(NP4.EQ.0)THEN
        MUL=4
      ELSE
        MUL=8
      ENDIF
      WRITE(3,9300)MUL,STRN,STRESS,T
    ELSEIF(T.GE.(SCTP5-(4.8+ZDELT1)).AND.T.LE.(SCTP5+ZDELT1))THEN
      IF(NP4.EQ.0)THEN
        MUL=5
      ELSE
        MUL=9
      ENDIF
      WRITE(3,9300)MUL,STRN,STRESS,T
    ENDIF
1550  ENDIF
C
C
C
      ***** GETTING THE SUM(PEAK TIME)DATA *****
      IF(ID.EQ.NP-1)THEN
        STRESS=0.0
        T=T+DELT
C
        DO 100 K=1,5
          ITAY(K)=0
100    CONTINUE
C
C
C
      ***** GET THE STRAIN *****
      IF(((T.GE.(SCTP2-ZDELT1).AND.T.LE.(SCTP3+ZDELT1))
2      .AND.(NP2.EQ.0)).OR.
2      ((T.GE.(SCTP4-ZDELT1).AND.T.LE.(SCTP5+ZDELT1))
2      .AND.(NP4.EQ.0)))THEN
        IF(JN.EQ.0)THEN
          STRN=RA*(T-CCHA)
        ELSE
          STRN=-RA*(T-CCHB)
        ENDIF
      ELSE
        IF(JN.EQ.0)THEN
          STRN=RA*(T-PSLTK)
        ELSE
          STRN=-RA*(T-PSTK)
        ENDIF
      ENDIF
C
      ***** GET THE STRESS *****
      DO 1600 IT=1,IN
        STRESS=STRESS+ROMBRG(A,B,Q,U,MM1,M,CK)
1600    CONTINUE
C
      ***** WRITE THE RAW AND SUMDATA *****
      IF(T.LE.(12.0+ZDELT1))THEN
        MUL=0
        WRITE(3,9300)MUL,STRN,STRESS,T
      ELSEIF(T.GE.(SCTP1-(4.8+ZDELT1)).AND.T.LE.(SCTP1-ZDELT1))THEN
        MUL=1
        WRITE(3,9300)MUL,STRN,STRESS,T
      ELSEIF(T.GT.(SCTP1-ZDELT1).AND.T.LE.(SCTP1+9.6+ZDELT1))THEN
        IF(NP2.EQ.0)THEN
          GOTO 1650
        ELSE
          MUL=2

```

```

        WRITE(3,9300)MUL,STRN,STRESS,T
      ENDIF
    ELSEIF(T.GE.(SCTP2-(4.8+ZDEL1)).AND.T.LE.(SCTP2-ZDEL1))THEN
      IF(NP2.EQ.0)THEN
        GOTO 1650
      ELSE
        MUL=3
        WRITE(3,9300)MUL,STRN,STRESS,T
      ENDIF
    ELSEIF(T.GT.(SCTP2-ZDEL1).AND.T.LE.(SCTP2+9.6+ZDEL1))THEN
      IF(NP2.EQ.0)THEN
        MUL=2
      ELSE
        MUL=4
      ENDIF
      WRITE(3,9300)MUL,STRN,STRESS,T
    ELSEIF(T.GE.(SCTP3-(4.8+ZDEL1)).AND.T.LE.(SCTP3-ZDEL1))THEN
      IF(NP2.EQ.0)THEN
        MUL=3
      ELSE
        MUL=5
      ENDIF
      WRITE(3,9300)MUL,STRN,STRESS,T
    ELSEIF(T.GT.(SCTP3-ZDEL1).AND.T.LE.(SCTP3+9.6+ZDEL1))THEN
      IF(NP4.EQ.0)THEN
        GOTO 1650
      ELSE
        MUL=6
        WRITE(3,9300)MUL,STRN,STRESS,T
      ENDIF
    ELSEIF(T.GE.(SCTP4-(4.8+ZDEL1)).AND.T.LE.(SCTP4-ZDEL1))THEN
      IF(NP4.EQ.0)THEN
        GOTO 1650
      ELSE
        MUL=7
        WRITE(3,9300)MUL,STRN,STRESS,T
      ENDIF
    ELSEIF(T.GT.(SCTP4-ZDEL1).AND.T.LE.(SCTP4+9.6+ZDEL1))THEN
      IF(NP4.EQ.0)THEN
        MUL=4
      ELSE
        MUL=8
      ENDIF
      WRITE(3,9300)MUL,STRN,STRESS,T
    ELSEIF(T.GE.(SCTP5-(4.8+ZDEL1)).AND.T.LE.(SCTP5+ZDEL1))THEN
      IF(NP4.EQ.0)THEN
        MUL=5
      ELSE
        MUL=9
      ENDIF
      WRITE(3,9300)MUL,STRN,STRESS,T
    ENDIF
1650  TYPE 9050,STRESS
      C   IF(STRESS.LT.0.0) GOTO 1700
      WRITE(4,9400)T,STRESS
1700  ENDIF
      C
      C
      C
      I=I+1
      C
      DO 110 K=1,5
        ITAY(K)=0
110   CONTINUE
      C

```

