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Relaxation of Prestressed Steel Used in Construction of the Confederation Bridge

Saleh Abu Dabous

A Thesis

In

The Department

of

Building, Civil and Environmental Engineering

(Civil Engineering Program)

Presented in Partial Fulfillment of the Requirements
for the Degree of Master of Applied Science
Concordia University
Montreal, Quebec, Canada

May 2000

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ABSTRACT

Relaxation of Prestressed Steel Used in Construction of the Confederation Bridge

Saleh Abu Dabous

Relaxation is one of the main sources of time–dependent stress losses in prestressed concrete construction. In the present study, an experimental investigation of the stress relaxation of the prestressing steel used in construction of the Confederation Bridge is undertaken. Relaxation is measured by monitoring the reduction in stress level in an elastically strained specimen and maintained at a constant extension.

Two testing methods are adopted for the experimental program, namely, the release method and the lateral deflection method. A special setup is built for each of the two testing methods. Six specimens are tested using the release testing method. Of these, two specimens are tested at each of the three initial stress levels: 60%, 70% and 80% of the ultimate strength of the steel. The lateral deflection testing method is conducted on two specimens at two initial stress levels of 60% and 70% of the ultimate strength of the steel.

The experimental results of this research are compared with steel stress relaxation estimated by the PCI expression and the CEB-FIP Code equation. These comparisons show that the available expressions underestimate the magnitude of stress relaxation losses. Based on the results of this research, an alternative equation to estimate stress relaxation of steel is proposed.

To My Parents

ACKNOWLEDGMENT

I wish to express my appreciation and gratitude to my supervisor, Dr. Mamdouh M. El-Badry, for his advice, guidance and encouragement throughout the course of this work.

This research has been financially supported by Collaborative Research and Development Grant provided by the Natural Sciences and Engineering Research Council of Canada (NSERC), Public Works and Government Services Canada, and Strait Crossing Inc. (SCI). This financial support is gratefully acknowledged.

Collaboration of the staff of SCI, particularly Dr. Gamil Tadros in providing the prestressing steel samples used in this research is very much appreciated. Mr. Eric Damson of the University of Calgary manufactured and provided the low precision load cells needed for the research.

The help of the technical staff, especially Mr. Andrew Chociwski and Mr. Danny Roy, of the Department of Building, Civil and Environmental Engineering, Concordia University, is greatly appreciated.

I am greatly thankful to my parents for their love and encouragement. Also, I wish to acknowledge the unlimited support that has been given to me by my sister, Amal, my brother in law, Mr. Ahmad Dekis, and their children Alaa, Anas, Muthana, Ayat, Koutyba and Houzyfa. I am forever indebted to them.

Finally, My greatest thanks go to my God, by whose blessing I was able to preserve throughout the completion of this research work.

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E	Modulus of elasticity of the material
J	Factor depending on steel type and equals to 1.5 for stress relieved wires, and strands $\frac{2}{3}$ for low relaxation strands
K	Factor depending on the type of steel and equals 10 for stress relieved wires and strands, and 45 for low relaxation steel
L	Length of specimen
M	Factor depending on steel type and equals 10 for stress relieved wires and strands, and 45 for low relaxation steel
η_t	Dimensionless parameter
P	Prestressing force in the steel specimen at time t
P_i	Initially applied prestressing force to steel specimen
t	Time in hours
t_i	Time of application of the initial prestressing force
W	Weight applied at the middle of the steel specimen in the lateral deflection test
Y	Lateral deflection at the middle of the steel specimen in the lateral deflection testing
σ_{pi}	Initial stress applied to prestressed steel
σ_{pt}	Stress in the prestressed steel at time t
σ_{pu}	The ultimate strength of the prestressed steel

σ_{py}	Yield strength of the prestressed steel
σ_r	Relaxation limit, that is, the maximum stress that can be applied to the specimen and stress relaxation will not occur
$\Delta\sigma_{ps}$	Loss in prestress due to creep, shrinkage and relaxation
$\Delta\sigma_{pt}$	Loss of steel stress due to relaxation at time period of t after application of the initial stress
ε	Total strain in steel wire
χ_r	Reduction factor to modify the intrinsic relaxation value to account for the effect of shortening of concrete
λ	Initial stress ratio with respect to yield stress (σ_{pi}/σ_{py})

CHAPTER ONE

INTRODUCTION

1.1 General

The Confederation Bridge connecting Prince Edward Island to the Province of New Brunswick is the largest prestressed concrete box-girder bridge in the world. The total length of the bridge is 12.9 km and consists of 45 main spans of 250 m each, in addition to approach spans. Each segment of the bridge is composed of three large precast units: the pier, the main girder and a drop-in sector. Each unit is cast in a number of segments, which are tied together by internal post-tensioned bonded cables. Externally prestressed tendons are also employed in the Confederation Bridge to supplement the internal bonded tendons and to provide continuity between the precast units.

The design criteria employed for this bridge are not covered by available design codes. Therefore, a comprehensive monitoring and research program is currently in progress to monitor and study the performance of the bridge under the effects of service loads and the surrounding environmental conditions. Included in the monitoring program are measurements of deformations, ice forces, temperature variations and dynamic behavior. The part of this monitoring program on deformations involves measurements of material properties, including the compressive strength, the modulus of elasticity, creep and shrinkage of concrete and relaxation of prestressed steel, which significantly affect the behavior of the bridge under service conditions. These material parameters are measured on samples of concrete and prestressed steel taken from the construction site and kept in the same or similar environment as the bridge. The research presented in this thesis is concerned with relaxation of the prestressed steel used in construction of the Confederation Bridge.

Monitoring of deformations of the Confederation Bridge during its construction and since its completion in 1997 provides a rare opportunity for calibration of the analysis techniques employed in its design. The monitored data will be valuable for improving the computer modeling techniques and the design standards for long-span prestressed concrete bridges and other structures. A detailed discussion of the monitoring program being carried out on the Confederation Bridge is presented by Cheung *et al* (1997).

Presterssing means applying a predetermined force to a structural member to control the internal stresses that will result in the concrete from the external loading and to limit these stresses to acceptable values. The early prestressing attempts were not successful since understanding of prestressing force losses was not well established.

Prestress loss is the reduction in the initial prestressing force to an effective value. In other words, the loss in prestressing is evaluated as the difference between the initially applied force and the effective prestressing that remains in the member. This loss of prestressing does not affect the strength of the member significantly but it does affect the member's serviceability including concrete stresses, cracking, camber and deflection.

In general, the prestress losses are of two types, instantaneous and time dependent. The instantaneous losses take place directly after application of the initial prestressing. These losses depend mainly on the prestressing procedure. In post-tensioned structures an instantaneous loss occurs due to friction between the prestressed steel tendon and the ducts during the post tensioning process, and due to anchor setting as the anchor slips few millimeters before it grips the end of the prestressing tendon. In pre-tensioned members the instantaneous losses are due to elastic shortening of the concrete. The time dependent losses in prestressing are mainly due to creep and shrinkage of concrete and relaxation of prestressed steel.

Relaxation is an important property of prestressed steel, which is of concern in the analysis of time-dependent behavior of prestressed concrete structures. Relaxation is a phenomenon similar to creep and defined as the decrease in stress with time under constant strain. Relaxation of prestressed steel is usually determined experimentally by stretching a tendon and maintaining its length constant between two fixed points and then measuring the decrease in stress with time. The relaxation obtained from this type of experiment is termed as the *intrinsic relaxation.*

The amount of intrinsic relaxation depends on the type of steel and, to a large extent, on the initial stress level in the tendon and on temperature. The intrinsic relaxation is almost negligible when the initial stress is less than 50 % of the ultimate strength, but increases rapidly as the initial stress approaches the ultimate strength. The intrinsic relaxation over a long period of time can be as high as 15 % of the initial stress (Podolny and Melvile, 1969).

In a prestressed concrete member, however, the prestressed steel commonly experiences a constantly dropping level of stress and its length shortens continuously with time due to the effect of creep and shrinkage of concrete. Thus, the actual relaxation is expected to be smaller than the intrinsic values measured in the tests. Therefore, a reduced relaxation value should be used in the design. This is discussed further in Chapter 2.

The value of intrinsic relaxation is normally provided by suppliers of prestressed steel based on tests of only 1000 hours duration. Several empirical expressions giving the variation of relaxation with time are available in the literature. However, these expressions were developed based on a few data of short-duration tests. A few tests have shown that relaxation of prestressed steel continues for a very long time, although at a very small rate (Gordon, 1952)

1.2 Objective and Scope

The objective of this research is to investigate experimentally the stress relaxation of prestressed steel used in construction of the Confederation Bridge. Samples of the steel tendons used in the bridge were transported from the construction site to Concordia University Structures lab. Eight specimens of the tendons were tested at three initial stress levels: 60%, 70% and 80% of the ultimate strength of the steel. Two methods were used to carry out the tests. Six specimens were tested using the release testing method. In order to verify the results obtained by the release method, two specimens were tested using the lateral deflection testing method.

The experimentally measured amounts of relaxation at temperature controlled environment (i.e., room temperature) are compared with values estimated by equations proposed by PCI Committee for prestress losses (1975) and by CEB-FIP Model Code, (1978). The experimental results have also been used to derive an alternative expression to be used for estimation of the steel relaxation.

Since the Confederation Bridge has been designed for a life span of 100 years, the steel relaxation tests are intended to continue for 20 years to investigate the effects of long-term relaxation on the performance of the bridge.

1.3 Outline of Thesis

In order to achieve the objective of understanding stress relaxation of high strength steel, the thesis includes the following chapters. Chapter Two contains presentation of the factors that affect the stress relaxation and the different testing methods that can be used to carry out the relaxation tests. In addition, a discussion of the theory of steel stress relaxation and the different empirical formulas available to estimate its magnitude are presented. Chapter Three contains a description of the test setup and the two test procedures that are used in this research. The test results are presented in Chapter Four in the form of graphs. A discussion of the test results is presented in Chapter Five. Also, an equation to estimate steel stress relaxation is proposed and discussed in the chapter. Finally, Chapter Six contains conclusions and recommendations for future work.

CHAPTER TWO

LITERATURE REVIEW

2.1 General

Relaxation of prestressed steel is defined as the decrease in stress with time in a tendon elastically strained and maintained at a constant length. This decrease in stress is due to the fact that some of the initial elastic strain is transformed to inelastic strain under the condition of constant strain; correspondingly, the stress will decrease according to the remaining elastic strain. This time dependent property of steel is similar to creep, which is the increase in shortening or elongation of a material subjected to a stress that is constant with time.

Stress relaxation of steel can be measured experimentally by using a special setup and equipment that determine the stress in the tendon while the strain is kept constant with time. Relaxation of steel can also be estimated theoretically by empirical formulas derived based on available experimental data. The amount of stress relaxation measured experimentally by testing a bare steel tendon between two fixed points is termed *intrinsic relaxation*. However, prestressed concrete members experience a continuous reduction in length with time due the effects of creep and shrinkage of concrete. Due to this shortening in member length, the initial prestressing force will decrease; as a result, the amount of stress relaxation will not be the same as estimated under the conditions of constant strain. The designer should be aware of this "reduced relaxation" and apply a certain reduction coefficient to account for the effect of creep and shrinkage of concrete on relaxation of prestressing steel.

This chapter discusses briefly the important factors that affect relaxation of prestressed steel. A review of the different testing methods commonly used to determine the intrinsic relaxation experimentally is given. A discussion of the various empirical equations recommended by the codes of practice for estimating the variation of relaxation with time is presented. The reduction coefficient necessary for calculating the reduced relaxation in prestressed concrete members is also discussed.

2.2 Factors Affecting Stress Relaxation of Steel

The magnitude of stress relaxation of steel is directly influenced by four factors: time, initial stress in the tendon, temperature, and type of steel.

2.2.1 Time

Stress relaxation of steel is a time dependent phenomenon that continues for long time even at a diminishing rate. Relaxation occurs at a very high rate in the first few hours after prestressing and continues at a reduced rate for quite a long period of time. Tests by Magura *et al.* (1964) showed that the amount of relaxation in the first 10 hours after prestressing is approximately 17% of the total relaxation that occurs after 500,000 hours (i.e., 57 years).

2.2.2 Initial Stress

The initial stress has a remarkable effect on the stress relaxation of steel. Experimental results have proven that the higher the initially applied stress, the higher relaxation rate and the percentage of stress loss as a ratio of the initial stress. However, the final stress would remain higher since the initial loading was higher.

Erdelyi (1989) studied the effect of initial stress on relaxation on a 4.4 mm diameter central wire of prestressing strands. The measured relaxation after 5000 hours were 1.8%, 2.75%, 3.9% and 5.1% of the initial stress for initial stress ratios (σ_{pi}/σ_{pu}) of 60%, 70%, 80% and 90% respectively. Also, test results on high strength steel wires by Spare (1952) showed that the projected 10,000 hours loss due to relaxation was 7% and 9.5% of the initial stress for initial stress ratios of 60% and 70% respectively.

2.2.3 Temperature

Temperature has a direct effect on relaxation and strongly influences the rate and amount of decrease in stress. Experiments have shown that increasing the temperature beyond the standard room temperature of 20°C increases the steel stress relaxation. Schwier (1958) found that the loss in stress due to relaxation at 100 °C is eight times the relaxation at 22 °C. ASTM A421-91 specifications for standard relaxation test indicate that the temperature of test specimen should be maintained at 20 ± 2 °C.

2.2.4 Type of Steel

The type of steel is determined by the percentages of its components and the processing treatment. High strength wires and strands are made of billets of high carbon steel and treated by heating, stress relieving and oil tempering. This treatment process is done during manufacturing to produce certain physical properties such as elasticity and ductility. Test results by Everling (1951) showed that the higher the elasticity is the better the relaxation resistance of steel.

Shiraga *et al.* (1996) investigated the effects of Nickel (Ni), Copper (Cu) and Silicon (Si) on stress relaxation of steel bars for prestressing. The test results showed Nickel has no effect on stress relaxation, although Silicon does reduce relaxation losses. In addition, Copper affects stress relaxation values only at elevated temperature. Test results by McLean and Siess (1956) showed that different steel types have different curvatures of logarithmic plots of stress relaxation versus time.

2.3 Relaxation Test Methods

The relaxation test is carried out by measuring the variation of force in a tendon at time intervals after application of the initial force while maintaining the specimen at constant strain. ASTM E 328-86 (1986) divides relaxation test into three categories: 1) tension, 2) compression and 3) bending. The relaxation test should represent the loading case that the mechanical or structural component will resist. For prestressed concrete, tension relaxation test is the one that represents the loading case of prestressing reinforcement. Different test setups and procedures are available in the literature to achieve the goal of carrying out the relaxation test. Magura *et al.* (1964) categorized the relaxation test into four groups according to the method used to measure the variation of force in the tested specimen. The following is a presentation of the four test methods, and the advantages and limitations of each test method.

2.3.1 The Lever Method

The lever method was the first testing technique to carry out the relaxation test in which a lever arm system is used to apply stress to a tendon and maintain the length of tendon at a constant extension. A relatively small load is normally needed to develop the required initial stress in the tendon. After application of the initial stress, a strain indicator connected to the tendon is set to zero. At certain time intervals, the strain gauge is reset to zero by reducing the applied load so as to keep the specimen gauge length constant. The weights used to keep the specimen length constant at different instants of time are used to estimate the remaining stress in the tendon at these time intervals by using a prepared calibration curve that relates weights to force in the tendon (Magura *et al.*, 1964).

The availability of the lever machine in laboratories, since it is used for different testing purposes, has made this testing method popular. However, the machine has certain disadvantages such as complexity of mechanical arrangements and the high cost of test since one test specimen can be tested per machine. Also, this test method does not measure pure stress relaxation directly since the load reduction that should take place to keep the strain constant is used to estimate the stress relaxation. In other words, the lever arm testing method examines the phenomena of creep more than stress relaxation. Also, the accuracy of readings in this method is reduced due to the use of other equipment such as a photocell, contact indicator, or ordinary dial gage (Mihajlov, 1968).

Muspratt (1971) used the lever machine as a load measuring device in testing the relaxation of alloy steel bars. They found that the accuracy of the lever machine was limited due to friction. The relative difficulty of measuring stress using the lever arm device limited the test duration. As a result, extrapolation was used to obtain long term values of relaxation. The trend to use statistical prediction to obtain long term values of stress relaxation is unreliable.

Giui and Reed-Hill (1969) discussed that most of stress relaxation tests that had been reported in literature were conducted using screw-driven testing machines. These machines deform significantly under load, which leads to pronounced error in test results. In machines that use the screw-driven technique to apply load, two problems arise (Medrano and Gillis, 1988). First, the relaxation behavior of the machine varies from test to test, although the machine stiffness is almost constant during each individual test. Second, the machine deformation has not been quantitatively considered in the analysis of test results.

However and in general, the lever arm testing method can be used to estimate stress relaxation. For instant, Goldowski and Hoff (1979) carried out relaxation tests on steel tendons using the Denison Model T55R machine. This machine is a lever arm machine that applies the load manually by a mechanical screw system. Goldowski and Hoff (1979) stated that although the strain was not constant during the test, it was restricted within a small range as allowed by ASTM E 328-75 to approximate a continuous relaxing condition.

2.3.2 The Vibration Method

In this method, a steel wire is stretched between two fixed points and a lateral vibration is produced at the mid-length of the wire at different time intervals. The frequency of lateral vibration is measured and converted to stress by means of calibration curves that relate frequency to stress (Magura *et al.*, 1964).

Testing by this method is relatively simple to carry out. The testing machine is provided with simple steel frame and frequency-measuring device that allows to test several specimens at the same time. This method also allows the use of relatively short-length specimens. Therefore, the testing frames require small laboratory space (Mclean and Siess 1956).

However, in order to obtain accurate results from this testing methods, some precaution have to be taken. First, movement of the anchors at the ends of the wire during frequency measurements may affect the results considerably. Therefore, special attention should be paid to restrain the anchorage system from movement when frequency is measured. Also, it is well known that the material behavior changes under dynamic loading, and therefore, vibration at high frequency may have an effect on the magnitude and rate of stress relaxation. Although it has not been established how significant the effect of vibration on the relaxation process is, the effect of vibration on the test results should be taken into consideration (Mihajlov, 1968).

Because of the simplicity of the test frame and small amount of laboratory required, Magura *et al.* (1964) adopted the vibration technique to study steel stress relaxation. The test results obtained by them shall be discussed in section 2.4.2 of this chapter.

2.3.3 The Deflection Method

In this method, a weight of known magnitude is applied spontaneously to impose a lateral deflection at the middle of a stretched steel tendon or wire. The amount of lateral deflection is converted to stress in the specimen by using a calibration curve that relates stress to lateral deflection (Matthys *et al.* 1995). This method is simple and no special equipment is required to carry out the test.

2.3.4 The Balance Method

The basic concept of this method is to determine the stress in a steel wire through balancing the tension by an external force. The external force is applied at one end of the specimen until the reaction of the near anchorage reaches zero; the force required to reach this condition is the tension in the specimen. This procedure is repeated at different time intervals in order to determine the stress relaxation in the steel specimen (Magura *et al.*, 1964).

A similar method, which does not require release of load, is by means of a load cell placed against one of the end anchors and reads the force in the specimen directly. The advantage of this method is that pure relaxation is directly measured without the need for calibration curves, as in the case of the lever method, the vibration method, and the deflection method. Also, simplicity of use, low cost and high accuracy of available load cells are additional advantages (Mihajlov, 1968).

Another direct measurement technique is implemented by attaching to the specimen a series of dynamometers that measure stress changes in the specimen through its deformation. In this technique, however, it is important that the deformations of the dynamometer to be very small in relation to the length of the specimen in order to ensure that the change in strain in the specimen is negligible. The lack of accurate rigid dynamometer that can be used to sustain large long term forces has made the use of this test method rare compared to the use of load cells or other testing methods (Mihajlov, 1968).

2.4 Mathematical Approach to Understand Stress Relaxation

The previously mentioned test methods are normally employed to observe the steel stress relaxation in order to derive mathematical formulations that describe the stress relaxation-time relationship. In this section, the various expressions available in the literature for estimating the stress relaxation of steel are discussed.

2.4.1 Expressions for Estimating Stress Relaxation

Magura *et al.* (1964) investigated the different factors that affect the stress relaxation of steel in order to develop an expression that estimates the remaining stress in a wire at any instant t after application of the initial stress. The ratio of the initially applied stress to the yield stress of steel, called the initial stress ratio ($\sigma_{pi} / \sigma_{py}$) was found to be the most significant factor that determines the amount of relaxation. Accordingly, Magura *et al.* (1964) decided to express the remaining stress in the wire as a function of time and initial stress ratio. The available test data were analyzed assuming that

$$\sigma_{pt} = \frac{\sigma_{pi}}{1+10^{n}} \tag{2.1}$$

where σ_{pt} is the remaining stress at any time t after application of the initial force; σ_{pi} is the initial stress; n is a function of time and the initial stress ratio and given by the following expression:

$$n = -1.3 + \frac{\log t}{3} \left(\frac{\sigma_{pi}}{\sigma_{py}} - 0.55 \right) \tag{2.2}$$

where σ_{py} is the yield strength obtained at 0.1% offset stress of the stress strain relationship; t is time in hours after application of the initial force. The amount of remaining stress at any time according to Equation (2.1) was plotted for different initial stress ratio as shown in Figure 2.1.

The variation of stress with time in Figure 2.1 was noted to be approximately in linear fashion with the logarithm of time. Based on this observation and on available test data, Magura, et al., (1964) recommended the following formula:

$$\frac{\sigma_{pt}}{\sigma_{pi}} = 1 - \frac{\log t}{10} \left(\frac{\sigma_{pt}}{\sigma_{py}} - 0.55 \right) \tag{2.3}$$

$$\text{for } \frac{\sigma_{pi}}{\sigma_{py}} \geq 0.55$$

The expression recommended by Magura *et al.* (1964) considered the microscopic structure of the material to be the same for all steel types, however, they considered the initial stress ratio (σ_{pi}/σ_{py}) as a variable that changes according to different steel types and takes into account part of the effect of the physical properties of steel.

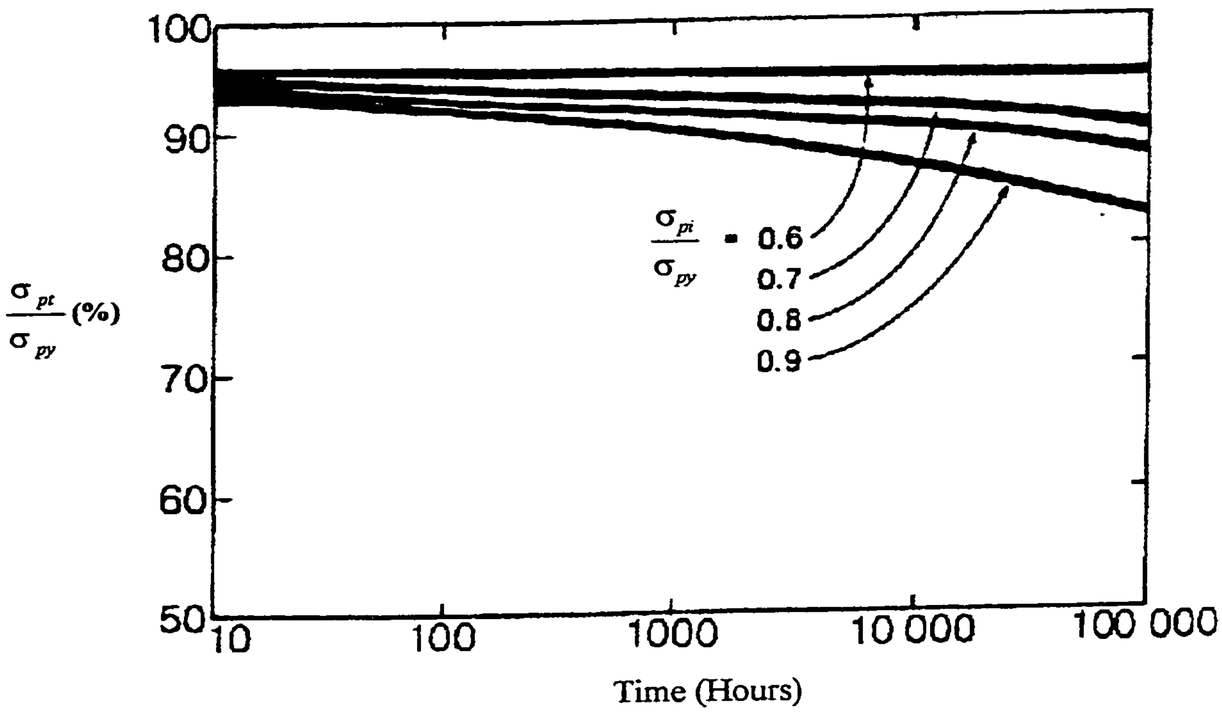


Figure 2.1 - Variation of Steel Stress Relaxation with Time According to Magura, Sozen and Siess (1964).

A statistical study was done also by the Magura *et al.* (1964) to compare the available test results with the empirical formula they proposed. The study showed that Equation (2.3) can be used to estimate the relaxation losses, although, it was not correct to extend the test data to longer duration or different conditions. Also, according to Equation (2.3) proposed by Magura *et al.* (1964), the relaxation in the first hour is zero. This is not true. Based on existing literature and national reports from European countries, Mihajlov (1968) stated that during the first hour of relaxation test on high tensile steel, about 50 to 60 % of the 100 hours relaxation takes place. It can be concluded that the first hour relaxation is of significant amount and should not be considered zero or negligible. Nevertheless, Equation (2.3) gave a better understanding of stress relaxation of prestressing steel and provided more accurate estimate of relaxation than applying a lump sum percentage to reduce the initial stress so as to account for stress relaxation.

Equation (2.3) describes stress relaxation as a simple, straight line semi log curve with 0% relaxation at time $t = 1$ hour, and with a slope that depends on the initial stress ratio. Glodowski, and Lorenzetti (1972) explained that the straight line semi log curve is not an accurate description of stress relaxation for short periods of less than 1000 hours. Based on laboratory experimental results, Glodowski and Lorenzetti (1972) proposed a quadratic equation for extrapolating short term experimental results to estimate long term stress relaxation losses. The recommended equation is of the following form:

$$\frac{\sigma_{pt} - \sigma_{pi}}{\sigma_{pi}} = A + B\,(\ln t) + C\,(\ln t)^2 \qquad (2.4)$$

where A, B and C are functions of the stress level ratio. The stress level ratio used in Equation (2.4) is defined as the initial stress divided by the ultimate strength of steel. The functions *A*, *B* and *C* are for different types of steel according to each type strength measurement.

Similar to Equation (2.3) by Magura *et al.* (1964), Equation (2.4) estimates higher stress relaxation losses at higher stress level ratios. Also, it is reasonably consistent with other methods of predicting stress relaxation. However, this equation has the advantage of being more accurate than Equation (2.3) in estimating stress relaxation at short times. Figure 2.2 is an example of curves predicted by Equation (2.3) and Equation (2.4).

Based on the theoretical and experimental work by Magura *et al.* (1964), the PCI committee on prestress losses (1975) recommended the following expression to estimate the intrinsic relaxation in steel at any time t after the initial stress is applied:

$$\Delta\sigma_{pt} = -\frac{1}{M}\,\sigma_{pi}\left(\frac{\sigma_{pi}}{\sigma_{py}} - 0.55\right)\log\left(\frac{t}{t_i}\right) \tag{2.5}$$

$$\text{for } \frac{\sigma_{pi}}{\sigma_{py}} \geq 0.6$$

where $\Delta\sigma_{pt}$ is the intrinsic relaxation at time t in steel tendon stressed initially at time t_i to σ_{pi}; time is in hours and t_i is greater or equal 1 hour; σ_{py} is the yield strength of prestressing steel; M is a factor depending on the steel type and equals 10 for stress relieved wires and strands, and 45 for low relaxation steel. The minus sign in Equation (2.5) is used to indicate that relaxation is a decrease in the initial stress; the remaining stress in the tendon would be the initially applied stress minus the amount of intrinsic relaxation given by this equation. The advantage of this formula over the equation of Magura *et al.* (1964) is that it takes into account the effect of physical properties of steel on relaxation as it distinguishes between stress relieved and low relaxation steel.

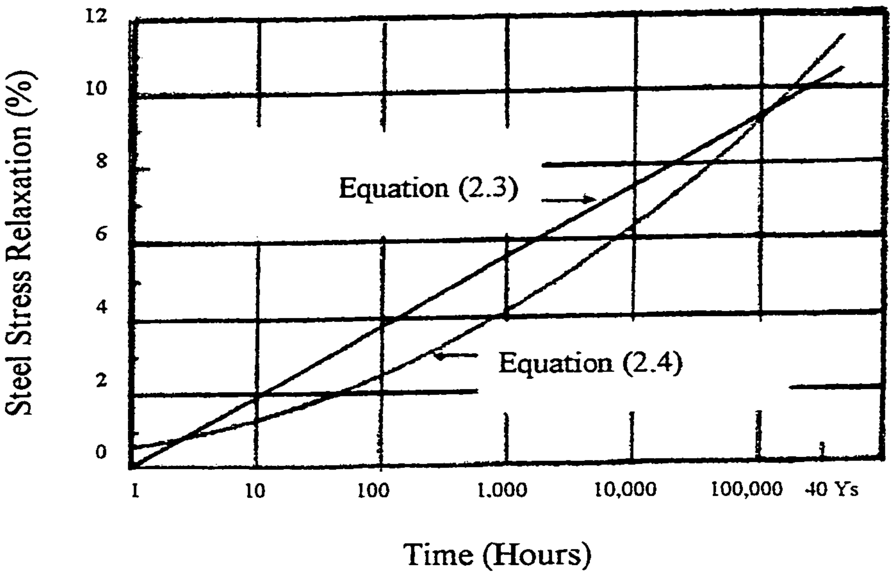


Figure 2.2 - Comparison between Stress Relaxation Values Estimated by Equation (2.8) and Equation (2.9).

The report on prestressing steel by the FIP (1976) employed the theoretical studies and experimental data which indicate that the variation in relaxation with time is linear after a period of time T and recommended the following formula:

$$\log\left(\frac{\Delta\sigma_{pt}}{\sigma_{pi}}\right) = \log\left(\frac{\Delta\sigma_{pT}}{\sigma_{pi}}\right) + k\,(\log t - \log T) \qquad (2.6)$$

where σ_{pi} is the initial stress; $\Delta\sigma_{pt}$ and $\Delta\sigma_{pT}$ are the loss of stress due to relaxation after a periods of time $(t - t_i)$ and $(T - t_i)$, respectively with t_i being the time of application of σ_{pi}; k is a factor depending on the type of steel and represents the slope of the line that relates time to relaxation after time T as shown in Figure 2.3. Values of k available in literatures range between 0.15 and 0.25

This formula recognizes different levels of steel stress and relaxation according to steel type. However, the adopted linear behavior of stress relaxation with time to estimate the remaining stress in steel should be limited by a certain time interval. At the end of this time limit, the steel stress relaxation should be assumed to vanish. This is because if no time limit is adopted, and after a long time period, t, the loss $(\Delta\sigma_{pt})$ derived from linear extrapolation would exceed the initially applied stress. Furthermore, the remaining stress in the steel would become compressive which is impossible. The FIP report indicated that after 10^6 hours (114 years), the actual relaxation would always be less than the value calculated by the formula.

The FIP report (1976) also distinguishes between two groups of prestressing steel according to their relaxation behavior. Group 1 which includes cold-drawn wires and strands and Group 2 which includes quenched and tempered wires and strands which are

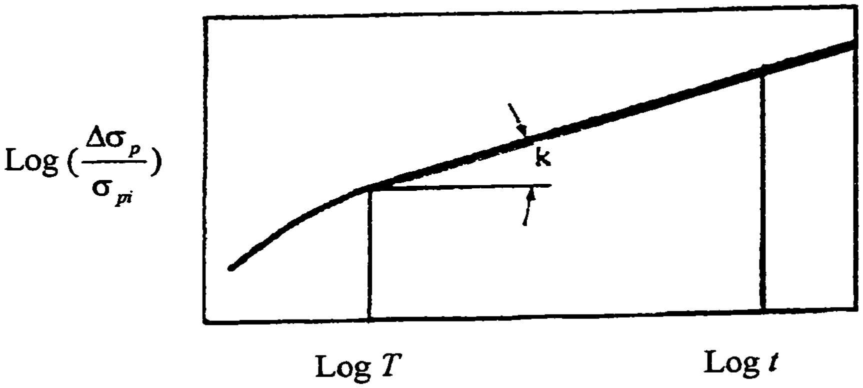


Figure 2.3 - The Relationship between Stress Relaxation and Time Recommend by FIP Committee Report on Prestressing Steel (1976).

specially treated to obtain low-relaxation values. Table 2.1 gives percentages of maximum relaxation after 1000 hours of initial loading for both groups.