```

      IF(1.LT.NDT)THEN
        GOTO 1000
      ELSE
        GOTO 2000
      ENDIF
C
C      ***** LOOPING END *****
C
2000  TYPE 9500
      ACCEPT 9550, IANS
C
      IF(IANS.NE.1)GO TO 6000
      GO TO 50
C
C      ***** FORMAT *****
C
8500  FORMAT('1','* QUASI LINEAR VISCOELASTIC LAW')
8600  FORMAT(' THIS PROGRAM PERFORM THE CYCLIC RELAXATION')
8610  FORMAT(' FOR THE 5-CYCLIC TEST PERIODS.')
9000  FORMAT('0',' PLEASE ENTER THE FOLLOWING INFORMATION: ')
9010  FORMAT('$ ENTER THE PROCESSED RAWFILE NAME: ')
9020  FORMAT(11A1)
9030  FORMAT('$ ENTER THE PROCESSED SUMFILE NAME: ')
9040  FORMAT('$ ENTER THE 1ST STRAIN LEVEL: ')
9050  FORMAT(F10.4)
9060  FORMAT('$ ENTER THE 2ND STRAIN LEVEL: ')
9070  FORMAT('$ ENTER THE 3RD STRAIN LEVEL: ')
9080  FORMAT('$ ENTER THE 4TH STRAIN LEVEL: ')
9090  FORMAT('$ ENTER THE 5TH STRAIN LEVEL: ')
9100  FORMAT('$ ENTER THE 1ST STRAIN RATE: ')
9110  FORMAT('$ ENTER THE 2ND STRAIN RATE: ')
9120  FORMAT('$ ENTER THE 3RD STRAIN RATE: ')
9130  FORMAT('$ ENTER THE 4TH STRAIN RATE: ')
9140  FORMAT('$ ENTER THE 5TH STRAIN RATE: ')
9150  FORMAT('$ ENTER THE 1ST CYCLIC TEST PERIOD: ')
9160  FORMAT('$ ENTER THE 2ND CYCLIC TEST PERIOD: ')
9170  FORMAT('$ ENTER THE 3RD CYCLIC TEST PERIOD: ')
9180  FORMAT('$ ENTER THE 4TH CYCLIC TEST PERIOD: ')
9190  FORMAT('$ ENTER THE 5TH CYCLIC TEST PERIOD: ')
9200  FORMAT('$ ENTER THE TIME BETWEEN DATA POINTS(DELTA): ')
9300  FORMAT('R',I1,2F10.4,F10.3)
9400  FORMAT('R1',F10.3,F10.4)
9500  FORMAT('$ DO YOU WANT TO CONTINUE? (1=YES,0=NO): ')
9550  FORMAT(I6)
C
6000  CLOSE(3)
      CLOSE(4)
C
      STOP
      END
C
C      ***** FUNCTION *****
C
C      ***** ROMBERG INTEGRATION *****
C
      FUNCTION ROMBRG(A,B,Q,U,MM1,M,CK)
C
C      COMMON T,CTP2,CTP4,IT,IN,NCTP(5),ITAY(5),TK(5),R(5)
C
      DOUBLE PRECISION T,XL,XU,XINT

```