For practical purposes, the FIP report (1976) recommends designers to assume that long term relaxation to be 3 times the 1000 hours relaxation. This recommendation was based on values of relaxation at time $t = 50$ years varying between 2.5 and 4.5 times the relaxation after 1000 hours. In case that experimental data is not available, the CEB - FIP Model Code, MC-78 (1978) suggests values of intrinsic relaxation for both types of steel as shown in Figure 2.4. According to this code, values of intrinsic relaxation are given as a function of λ, which is the ratio of initial stress to characteristic tensile strength of steel, $(\sigma_{pi}/\sigma_{py})$. The function is valid for duration of up to 0.5×10^{6} hours. After this long period of time, relaxation can be considered negligible.

Based on experimental results reported in the CEB FIP Model Code (1978) and the FIP report on prestressing steel (1976), Ghali and Trevino (1985) recommended the following formula to estimate the intrinsic relaxation:

$$\frac{\Delta\sigma_{pt}}{\sigma_{pi}} = -J\ \eta_t\ \left(\frac{\sigma_{pi}}{\sigma_{pu}} - 0.4\right)^2 \qquad (2.7)$$

$$\text{for} \quad \frac{\sigma_{pi}}{\sigma_{pu}} \geq 0.4$$

$$\text{and,} \quad \frac{\Delta\sigma_{pt}}{\sigma_{pi}} = 0 \quad \text{for} \quad \frac{\sigma_{pi}}{\sigma_{pu}} < 0.4 \qquad (2.8)$$

where $\Delta\sigma_{pt}$ is the amount of intrinsic relaxation at time t after application of the initial stress, σ_{pi} at time t_i with the time being in hours and t_i is not less than 1 hour; σ_{pu} is the

Table 2.1 - Percentages of Maximum Relaxation After 1000 Hours of Initial Loading for Both Steel Groups Defined in the FIP Report (1976).

$(\sigma_{pi}/\sigma_{py})$	0.6	0.7	0.8
Group 1	4.5%	8%	12%
Group 2	1%	2%	4.5%

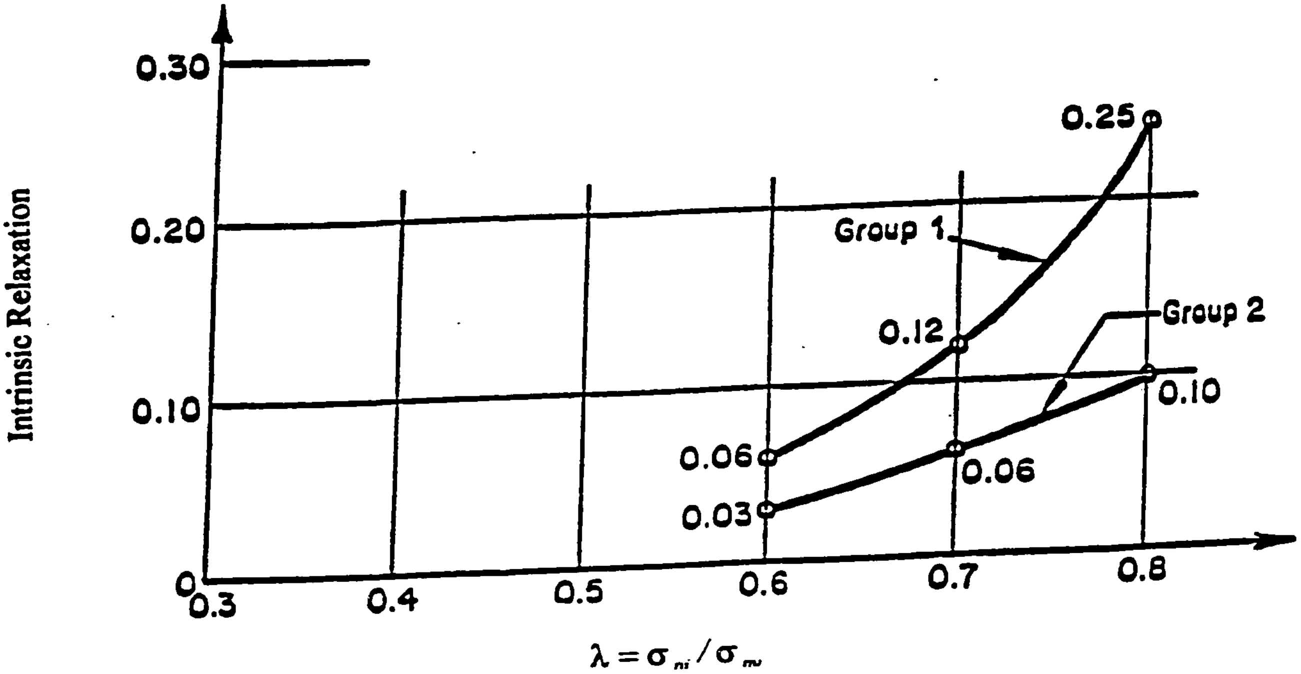


Figure 2.4 - Long-Term Intrinsic Relaxation of Prestressed Steel According to CEB-FIP Model Code (1978).

ultimate tensile strength of steel; J is constant depending on the steel type, $J = 1.5$ for group 1 steel (stress relieved) and $2/3$ for group 2 steel (low relaxation); η_t is a dimensionless coefficient given by

$$\eta_t = \frac{1}{16}\ln\left(\frac{t-t_i}{10}+1\right) \qquad \text{for} \qquad 0 \le (t-t_i) \le 1000 \tag{2.9}$$

$$= \left(\frac{t-t_i}{0.5\times10^6}\right)^{0.2} \qquad \text{for} \qquad 1000 \le (t-t_i) \le 0.5\times10^6$$

$$= 1 \qquad \text{for} \qquad (t-t_i) > 0.5\times10^6$$

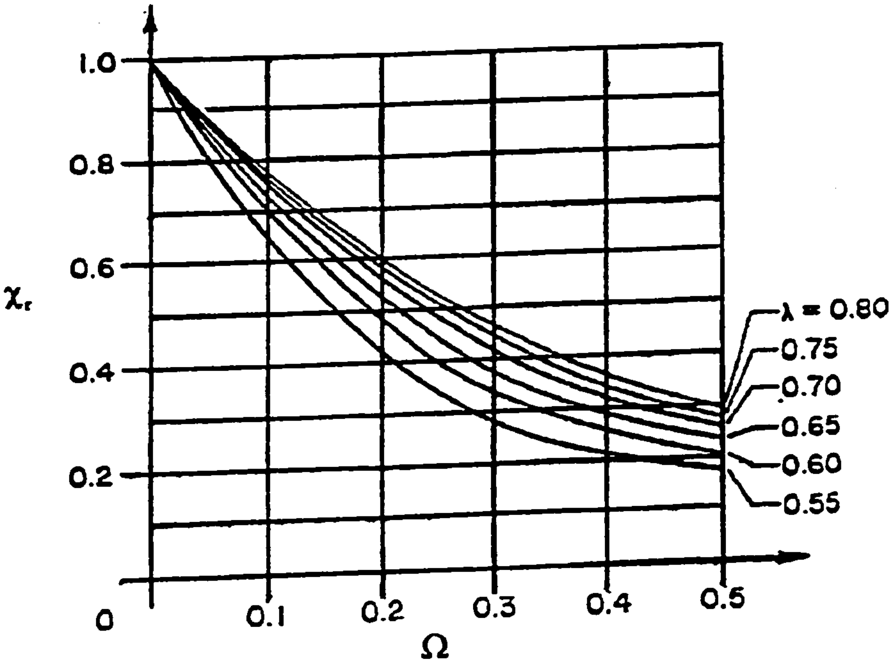
2.5 Reduced Relaxation

As was discussed earlier in this chapter, due to the effect of creep and shrinkage of concrete, prestressed concrete member will experience continuous decrease in length. This shortening will reduce the applied prestressing force in the tendon and, consequently, the amount of steel relaxation. To account for this, the intrinsic relaxation measured experimentally or calculated using one of the empirical formulas should be reduced by a certain amount before using it for design purposes. The CEB-FIP Model Code (1978) recommendation is to reduce the initial tension of the tendon in concrete by subtracting 30% of the actual tension so as to account for the combined effect of creep and shrinkage.

Ghali and Trevino (1985) developed more accurate approach to account for the effect of concrete shortening by reducing the intrinsic relaxation by a reduction coefficient χ_r. The values of χ_r can be obtained directly from Figure 2.5 or calculated using the following fitting equation:

$$\chi_r = e^{(-6.7+5.3\lambda)\Omega} \tag{2.10}$$

Where $\Omega = (\Delta\sigma_{ps} - \Delta\sigma_{pt})/\sigma_{pi}$; the $\Delta\sigma_{ps}$ is the absolute value of change of stress in prestressing steel due to creep, shrinkage and relaxation; the $\Delta\sigma_{pt}$ is the absolute value of the intrinsic relaxation; σ_{pi} is the initially applied stress. The parameter λ is the initial stress to characteristic tensile strength ratio, $(\sigma_{pi}/\sigma_{pu})$.



$$\Omega = -\frac{\text{total prestress change - intrinsic relaxatior}}{\text{Steel stress immediately after tranfer}}$$

$$\lambda = \frac{\text{steel stress immediately after transfer}}{\text{Characteristic tensile strength}}$$

Figure 2.5 - Steel Stress Relaxation Reduction Coefficient According to Ghali and Trevino (1985).

CHAPTER THREE

EXPERIMENTAL PROGRAM

3.1 Objective and Description of the Program

The objective of this experimental program is to investigate the stress relaxation behavior of the prestressed steel used in the construction of the Confederation Bridge. As was defined and discussed previously, stress relaxation of steel is the decrease in the initial stress that is applied to a steel wire or tendon, which is kept at the same initial elongation. Stress relaxation of steel is a time dependent phenomenon and happens over a long period of time starting at a very high rate then slowing down to happen at a vanishing rate. Two requirements need to be fulfilled in the stress relaxation test: 1) the ability to measure the stress in the specimen at different points of time, and 2) to maintain the specimen at a constant elongation equal to that initially applied throughout the test period.

Two of the four testing methods that were discussed in Chapter Two were adopted in this research. These are the release method and the lateral deflection method. Six high strength, seven wire prestressing steel strands were tested using the release method at three initial stress: 60%, 70% and 80% of the ultimate strength of the steel; two specimens were tested at each loading level. Two steel specimens of the same strand type were tested using the lateral deflection method at initial stress levels of 60% and 70% of the ultimate strength of the steel.

3.2 Test Specimens

The test specimens were grade 270, low relaxation prestressing steel strand. The specimens were 3 m long and had a nominal diameter of 15.24 mm. This type of strand is the most commonly used in prestressed concrete construction and can be used in both pretensioned and post-tensioned prestressed concrete structures.

In general, grade 270, seven-wire prestressing strands have a nominal diameter of 9 mm, 13 mm or 15 mm, and typically an ultimate tensile strength of 1860 MPa. Two different types of strands are available: stress relieved and low relaxation. Figure 3.1 shows the manufacturing process of these two types of steel. Stress relieving is the process of removing the residual stress that remains in the strand after the manufacturing process in order to improve the strand elasticity. The low relaxation strand is more effectively improved using strain tempering to reduce time-dependent losses due to stress relaxation of the strand. Table 3.1 presents some characteristics of seven wire strands.

3.3 The Tensile Test

Stress-strain diagram is an important characteristic of a material since different materials have different stress-strain diagrams. The stress-strain diagram for a certain material represents the relationship between the elongation of one unit length of the material, and the applied load. The test to obtain the stress-strain diagram is known as the tensile test and can be conducted by using a universal testing machine. The tensile test is basically carried out by applying axial force to a sample of a certain material that has a gauge length, L, and a uniform cross section. The applied force is gradually increased until the

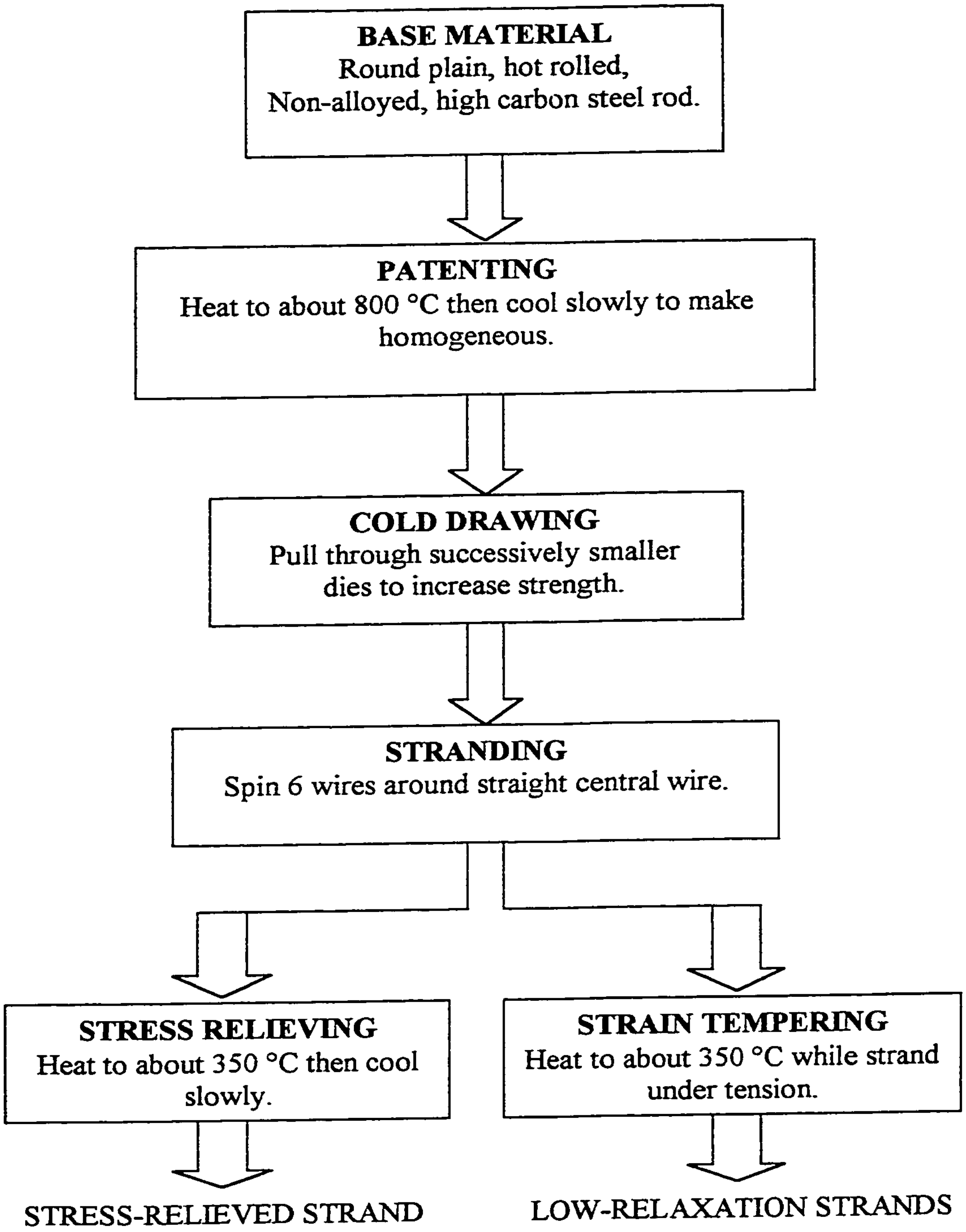


Figure 3.1 - Manufacturing Process of Seven Wire Strands (Doctor, 1996).

Table 3.1 - Major Characteristics of Seven Wire Prestressing Steel Strands (ASTM A416-93, 1993).

Tendon Type	Grade σ_{pu} (Mpa)	Size Designation	Nominal Dimension		Nominal Linear Mass (Kg/m)
			Diameter (mm)	Area (mm^2)	
Seven Wire Strand	1860	9	9.53	55	0.432
		11	11.13	74	0.582
		13	12.70	99	0.775
		15	15.24	140	1.109
	1760	16	15.47	148	1.173

specimen reaches failure. The elongation of the gauge length and the applied force are used to plot the stress-strain diagram. The maximum force applied to the specimen during the tensile test is known as the ultimate strength.

For most of the materials, the relationship between stress and strain is linear until the applied stress reaches a certain limit after which the material properties start changing and the linear relationship is no longer exist. This stress limit is defined as the yield strength of the material. The slope of the linear portion of the stress-strain curve defines the modulus of elasticity of the material, E. The modulus of elasticity, which is also known as Young's modulus is defined by the following relation:

$$\sigma = E \times \varepsilon \tag{3.1}$$

where σ is the stress and ε is the corresponding amount of strain. Young's modulus has the same unit as stress since strain is dimensionless.

Beer and Johnston (1992) discussed the characteristics of different materials. For certain materials such as reinforcing steel, the yield point is obvious on the stress-strain curve. After the yielding point, the material undergoes a large deformation with small increase of the applied stress as shown in Figure 3.2. For other materials such as high strength steel, the yielding point is not clear on the curve. In order to define the yielding point of such materials, the 0.2% offset stress on the curve is considered to be the yield stress as shown in Figure 3.3. In other words, at the strain value of 0.002, a parallel line to the linear portion of stress strain curve is drawn. The point where this parallel line intersects with the stress strain curve defines yield stress of the material.

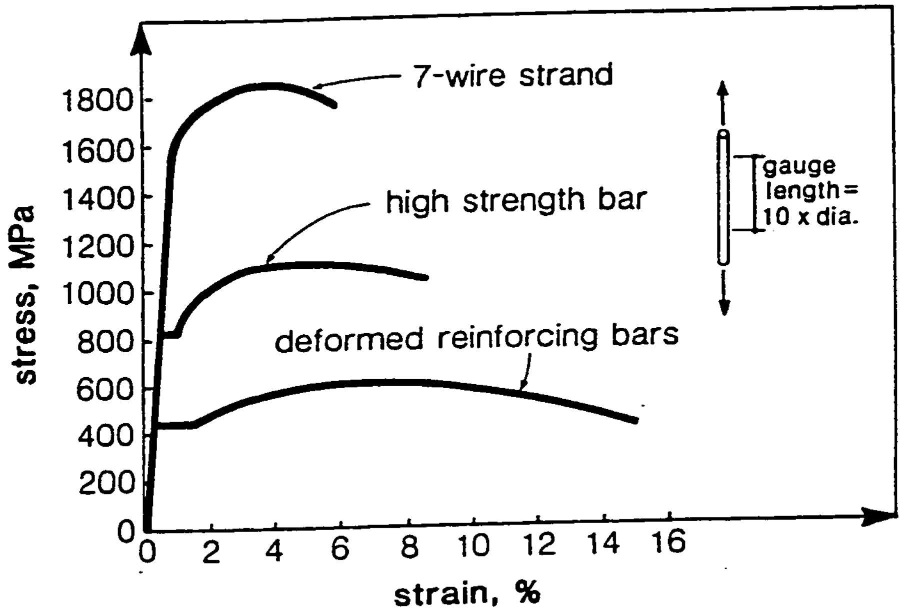


Figure 3.2 - Stress Strain Curve of different types of reinforcement (Collins and Mitchell, 1987).

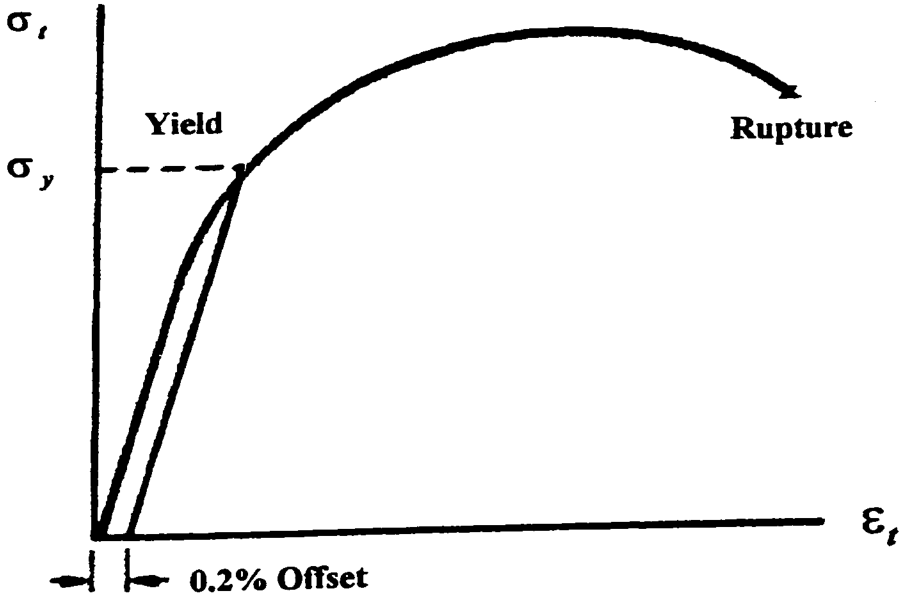


Figure 3.3 - Stress Strain Curve for a Material without Clear Yielding Point (Beer and Johnston, 1992).

Different materials have different stress-strain diagrams and even the stress-strain diagrams from different tensile tests conducted on the same material may vary. This is due to the fact that specimens of the same materials are not exactly identical. Also, the different test conditions, such as the loading rate and the temperature, may lead to different results. Consequently, the tensile test should be conducted on more than one specimen of the material under the same conditions and the mean values of the yield and ultimate strength can be calculated to represent the tested material.

In order to determine the characteristics tensile strength and stress-strain diagram of high strength steel used in construction of the Confederation Bridge, the tensile test was conducted on three specimens. This test was carried out using the universal testing machine on 15 cm gauge length specimens; the gauge length is the length of the specimen that would be affected by the applied stress and was chosen to be 10 times the diameter of the specimen (Collins and Mitchell, 1987).

Once the specimen was placed, the machine was started to apply axial force to the specimen. The machine sensors directly measured the amount of increase in the length of the specimen and automatically plotted a curve that relates the amount of elongation to the applied force. Application of the force was continued until the specimen reached failure. This test was repeated on each of the three specimens. The ultimate strength average value for the three specimens was 264 kN and the yield strength was 249.3 kN. The obtained yield strength meets the ASTM A 416-93 (1993) requirement for minimum yield strength of 234.6 kN. The results of the tensile test and the elongation-force diagrams are presented in appendix A.

In addition, the manufacturer of the steel strands provided a report to certify that the steel strands met the requirements of CSA G279-M and ASTM A416 specifications. The strand certificates provided by the manufacturer are presented in appendix B.

3.4 The Release Testing Method

In general, the release testing method is performed by measuring the force in the tendon by releasing it with a known force. Different procedures and techniques have been proposed to implement this method. In this research, a custom made low precision load cell was inserted to support one of the end anchors so that the force in the tendon could be read directly. A steel frame was designed to release the force from the low precision load cell to a high precision load cell. In addition, this frame was used to apply the initial force to the tendon. A more comprehensive discussion of the setup that was used for the release testing method is given in the following section.

3.4.1 Test Setup and Instrumentation of the Release Testing Method

A testing bed consisting of two steel channels welded together 30 cm apart back to back was used to carry out the test. These channels were bolted to two rigid concrete bases to support them. At the top of the testing bed, two heavy steel plates were welded 130 cm apart to support the specimen during the test. A loading frame was welded to one of these two steel plates. The steel specimen was inserted in a steel pipe. Two end plates and anchors were used to hold the force in the specimen.

Figure 3.4 shows the testing setup. In addition, appendix C includes pictures of the setup. A more detailed description of the test setup is given below.

In order to keep the specimen at the same extension that it reached once the initial force was applied, a 1.5 meter long strong steel pipe with an outer diameter of 102 mm and 25 mm thickness was used for each specimen. Two square ($127 \times 127 \times 25$ mm) end plates with a 25 mm diameter hole drilled at the center of the plate, were used at the ends of the steel pipe to hold the stressed steel specimen against the steel pipe. Two 15-mm anchors were used to maintain the steel specimen at the same extension after application of the initial prestressing force. The 15-mm anchor was the suitable size for the tested strand. This test setup is shown in Figure 3.5.

A bolt and two nuts were inserted between the end steel plate and the low precision load cell. The bolt was drilled along its length so that the steel tendon could pass through it. One of the two nuts was welded to the end plate and the other was left free to move. The mode of operation consists of turning the bolt against the fixed nut to make it move inside or outside the nut which will increase the bolt length or decrease it. If the bolt length increases, this will press on the anchor behind it against the end steel plate and correspondingly maintain or increase the force in the tendon. If the bolt length decreases, the specimen elongation will subsequently decrease which will decrease the force in the specimen. The second nut is used to support the welded nut when the required force in the tendon is reached.

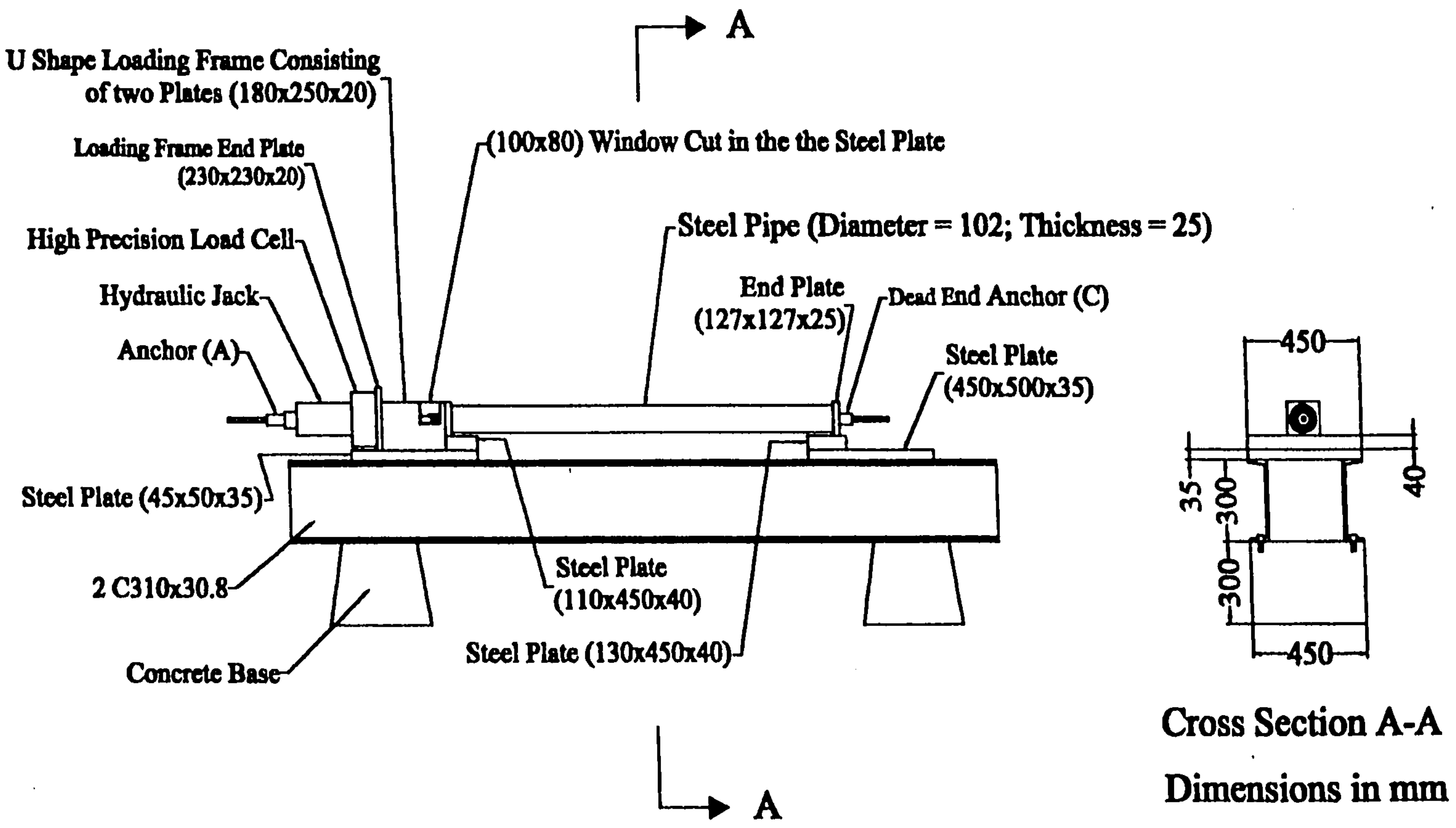


Figure 3.4 – Steel Relaxation Testing Frame at Time of Load Application (Release Testing Method).

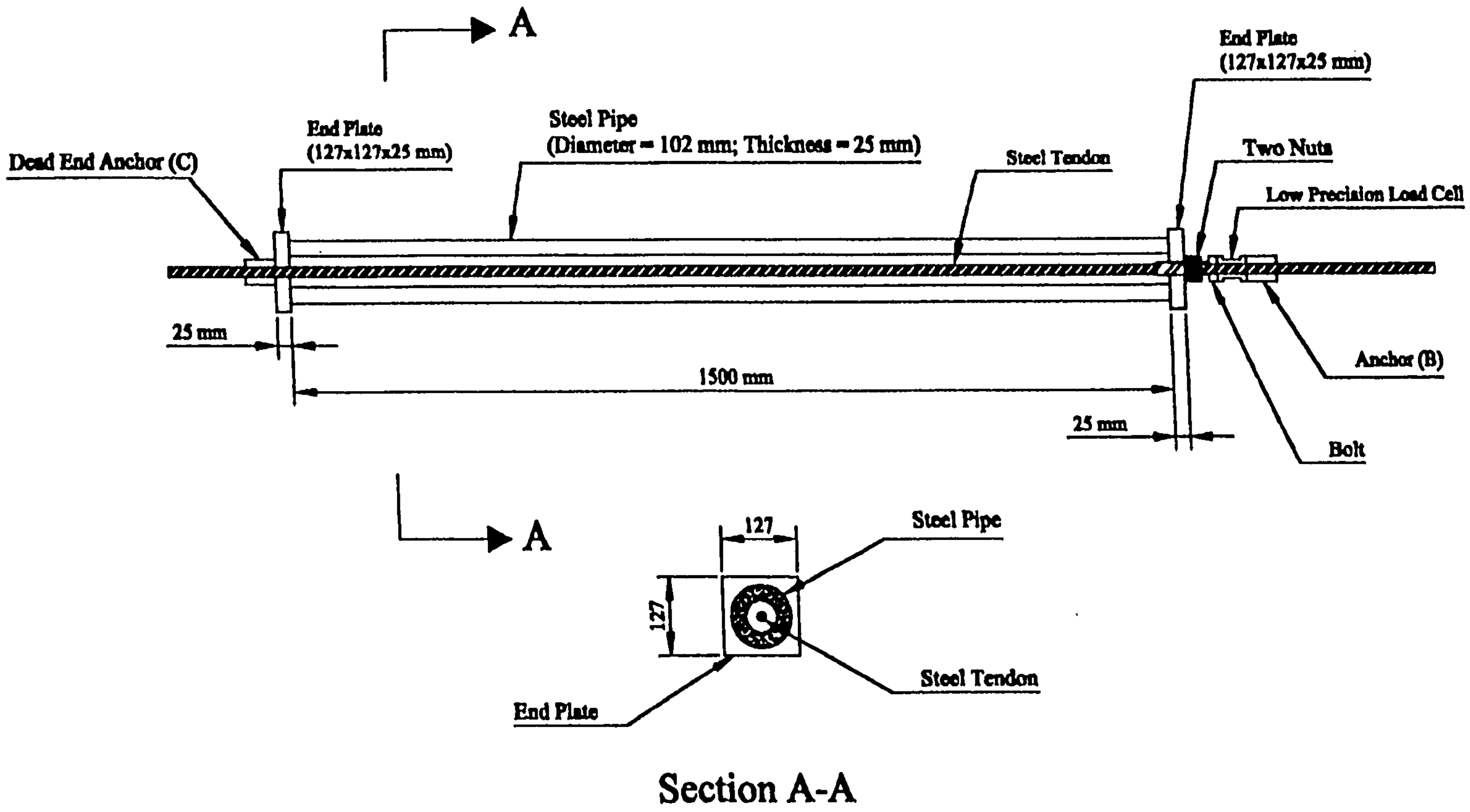


Figure 3.5 – Steel Relaxation Test Setup (Release Testing Method).

The bolt and nuts device was very significant in the testing procedure since it had two important roles. First, to reduce the anchorage slip loss. Since it was difficult to lock the anchor by hand, the bolt and nuts device helped in this task. By turning the bolt to increase its length, the anchor was pushed against its internal jaws. This forced the jaws inside the anchor to grip on the tendon and consequently, reduced the slippage of the anchor to minimum. Second, the bolt and nuts device made it possible to modify the amount of force in the tendon after locking the anchor. Practically speaking, it was almost impossible to release the anchor once it is locked to hold the force in the tendon or more precisely to hold the tendon at the same extension. However, inserting the bolt and nuts device made it possible to adjust the force in the tendon since it was possible to modify the bolt length in order to change the force in the tendon. Modifying the bolt length to adjust the force in the specimen was done without the need to release the anchor.