```

2, EK, TXL, TXU, H, TXLQZ, TXUQZ, EXPXL, EXPXU, ELSXL, ELSXU, FL, FU
2, XH, TXH, TXHQZ, EXPXH, ELSXH, FH, V, PP1(6,6), ROMBRG
C
C
JT=IT-INT(IT/2.0+0.3)*2-1
KT=JT+1
N=1
C
120 IF(IT.LE.NCTP(N))THEN
      KK=N
      TKK=TK(KK)
      RR=R(KK)
      ITAY(KK)=IT
    ELSE
      N=N+1
      GOTO 120
    ENDIF
C
***** GET THE X-INTERCEPT *****
IF(IT.EQ.1)THEN
  XINT=0.0
ENDIF
JTEM1=ITAY(3)-ITAY(1)
JTEM2=ITAY(5)-ITAY(3)
IF(KT.EQ.1)THEN
  IF(JTEM1.EQ.1)THEN
    XINT=XINT+CTP2
  ELSEIF(JTEM2.EQ.1)THEN
    XINT=XINT+CTP4
  ENDIF
  XINT=XINT
ELSEIF(KT.EQ.0)THEN
  XINT=XINT+2.0*TKK
ENDIF
C
***** GET THE LOWER AND UPPER LIMIT *****
IF(IT.EQ.1)THEN
  XL=0.0
ELSEIF(JTEM1.EQ.1)THEN
  XL=XL+CTP2
ELSEIF(JTEM2.EQ.1)THEN
  XL=XL+CTP4
ENDIF
C
IF(IT.NE.IN)THEN
  XU=XL+TKK
ELSE
  XU=T
ENDIF
C
***** INSTANT ELASTIC RECOVERY('EK') *****
IF(KT.EQ.1)THEN
  EK=0.0
ELSEIF(KT.EQ.0)THEN
  EK=0.0085*(1.0/(IT/2.0))
ENDIF
C
***** START THE ROMBERG INTEGRATION *****
IF(T.GE.XU)THEN
  TXU=T-XU
ELSE
  TXU=0.0
ENDIF
IF(T.GE.XL)THEN
  TXL=T-XL
ELSE
  TXL=0.0
ENDIF
IF(XU.GE.XL)THEN
  H=XU-XL

```



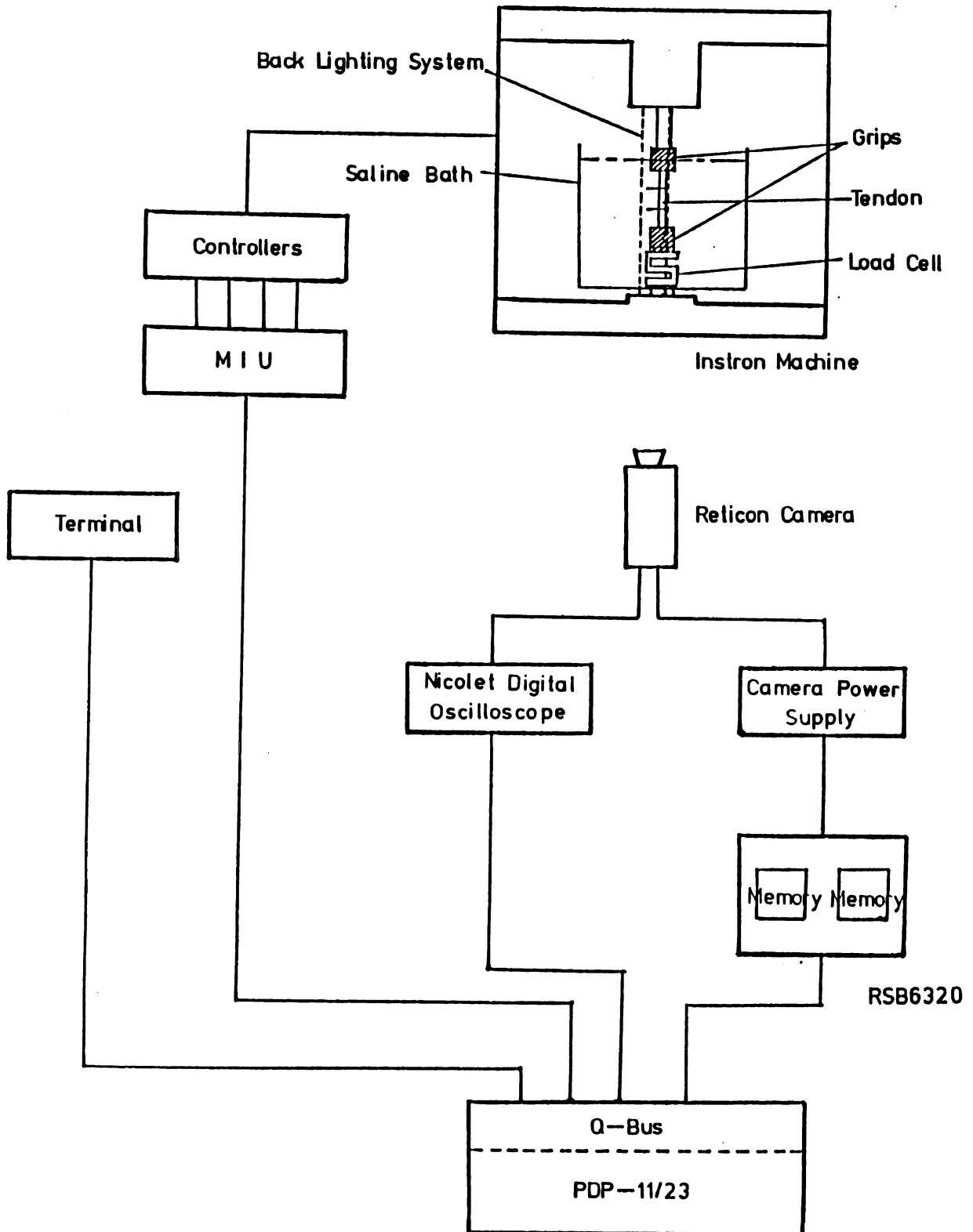
```