The loading frame consisted of two rectangular steel pieces (180×250×20 mm) welded 100 mm apart from each other to the strong steel plate placed at the testing bed. The three steel plates formed a U shape frame. One of these pieces was cut at the corner to form a 100×80 mm window. The purpose of this window was to enable the use of the wrench to modify the bolt length. In addition, a 230×230×20 mm steel plate was welded at the back of both the steel pieces as shown in Figure 3.6. This back steel plate had a 25 mm diameter hole at its center through which the tendon was passing. The purpose of the back steel plate was to support the high precision load cell. Finally the hydraulic jack cylinder was placed right behind the external load cell and an anchor was used to lock the loading end of the specimen.

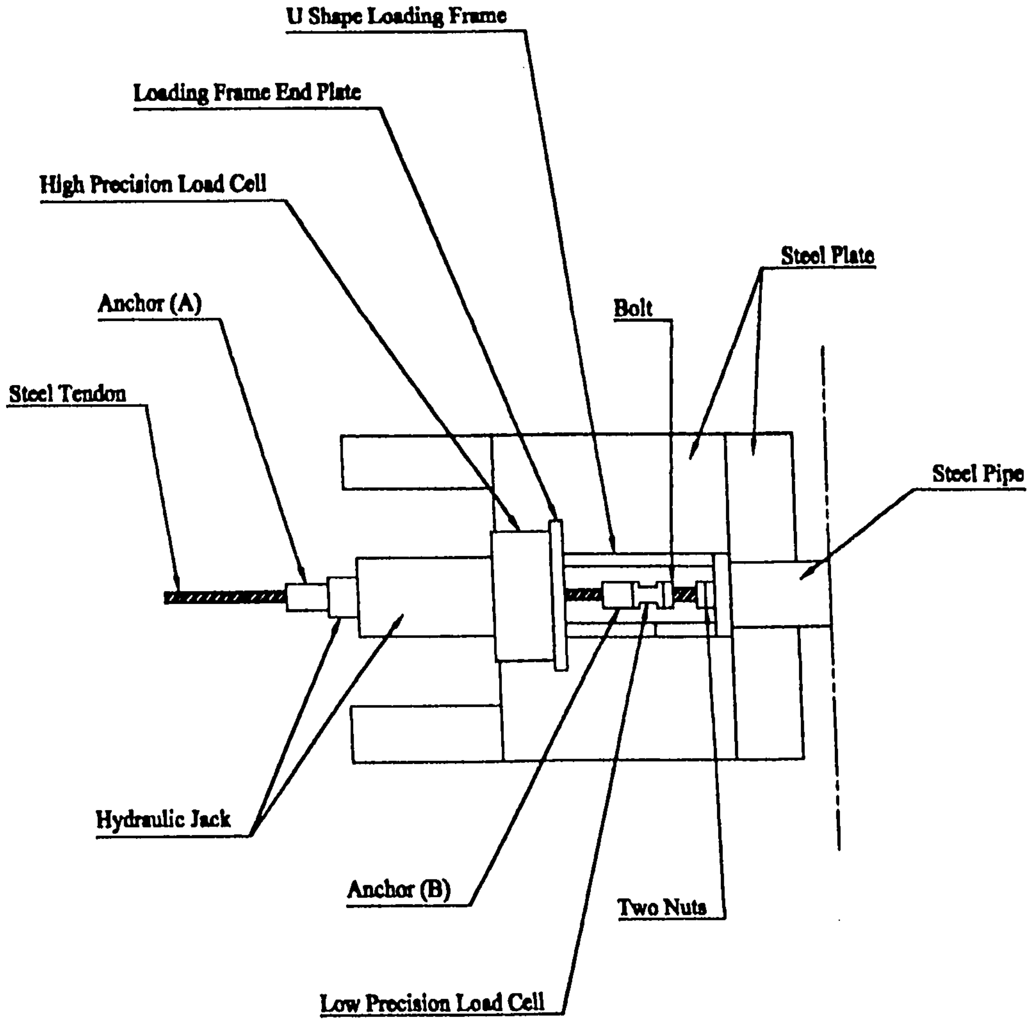


Figure 3.6 - Plan View of the Specimen Attached to the Loading Frame (Release Testing Method).

3.4.2 Procedure of the Release Testing Method

The decrease in the prestressing force in each specimen was monitored in this stage after application of the initial prestrssing. Since relaxation takes place at a very high rate within the first few hours after application of the initial prestressing, a data acquisition computer system was used to record the readings on hourly basis during the first 200 hours. After this period of time a load indicator with a switch box was used to take the readings of the load cells.

Before testing any of the specimens, calibration of all the load cells, the data acquisition system and the load indicator was carried out. Seven channels of the data acquisition system were calibrated; six were used for the low precision load cell. Six channels of the load indicators were used for the low precision load cells.

Calibration of the data acquisition system was carried out by connecting each load cell to one channel and loading the load cell in the universal testing machine by the maximum required load. The reading of the data acquisition system was adjusted by modifying the calibration factor of the channel connected to the load cell until it gave the same reading as the testing machine. The calibration factor was also checked by comparing the readings of the calibrated load cell and the universal testing machine at different levels of load. The calibration process was repeated for each of the seven load cells. The correct calibration factor was saved for each channel to be used in the actual relaxation test. The same calibration procedure was carried out for the load indicator.

After calibration of all load cells, the data acquisition system and the load indicator, the test setup was assembled and the test proceeded in the following steps.

1) The steel pipe with its two end plates were placed on the testing bed in such a way that the end plate with the welded nut was in contact with the loading frame. The bolt was then screwed completely into the two nuts. The U-shape loading frame included the low precision load cell and an anchorage, B, loose inside it as shown in Figure 3.6
2) The steel tendon was inserted inside the steel pipe, the two end plates, the bolt and the two nuts, the low precision load cells and the interior anchorage, B. A length of 150 mm of the steel tendon was left outside the steel pipe on the side of the dead anchorage, C. The dead end anchorage was locked at this stage,
3) At the jacking end, the high precision load cell was bolted to the end plate of the loading frame, with the tendon passing through central hole of the load cell. The hydraulic jack was placed right behind the high precision load cell. Anchorage A was placed and locked so that the hydraulic jack would apply the force against it, causing tension in the tendon. Anchor C was released after application of the total prestressing force to the tendon.
4) The two load cells were connected to the proper channels of the data acquisition system.
5) The initial prestressing force was applied uniformly through the hydraulic jack, which pushed anchor A against the loading frame and the steel pipe. The applied force was monitored by the high precision load cell. Application of the load continued until the reading of the load cell was higher than the required force.
6) The interior anchor B was locked inside the loading frame and the bolt and nuts device was used to seat the wedges of the anchor inside the barrel. This process reduced the anchorage slip loss.

7) At this stage, anchor A and the hydraulic jack were released and the force transmitted to the 1.5 m long tendon inside the steel pipe. The low precision load cell should read the required initial prestressing force in the tendon.

8) If the force recorded by the low precision low cell was not equal to the required initial force, the bolt and nut device was used to adjust the force in the tendon to be equal to the required initial force. If the force in the tendon was higher than the required initial force, the bolt was then screwed inside the nut to reduce its length. To increase the force in the tendon, the same procedure was carried out but the bolt should be screwed out to increase its length and to increase the force in the tendon. The force was adjusted till the required initial force was reached in the tendon. This point of time was designated the zero time of the test. The data acquisition system was then set to take readings for 200 hours starting from the zero time on an hourly basis.

9) After the first 200 hours readings were recorded by the data acquisition system, the specimen was placed on a steel frame that was built to carry the specimens during the long term test. The low precision load cell was connected to the proper channel of the load indicator for which the load cell was calibrated. Readings were taken using the load indicator on daily basis.

10) The same procedure was repeated for the other five specimens. Two specimens were tested at each of the mostly used loading levels in prestressed concrete structures, namely 60%, 70% and 80% of the ultimate strength.

3.5 The Lateral Deflection Testing Method

The basic principle of the lateral deflection testing method is to estimate the force in a stressed steel tendon through measuring the lateral deflection at the middle of the specimen due to a known applied weight. The lateral deflection at the middle of the specimen due to the applied weight will increase if the tensile stress in the specimen decreases. Taking advantage of this fact, steel stress relaxation can be determined by measuring the lateral deflection, which can be used to estimate the force in the tendon.

The lateral deflection values measured experimentally at the middle of the specimen can be used to calculate the force in the tendon using one of the following two methods (Matthys, et al., 1995). First, assuming that the steel tendon is a perfect rope with no flexural stiffness, the following equation applies:

$$P = \frac{W \times L}{4Y} \tag{3.2}$$

where P is the tensile force in the tendon; W is the weight applied at the middle of the tendon; Y is the lateral deflection at the middle of the specimen due to the applied weight; L is the length of the specimen.

Second, since the prestressing steel tendon is not a perfect rope, it is more accurate to use a pre-prepared calibration curve that relates the force in the tendon to the lateral deflection at the middle of the specimen due to the known weight. The same weight should be used in preparing the calibration curve and measuring the lateral deflection at the middle of the specimen.

3.5.1 Instrumentation and Setup of the Lateral Deflection Test

The testing concepts are the same for both the release method and the lateral deflection method. Both of the testing methods can be carried out by maintaining the steel specimen at the same extension that it reaches once the initial force is applied, then measuring the force in the specimen as the time passes. The difference between the two methods is in the instrumentation and in the force measuring technique.

To maintain the specimen at the same extension that it reached once the initial force was applied, strong steel boxes were built. The steel box was made of two 100×1500×25 mm steel plates connected together with two 100×200×25 mm plates welded at both ends of the long steel plates. A 25 mm diameter hole was drilled at the center of each end plate. Twelve 150×200×15 mm steel plates were welded at the top and the bottom of the steel box at 120 mm spacing to make this box stronger. Figure 3.7 shows the steel box with the specimen inside it.

The loading steel frame was the same one used in the release testing method. In addition, the same bolt and nut device was used. Low precision load cells were not used in the lateral deflection method. This was the only difference between using the loading frame in the two testing methods. In the lateral deflection method, force in the specimen was estimated by measuring the lateral deflection and not through a load cell. Figure 3.8 shows the loading frame used to apply force to steel specimen. Also, the loading frame picture is included in appendix C.

Similar to the loading procedure for the release testing method, the high precision load cell was bolted to the end plate of the loading frame and the hydraulic jack was used to apply the initial prestressing force. At the mid length of the steel tendon, a 50×150×20

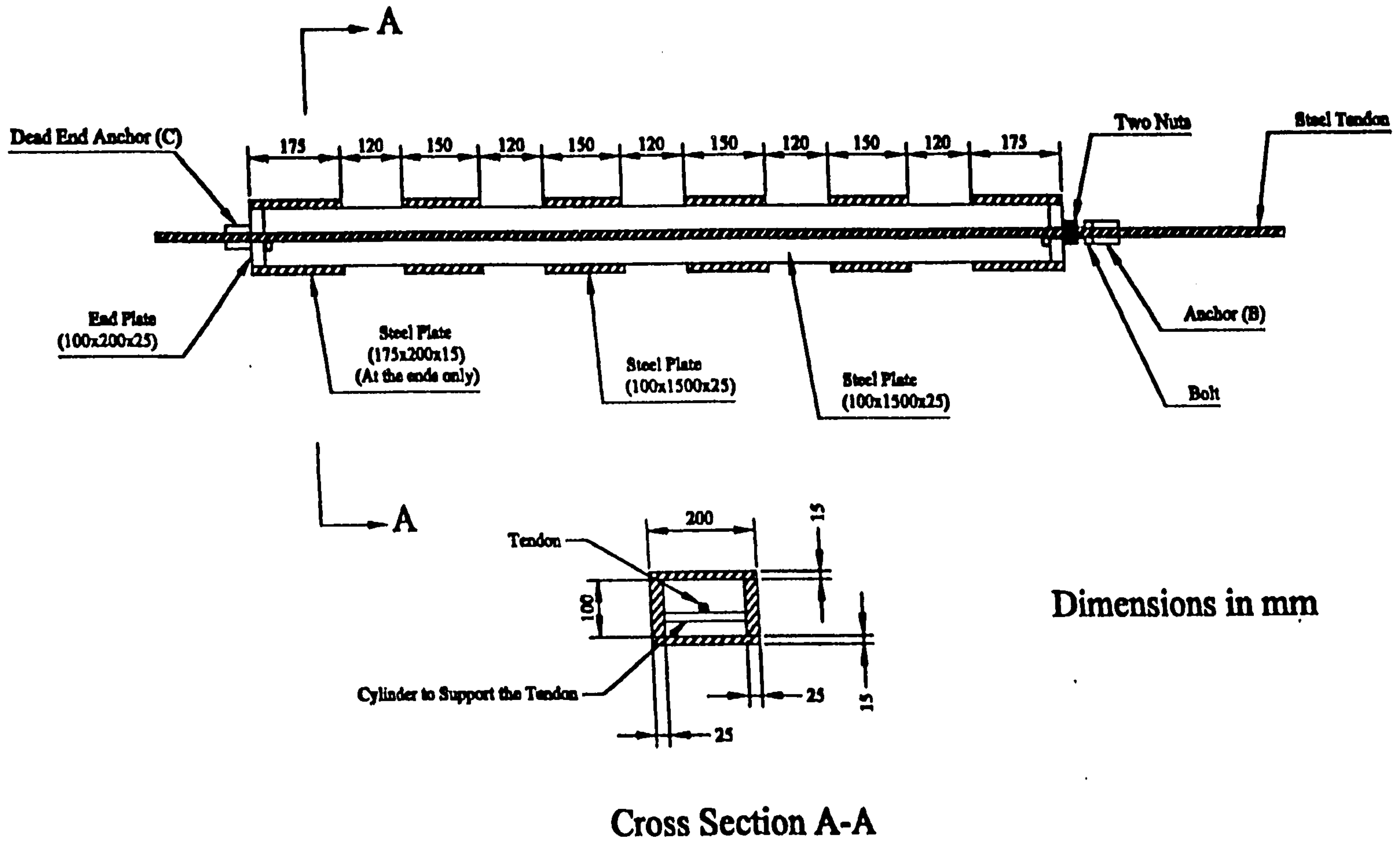


Figure 3.7 – Steel Relaxation Test Setup (Lateral Deflection Method).

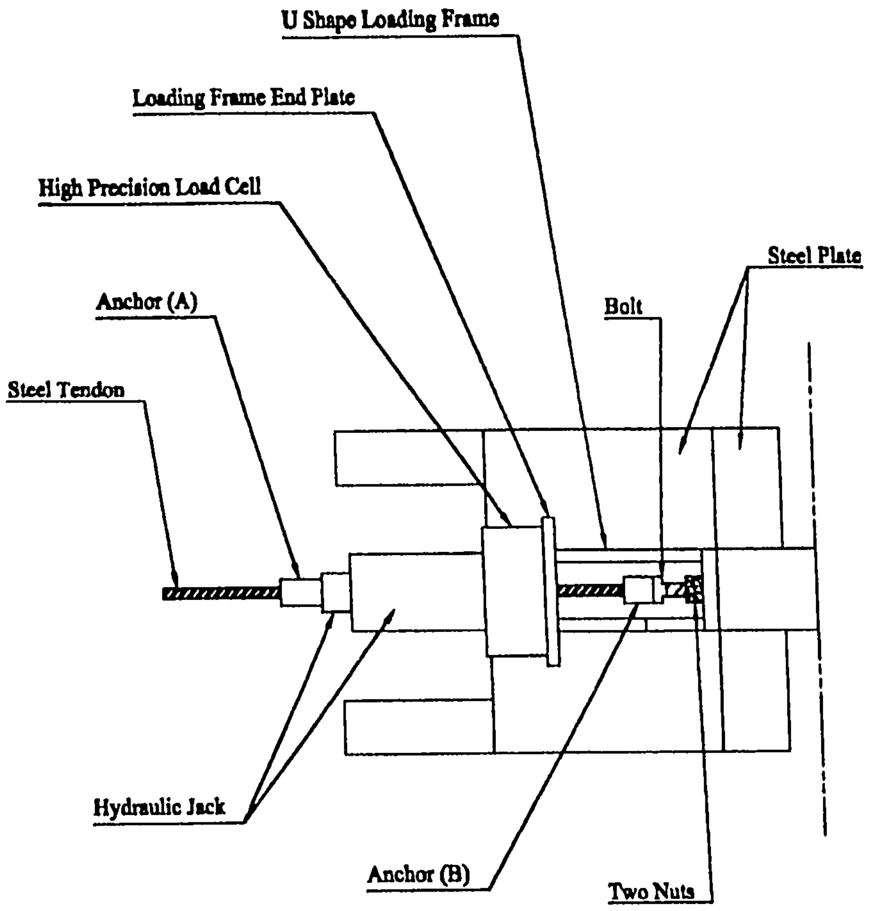


Figure – 3.8 Plan View of the Specimen Attached to the Loading Frame (Lateral Deflection Method).

mm steel plate was used to connect the specimen with the weight that induced the lateral deflection. A steel cage was built to carry rectangle pieces of steel. The total weight of the steel cage including the steel plates was 335 kg. A hydraulic jack was welded to the bottom of the cage to move the weight and apply it to the tested specimen. In addition, a dolly was built to move the weight back and forth from one specimen to another. To measure the lateral deflection at the middle of the specimen, a dial gauge with accuracy of 0.01 millimeter was used. The dial gauge was attached to the specimen to measure the lateral deflection at the middle of the steel tendon. It is important to emphasize that the lateral deflection measurements were taken at exactly the same point where the weight was applied, which was the middle length of the specimen. The lateral deflection testing setup is shown in Figure 3.9.

3.5.2 Calibration Curve of the Force versus Lateral Deflection

In order to be able to relate the lateral deflection at the middle of the stressed specimen to the tensile force in the specimen, a calibration curve describing the relationship between these two variables was needed. In order to establish this calibration curve, a steel tendon was placed longitudinally at the center of the steel box. One end of the tendon was anchored against one of the end plates used as the dead end anchor C. At the other end, which was the loading end, the same U-shape frame that was used to apply the load in the release method was used to apply the force in this test as well. The loading frame front part leaned against the end plate of the steel box whereas the frame rear part supported the high precision load cell. The hydraulic jack was placed behind the load cell

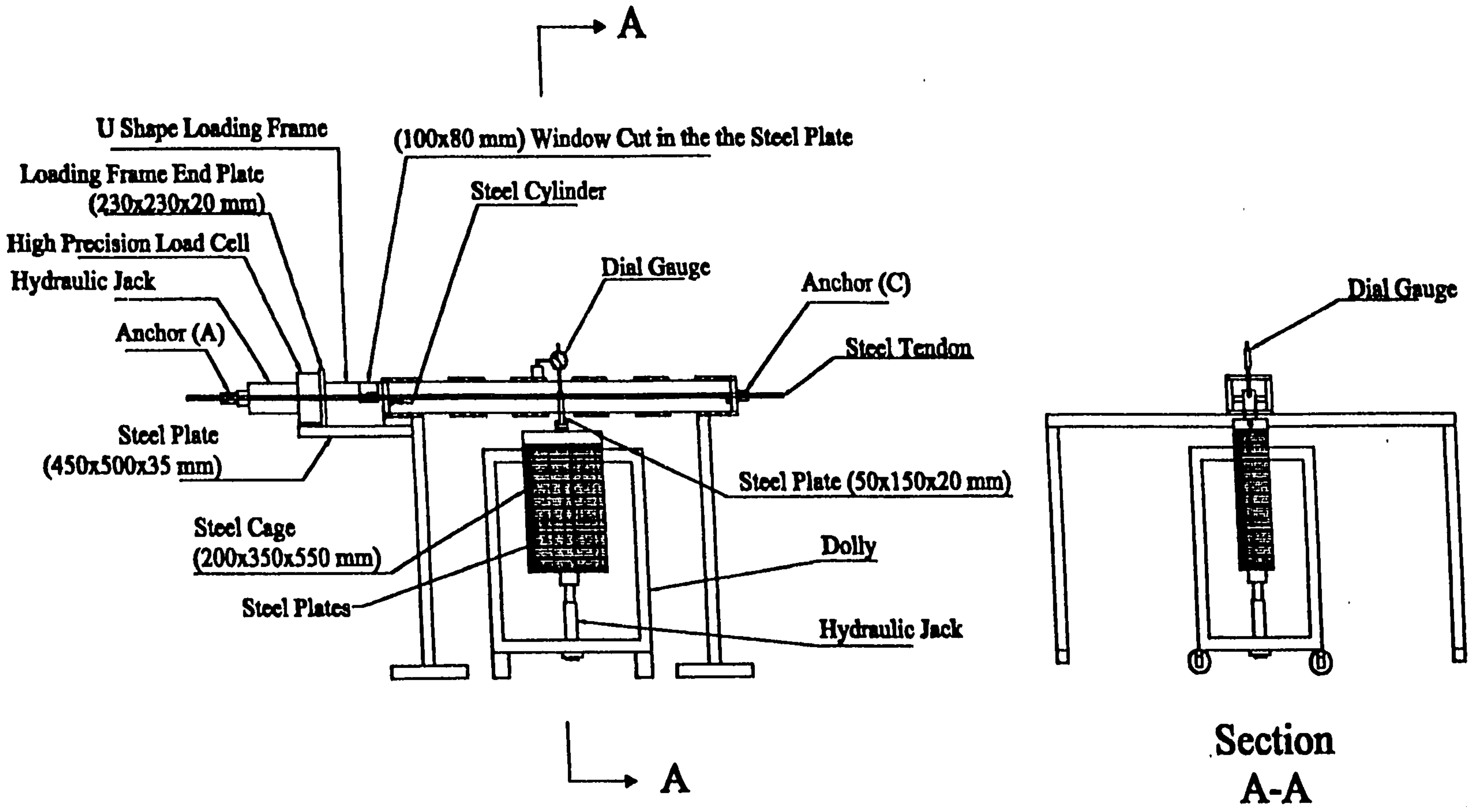


Figure 3.9 - Steel Relaxation Testing Frame at Time of Load Application (Lateral Deflection Method).

and was followed by anchor A. It should be mentioned that the bolt and nut device and anchor B were placed inside the loading frame but left loose to be used in the actual relaxation test. These two parts were not needed in the calibration test.

Thus, the setup consisted of the following elements: the steel box, the loading frame, the external load cell and the hydraulic jack. The same loading setup configuration that was used in the release test was also used in the lateral deflection test, except that the low precision load cell was not used. These elements were connected together by the steel tendon that passed through their centers and was anchored with two anchors, one at each end.

Since the setup elements were supporting each other as one unit, pumping the hydraulic jack pushed anchor A behind the jack against the anchor C placed at the other end of the specimen. This applied the tensile force to the specimen. The force in the specimen was measured by the high precision load cell. The force was gradually increased until the load cell read the required initial stress. At this point of time, the weight was applied at the middle of the specimen to induce a lateral deflection. The magnitude of lateral deflection was measured by means of a dial gauge attached at the middle of the specimen.

After both the force in the tendon and the corresponding lateral deflection were recorded, the lateral deflection was gradually released from the tendon by pumping the hydraulic jack that was placed at the bottom of the cage to move the weight. The complete release of the weight was reached once the dial gauge reading was zero. In other words, no lateral deflection was in the tendon at this time. To take the second lateral deflection measurement, the valve of the hydraulic jack at the loading end of the specimen was slowly released until a decrease of 2 kN in the tendon force occurred. At this new magnitude of force in specimen, the lateral deflection was measured. The same procedure was repeated by decreasing the force in the tendon by decrements of 2 kN and measuring the corresponding lateral deflection. The lateral deflection measurements were recorded for different values of force in the specimen. This procedure was repeated until the force in the tendon was less than the expected remaining force in tendon after all losses due to relaxation took place. For instance, the amount of relaxation loss was estimated to be 20 % of the initial force so the calibration test was stopped when the force in the tendon was 80 % of the initially applied force. The values of the lateral deflection were plotted against the force in the tendon to form a calibration curve.

3.5.3 The Lateral Deflection Test Procedure

Once the calibration test was prepared, the lateral deflection test was conducted. The hydraulic jack was pumped to increase the force in the tendon to reach the required initial force. Then the internal anchor B was seated and locked by the bolt to reduce slippage loss. The hydraulic jack was then released to transmit the force to the 1.5 meter segment of the specimen placed between the steel box end plates. At this point, the exact magnitude of force in the tendon was not known. However, from the calibration curve, the corresponding lateral deflection at the required initial force was estimated. The weight was applied to the specimen to measure the lateral deflection in order to estimate approximately the force. If the measured lateral deflection was more than the deflection corresponding to the initial force, the force in the tendon was increased. To increase the force in the tendon, the hydraulic jack was pumped to release the force from the 1.5 meter specimen segment and the bolt was screwed to increase its length. The force was then released to the 1.5 meter segment and the lateral deflection was checked. This procedure was repeated until the measured lateral deflection was closest to the lateral deflection that corresponds to the initial force. If the force in the tendon was larger than the initially required force, the same procedure repeated but the bolt length was reduced to decrease the force in the tendon.

Once the initial force in the tendon was reached, the time was considered to be the zero time. The lateral deflection was measured at different time intervals by applying the weight temporarily at the middle of the specimen. Lateral deflections measurements were recorded on an hourly basis for the first 8 hours then recorded on daily basis.

The values of the lateral deflection recorded in this test were used to determine the force in tendon from the calibration curve. The values of tensile force in the tendon at different points of time were used to estimate the relaxation with time using the following formula:

$$\%\ \text{Relaxation} = \frac{P_i - P}{P_i} \times 100 \tag{3.3}$$

where P_i is the initial prestressing force and P is the force in the tendon at any time t.

CHAPTER FOUR

TEST RESULTS

4.1 General

Stress relaxation of steel is a time-dependent phenomenon that lasts for a long period of time even at a small rate. As a result, studying this phenomenon requires continuos monitoring program that last for adequate time period. Several researchers have established different time limits to represent the infinity point of time after which stress relaxation will be negligible with respect to the relaxation that have occurred in the previous period. Some researchers consider that most of the relaxation losses take place during the first 1000 hours while others have gone far beyond that and studied relaxation for a long period of time, up to 500,000 hours.

In this research, a total of six specimens of the prestressing steel used in the construction of the Confederation Bridge were tested using the release method. Two specimens were tested at each of three initial loading levels, namely, 60%, 70% and 80% of the ultimate strength of the steel. Two additional specimens were tested using the lateral deflection method. One specimen was initially prestressed with 60% and the other with 70% of the ultimate strength of the steel. This chapter presents the results of the experiments conducted to measure stress relaxation with time.

4.2 Results of the Release Testing Method

After application of the initial prestressing force to the tested specimen and maintaining it at a constant extension, force measurements in the tendon were recorded through the load cell that was inserted at the loading end of the specimen. This load cell sustained the same amount of force in the specimen. As a result, its readings represented direct measurements of the force. Initially readings were recorded at short time intervals since the stress relaxation rate was high after application of the initial force. The relaxation rate slowed down as time passed and therefore steel relaxation readings were taken at longer time intervals after the first 200 hours. A data acquisition system and a load indicator were used to record the readings. The data acquisition system was used to record hourly force readings during the first 200 hours after which the load indicator was used.

The release test setup was built to release the force in the specimen from the low precision load cell to the high precision one. The goal of this release was to check the low precision load cell measurements against the measurements of the high precision one. Theoretically, it should be possible to completely relieve the load cell without affecting the tension in the specimen. The test setup was successful in performing this task. The force release was carried out on the first specimen then it was stopped for of the following reasons. First, the low precision load cells have a different elastic response than the high precision one since they were made from different materials. The low precision load cells have a low elasticity because they were made of aluminum material and required long time to rebound. As a result, it was not possible to determine the point of time when the load was completely released to the high precision load cell. Thus, force measurements recorded by releasing the force to the high precision load cell were subjected to high error. Second, because of the impact of releasing and reloading, a drift in the low precision load cell reading occurred. In addition, it was a concern that the repeated releasing and reloading will destroy the low precision load cell. Given that the low precision load cells were calibrated using the high precision one. In addition, since the continuity of stress relaxation readings was very important and this test is intended to be long term test, up to 20 years period, all data obtained were based on the readings of the low precision load cells.

Magura *et al.* (1964) recommended that relaxation data should be plotted using the logarithmic scale of time. Most of the researchers adopted this approach to represent stress relaxation data. They made this recommendation for two reasons. First, they noticed that the relationship between the ratio of force in the tendon to the initial force and the logarithm of time is linear. This enabled the derivation of a mathematical equation to estimate the relaxation losses. Second, steel stress relaxation is a long-term test and the logarithmic scale is suitable to plot long periods test results. The graphs in this chapter present the relationship between the percentage of stress relaxation and the time. The percentage of relaxation is the ratio of the decrease in the tendon force to the initially applied force as given in equation (3.3).

The release testing method was carried out on six high strength steel specimens. The specimens were tested at the three most frequently used loading levels, namely, 60%, 70% and 80% of the ultimate tensile strength of this type of steel. According to the ASTM A416-93, Grade 270, seven-wire steel strand has an ultimate strength of 1860 MPa and a nominal area of 140 mm ^{2}. The corresponding ultimate force is 260 kN. The three loading levels of 60%, 70% and 80% P_u are 156, 182 and 208 kN respectively. Figures 4.1 to 4.3 show the experimental results of the measured steel stress relaxation using the release method for initial stress levels of 60%, 70% and 80% P_u.

It is important to mention that the actual initial prestressing applied to each tendon differed slightly from the theoretical value. For example, the theoretical value of 80% P_u is 208 kN while the two specimens were tested at initial load of 209.55 kN and 211.2 kN, respectively. This is due to the fact that it was a trial and error procedure to obtain the required initial stress. It was preferable to reduce the number of repeated load applications to reach the required initial force since repeating loading and unloading for many times affects the specimen properties. Once the force in the tendon was about ± 1.5 % of the required initial force, that force was deemed to be the initial force.

Temperature is an important factor that affects directly the stress relaxation. It is well established that increasing the temperature will increase the stress relaxation losses. For example, the relaxation losses at 40 °C are twice the relaxation losses at 20 °C. This research was intended to be carried out at standard room temperature of 20 °C. Temperature was recorded whenever stress relaxation reading was taken. The lab temperature was 20 °C most of the time. However, some relaxation measurements were recorded at a temperature range of 20 ± 2 °C. This temperature fluctuation did not affect the amount of stress relaxation. For standard stress relaxation testing, ASTM A 416-93 specifies that the test specimen temperature should be maintained at 20 ± 2 °C.

Another important factor that should be discussed is the ability of the test setup to keep the test specimen at the same extension that it reached once the initial force was applied. Three major components contributed to the accomplishment of this task. First, the end anchors, which were used to hold the stressed specimen at a constant extension. Since the anchors were of good quality and proper size for the tested steel tendon, no slippage happened once the anchor gripped the tendon. Nevertheless, special attention was paid to make sure that the anchors were locked properly.

Second, the bolt and nuts device that was used to modify the force in the tendon. This device was to sustain the same amount of force in the stressed tendon. As a result, it had to be strong enough to sustain this load without any reduction in its length. The bolt and nuts device was tested by subjecting it to a 220 kN compressive force and measuring the shortening in its length due to this force. The shortening in the bolt length was 0.02 mm. Since the applied load of 220 kN was higher than the highest initial force, the very small reduction in bolt length was considered negligible.

Third, the steel pipe that was used to hold the specimen at a constant extension after the application of the initial force. The pipe was 1.5 m long and had a cross-sectional area of 3547 mm^2. For the largest initial force of 208 kN, the stress in the steel pipe was:

$$\sigma = \frac{Force}{Area} = -\frac{208 \times 10^3}{3547} = -58.64 \text{ MPa}$$

The strain corresponding to this of stress was:

$$\varepsilon = \frac{\sigma}{E} = -\frac{58.64}{200000} = -0.00029$$

where E is the modulus of elasticity of steel ($E = 200$ G Pa).

The shortening of the 1.5-meter steel pipe was:

$$\Delta L = 0.00029 \times 1.5 = 0.435 \text{ mm}$$

This small amount of less than a half of a millimeter can be neglected. In addition, this shortening corresponds to the highest level of loading and it was even less at the two lower levels of loading. In addition, the elastic shortening of the pipe took place while the load was being applied. Once the initial force was reached, the elastic shortening had taken place. Since stress measurements were recorded after applying the initial stress, the elastic shortening did not affect its values.

The total shortening in the setup that was used to maintain the specimen at a constant length did not exceed half millimeter total at the highest load level of 80% P_u and was less than half millimeter for the two loading levels of 60% and 70% P_u. Also, most of the shortening took place even before stress relaxation measurements. As a result, it can be concluded that the test setup was adequate to perform the experiment.

Two expressions are most commonly used in estimating stress relaxation losses, namely, the CEB FIP Code and the PCI expressions.

The PCI committee on prestress losses (1975), and based on the theoretical and experimental work by Magura, Sozen and Siess, recommended the following expression to estimate the intrinsic relaxation in steel at any time t after the initial stress is applied:

$$\Delta\sigma_{pt} = -\frac{1}{M}\,\sigma_{pi}\,\left(\frac{\sigma_{pi}}{\sigma_{py}} - 0.55\right)\,\log\left(\frac{t}{t_i}\right) \qquad (4.1)$$

$$\text{for } \frac{\sigma_{pi}}{\sigma_{py}} \geq 0.6$$

where $\Delta\sigma_{pt}$ is the intrinsic relaxation at time t in steel tendon stressed initially at time t_i to σ_{pi}; time is in hours and t_i is greater or equal 1 hour; σ_{py} is the yield strength of prestressing steel; M is a factor depending on the steel type and equals 10 for stress relieved wires and strands, and 45 for low relaxation steel.