ELSE
  H=0.0
ENDIF
C
SIT=-1.0**(IT+1)
BB1=SIT*RR**M*M*CK
TXLQZ=TXL**Q*U
TXUQZ=TXU**Q*U
EXPXL=1.0/DEXP(TXLQZ)
EXPXU=1.0/DEXP(TXUQZ)
ELSLX=(SIT*(XL-XINT)+EK)**MM1
ELSXU=(SIT*(XU-XINT)+EK)**MM1
FL=BB1*(A+B*EXPXL)*ELSLX
FU=BB1*(A+B*EXPXU)*ELSXU
C
PP1(1,1)=0.5*H*(FL+FU)
C
K=5
KP=K+1
KC=1
DO 4 I=1,K
V=0.0
DO 3 J=1,KC
X=J
XH=XL+(X-0.5)*H
C
IF(T.GE.XH)THEN
  TXH=T-XH
ELSE
  TXH=0.0
ENDIF
TXHQZ=TXH**Q*U
EXPXH=1.0/DEXP(TXHQZ)
ELSXH=(SIT*(XH-XINT)+EK)**MM1
FH=BB1*(A+B*EXPXH)*ELSXH
3
V=V+FH
C
V=V*H
PP1(I+1,1)=0.5*(PP1(I,1)+V)
KC=2*KC
H=0.5*H
4
C
C
C
***** ROMBERG EXTRAPOLATION *****
C
W=4.0
DO 8 I=2,KP
WM=W-1.0
DO 6 J=I,KP
6
PP1(J,I)=(W*PP1(J,I-1)-PP1(J-1,I-1))/WM
8
W=4.0*W
C
ROMBRG=PP1(6,6)
C
C
***** GET THE LOWER LIMIT FOR NEXT 'IT' *****
C
XL=XL+TKK
C
C
RETURN
END

```

Appendix 9

Test Diagram for Measuring Surface Strain with Reticon Camera



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