Based on experimental results reported in the CEB FIP Model Code (1978) and the FIP report on prestressing steel (1976), Ghali and Trevino (1985) recommended the following formula to estimate the intrinsic relaxation:

$$\frac{\Delta\sigma_{pt}}{\sigma_{pi}} = -J\ \eta_t\ (\frac{\sigma_{pi}}{\sigma_{pu}} - 0.4)^2 \tag{4.2}$$

$$\text{for} \quad \frac{\sigma_{pi}}{\sigma_{pu}} \geq 0.4$$

$$\text{and,} \quad \frac{\Delta\sigma_{pt}}{\sigma_{pi}} = 0 \quad \text{for} \quad \frac{\sigma_{pi}}{\sigma_{pu}} < 0.4 \tag{4.3}$$

where $\Delta\sigma_{pt}$ is the amount of intrinsic relaxation at time t after application of the initial stress, σ_{pi} at time t_i with the time being in hours and t_i is not less than 1 hour; σ_{pu} is the ultimate tensile strength of steel; J is constant depending on the steel type, J = 1.5 for group 1 steel (stress relieved) and $2/3$ for group 2 steel (low relaxation); η_t is a dimensionless coefficient given by

$$\begin{aligned} \eta_t &= \frac{1}{16}\ln(\frac{t-t_i}{10}+1) && \text{for} \quad 0 \leq (t-t_i) \leq 1000 \\ &= (\frac{t\text{-}t_i}{0.5\times10^6})^{0.2} && \text{for} \quad 1000 \leq (t-t_i) \leq 0.5\times10^6 \\ &= 1 && \text{for} \quad (t-t_i) > 0.5\times10^6 \end{aligned} \tag{4.4}$$

Figures 4.4 to 4.9 compare the values of stress relaxation measured experimentally with the values estimated by using the CEB FIP Code expression and the PCI expression for both stress relieved and low relaxation steel. Each figure compares the stress relaxation values for the same initial stress level. According to the tensile test results, the ultimate strength of steel is 264 kN and the yield strength is 249.3 kN. These values were used in the CEB FIP Code expression and the PCI expression to plot stress relaxation curves. The ultimate forces for the experimental curves were 264 ± 1.3%. This deviation is very small and does not affect the comparison presented in Figures 4.4 to 4.9.

As the figures show, the experimentally measured values of stress relaxation are higher than the values calculated using the PCI and the CEB FIP Code expressions. This leads to the conclusion that these expressions underestimate the value of steel stress relaxation.

Another important aspect of these figures is the first hour relaxation. The magnitudes of relaxation measured experimentally after the first hour from applying the initial force were 0.84%, 0.94% and 1.35% of the initial force for initial loading levels of 60%, 70% and 80% of the ultimate force respectively. Figure 4.10 presents stress relaxation values measured during the first hour after application of the initial prestressing force.

It is well established that the relaxation rate is high initially and slows down as time passes. Based on existing literature and national reports from European countries, Mihajlov (1968) pointed out that during the first hour of relaxation testing on high tensile strength steel, about 50 to 60 % of the 100 hours relaxation took place. It can be concluded that the first hour relaxation is significant and should not be considered zero or negligible.

4.3 Results of the Lateral Deflection Method

The calibration curve was prepared by measuring the lateral deflection at the middle of the specimen at different values of force in the tendon. The calibration curve relates the lateral deflection at the middle of the specimen to the corresponding amount of force in the tendon. The main concept is that the lateral deflection, due to the applied weight at the middle of the specimen, will increase once the force in the tendon decreases. Figures 4.10 and 4.11 represent the calibration curves prepared experimentally for the two initial loading levels of 60% and 70% P_u.

The two curves are to be used to convert the lateral deflection reading to force in the tendon. It can be noticed that the curves are not smooth. This can be attributed to the friction between the tendon and the nuts and bolt device at the end plate while conducting the calibration curve test. The calibration curves were fitted into equations with two variables, which are the lateral deflection and the force in the tendon. The best fitting curves and the corresponding equations are shown in Figures 4.10 and 4.11.

The best fit equations were used to calculate the magnitudes of force in the tendon that correspond to the lateral deflection values measured experimentally at different time periods. Figures 4.12 and 4.13 present the percentage of relaxation at different points of time that was measured by the lateral deflection testing method.

The lateral deflection was induced by applying weight of 335 kg at the middle of the stressed specimen. This weight was estimated to obtain a maximum deflection of 10 mm at the middle of the specimen. It is evident that this was a large weight. The reasons for requiring such a large weight were the short specimen and the high initial force. The goal of the lateral deflection test was to verify the test results obtained by the release method. As a result, the specimen length was chosen 1.5 m to be same as the specimen length that was tested in the release method. In addition, the same loading levels were adopted.

The results of the lateral deflection testing method have shown fluctuation of lateral deflection readings, especially at the beginning of the test. This fluctuation was due to disturbing the specimen by applying a lateral deflection directly after applying the initial stress. In the initial period after the initial force application, a part of the elastic strain converted to inelastic rapidly since the material had started to rearrange its particles to reach a more stable state under the effect of the applied stress and the corresponding strain. Application of the weight at the middle of the specimen, directly after applying the force to the tendon, was a direct disturbance to the process of atomic stabilizing and converting the strain from elastic to inelastic. As the time progressed, the atomic structure of the steel was more stable and that reflected on the later lateral deflection readings, which were steadier.

In general, the concept of the lateral deflection test method is valid. However, since the force measurement technique used in this method is indirect, different sources of errors contributed in reducing the accuracy of the results. These sources of errors shall be discussed in details in Chapter Five.

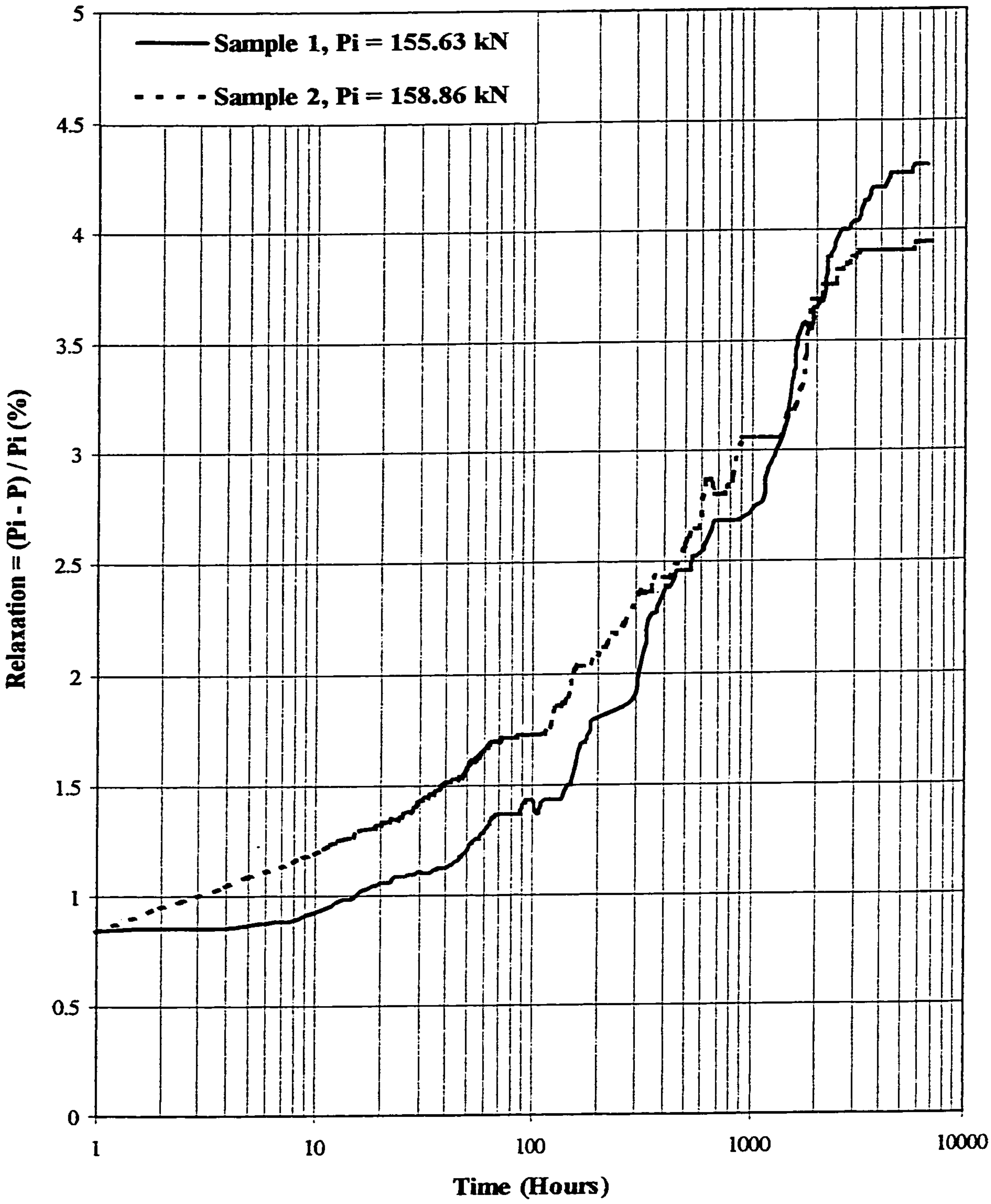


Figure 4.1 – Steel Stress Relaxation Values Measured Experimentally Using the Release Test Method; ($P_i = 0.60\,P_u$).

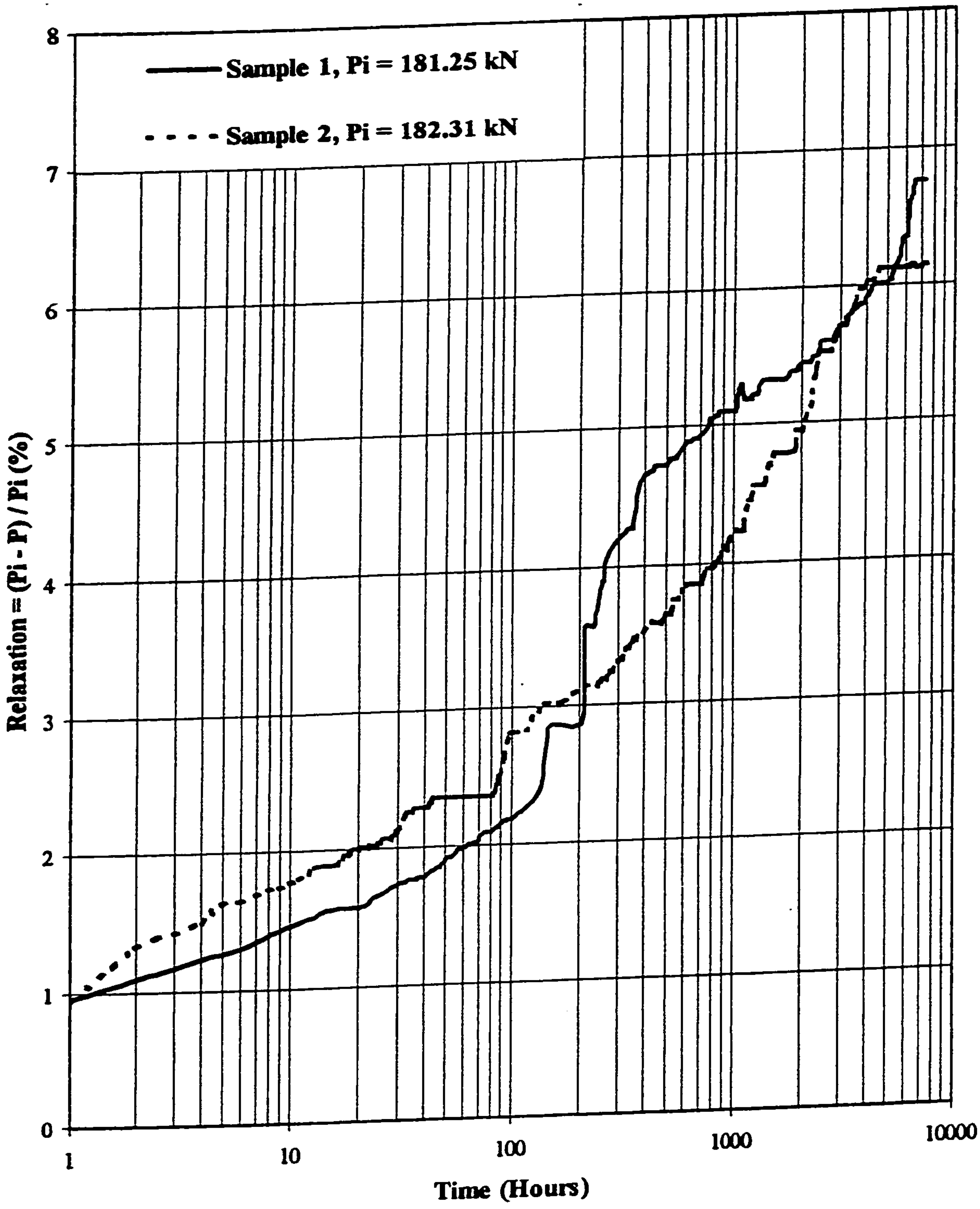


Figure 4.2 – Steel Stress Relaxation Values Measured Experimentally Using the Release Test Method; ($P_i = 0.70\,P_u$).

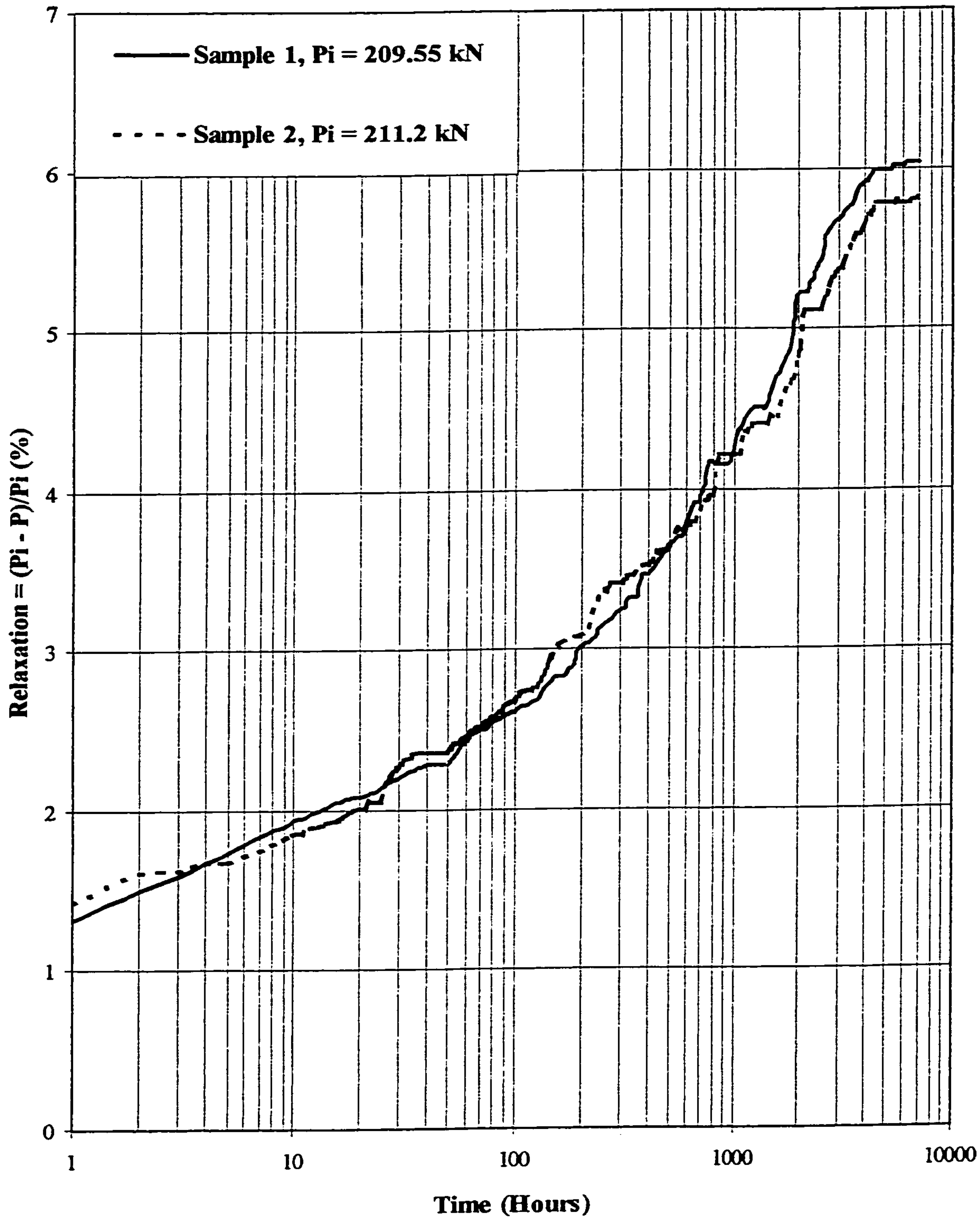


Figure 4.3 – Steel Stress Relaxation Values Measured Experimentally Using the Release Test Method; ($P_i = 0.80 P_u$).

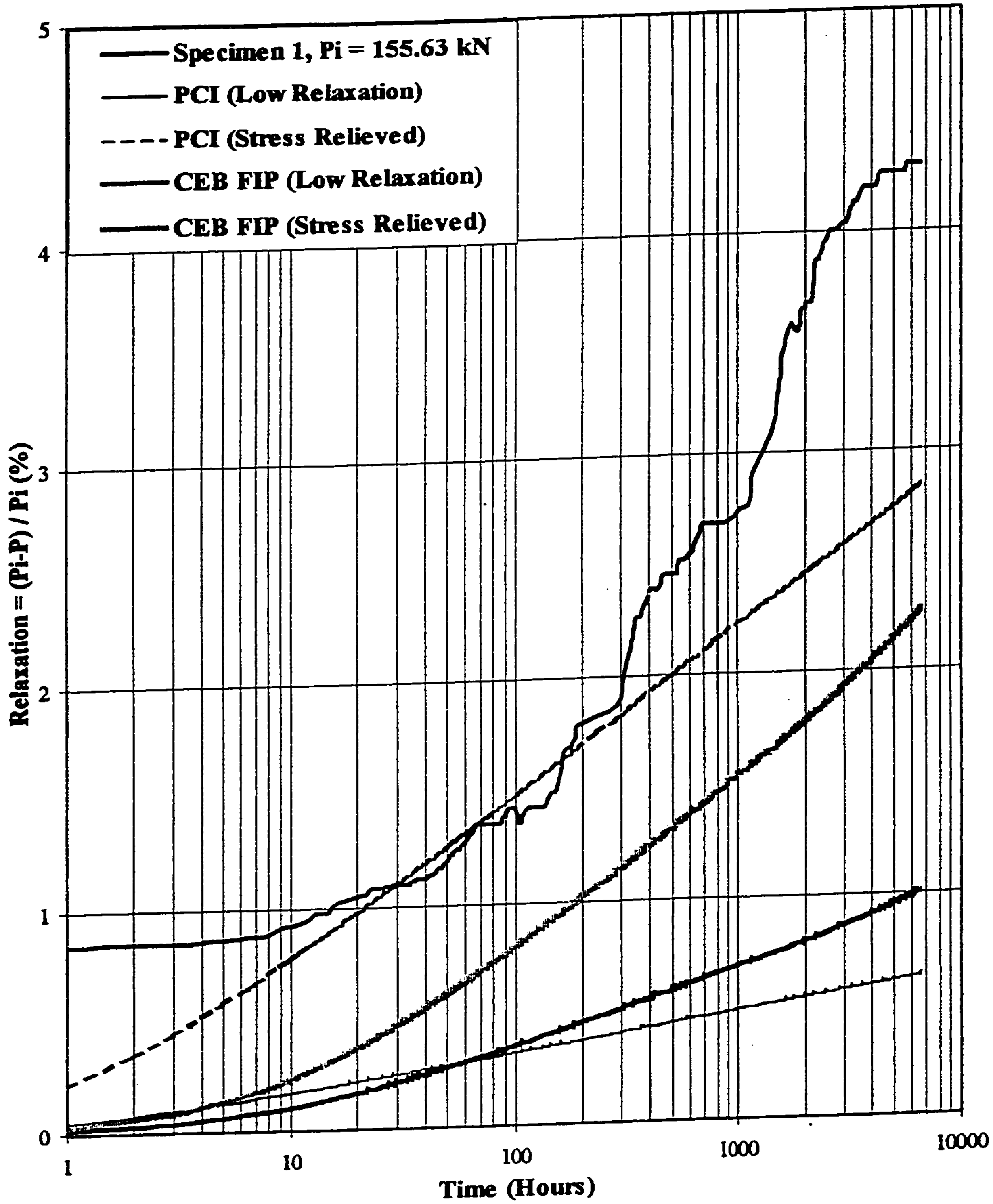


Figure 4.4 – Comparison of Measured Stress Relaxation with Values Calculated Using PCI and CEB-FIP Expressions; ($P_i = 0.60 P_u$).

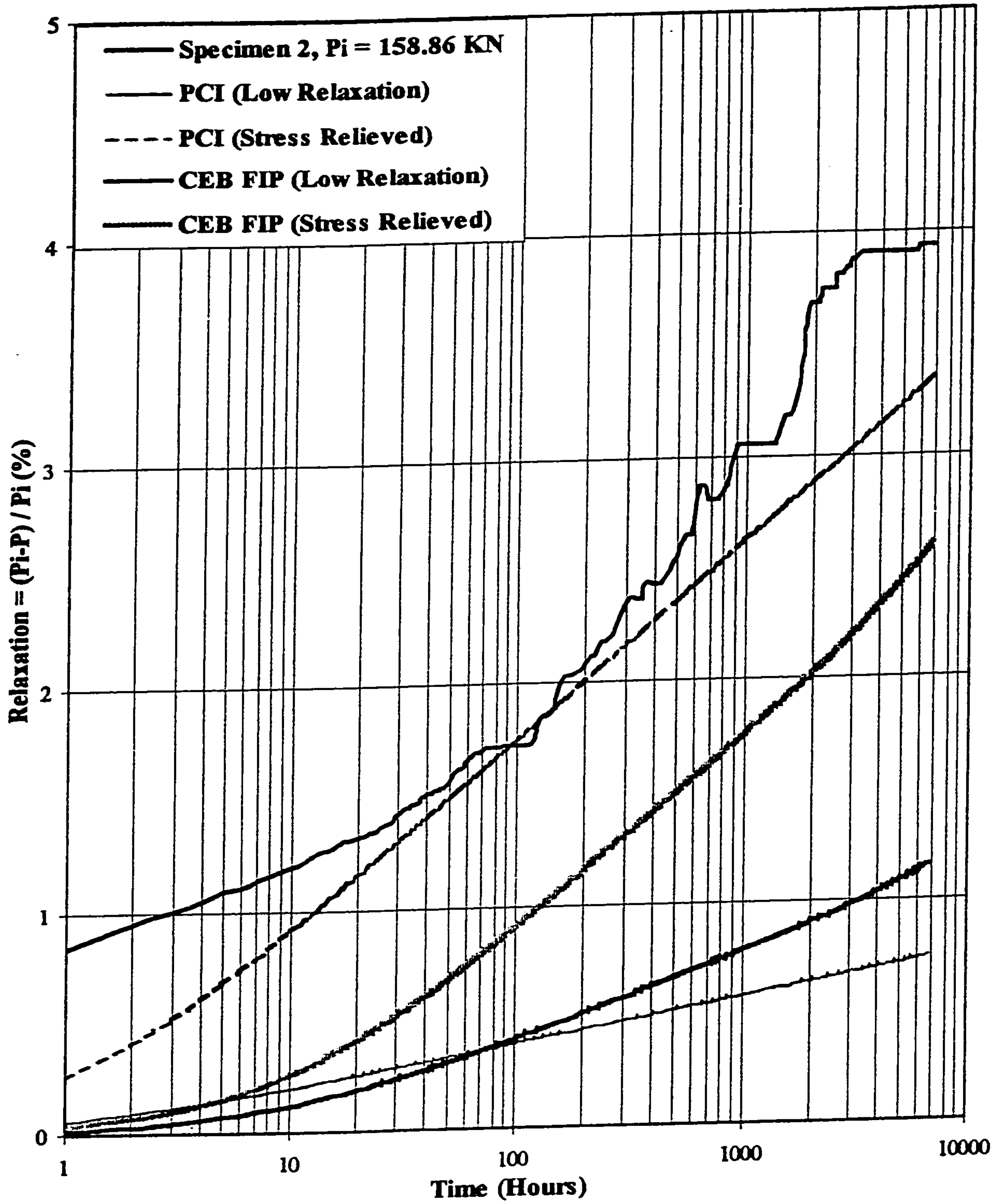


Figure 4.5 – Comparison of Measured Stress Relaxation with Values Calculated Using PCI and CEB-FIP Expressions; ($P_i = 0.60 P_u$).

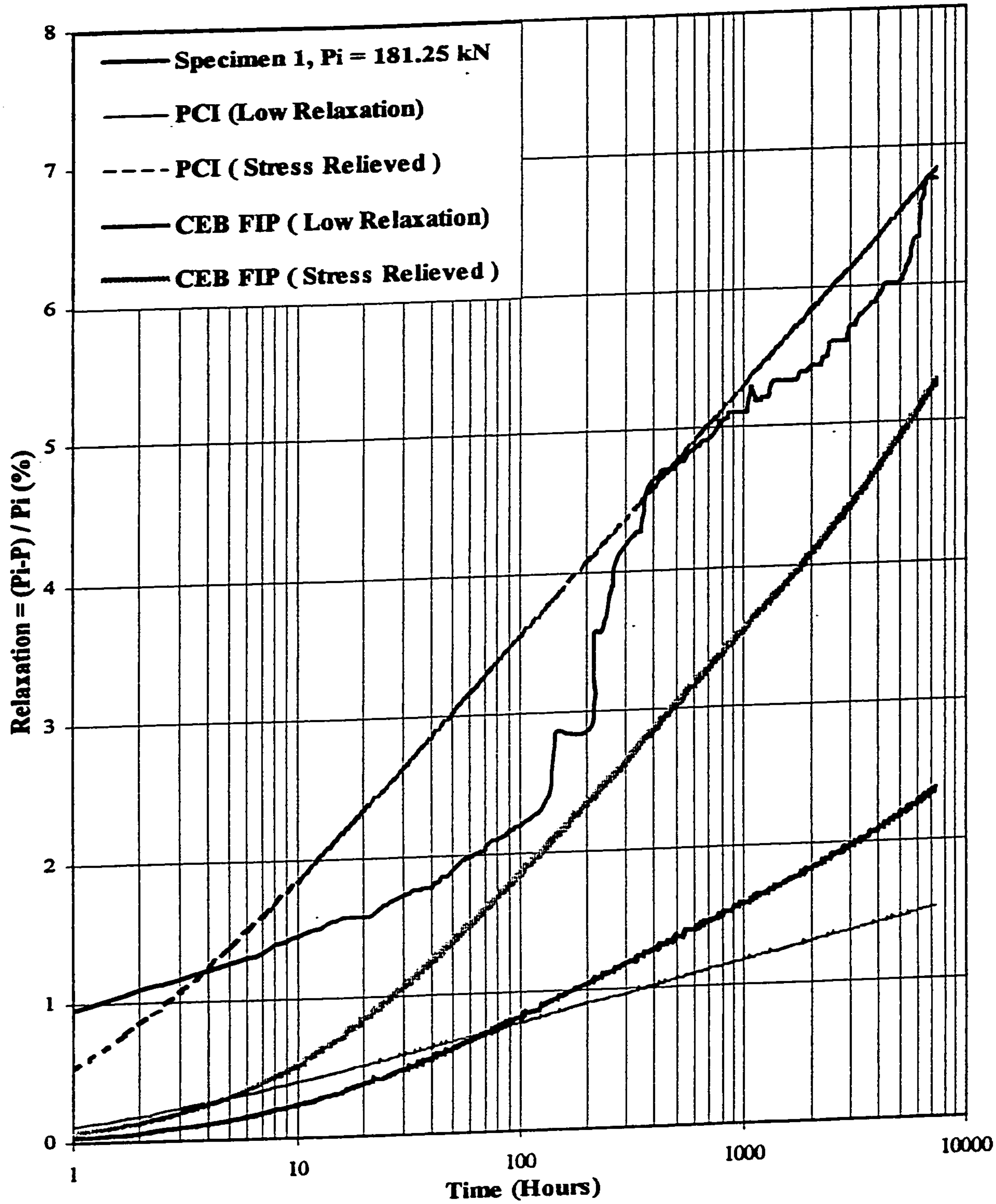


Figure 4.6 – Comparison of Measured Stress Relaxation with Values Calculated Using PCI and CEB-FIP Expressions; ($P_i = 0.70\,P_u$).

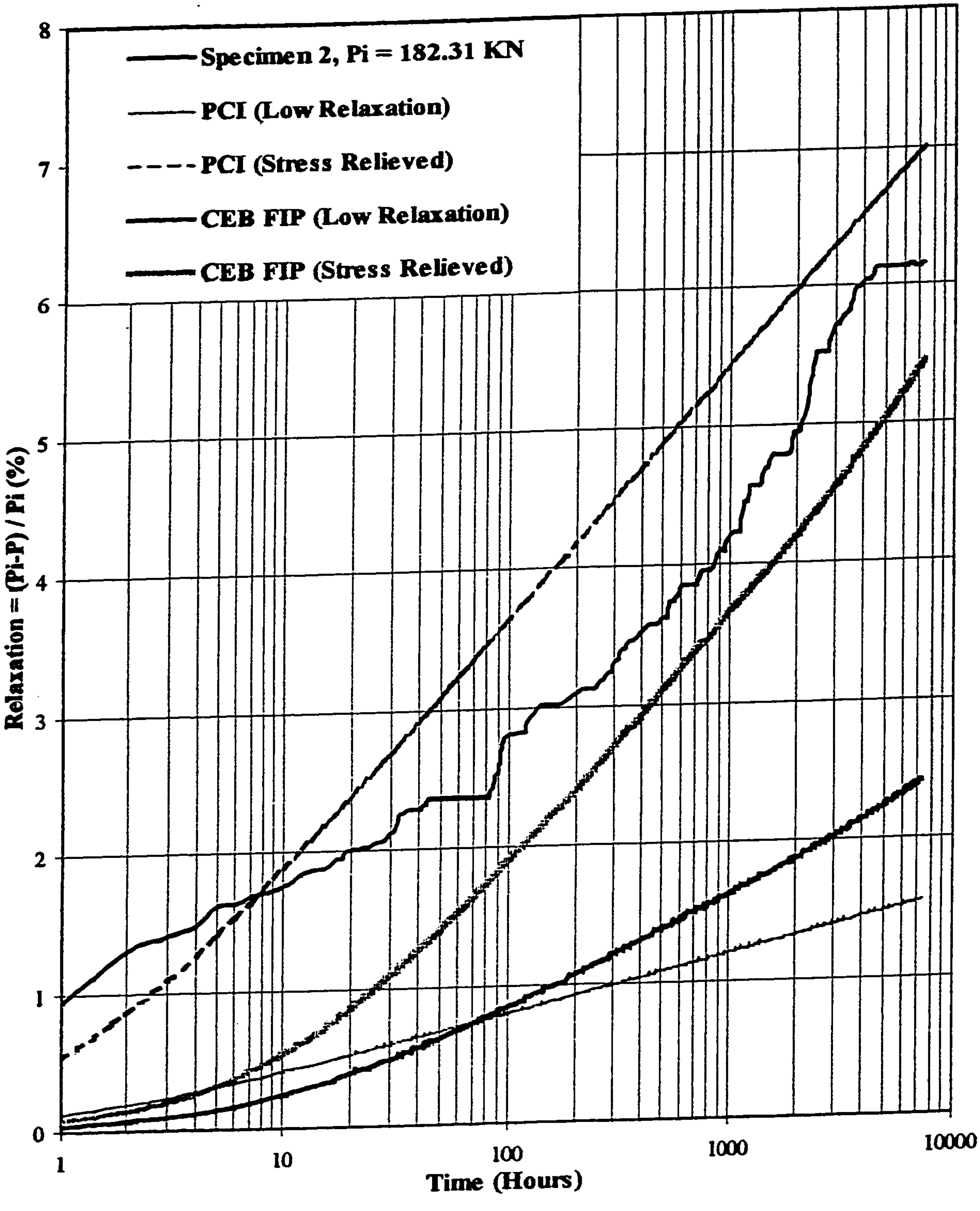


Figure 4.7 – Comparison of Measured Stress Relaxation with Values Calculated Using PCI and CEB-FIP Expressions; ($P_i = 0.70 P_u$).

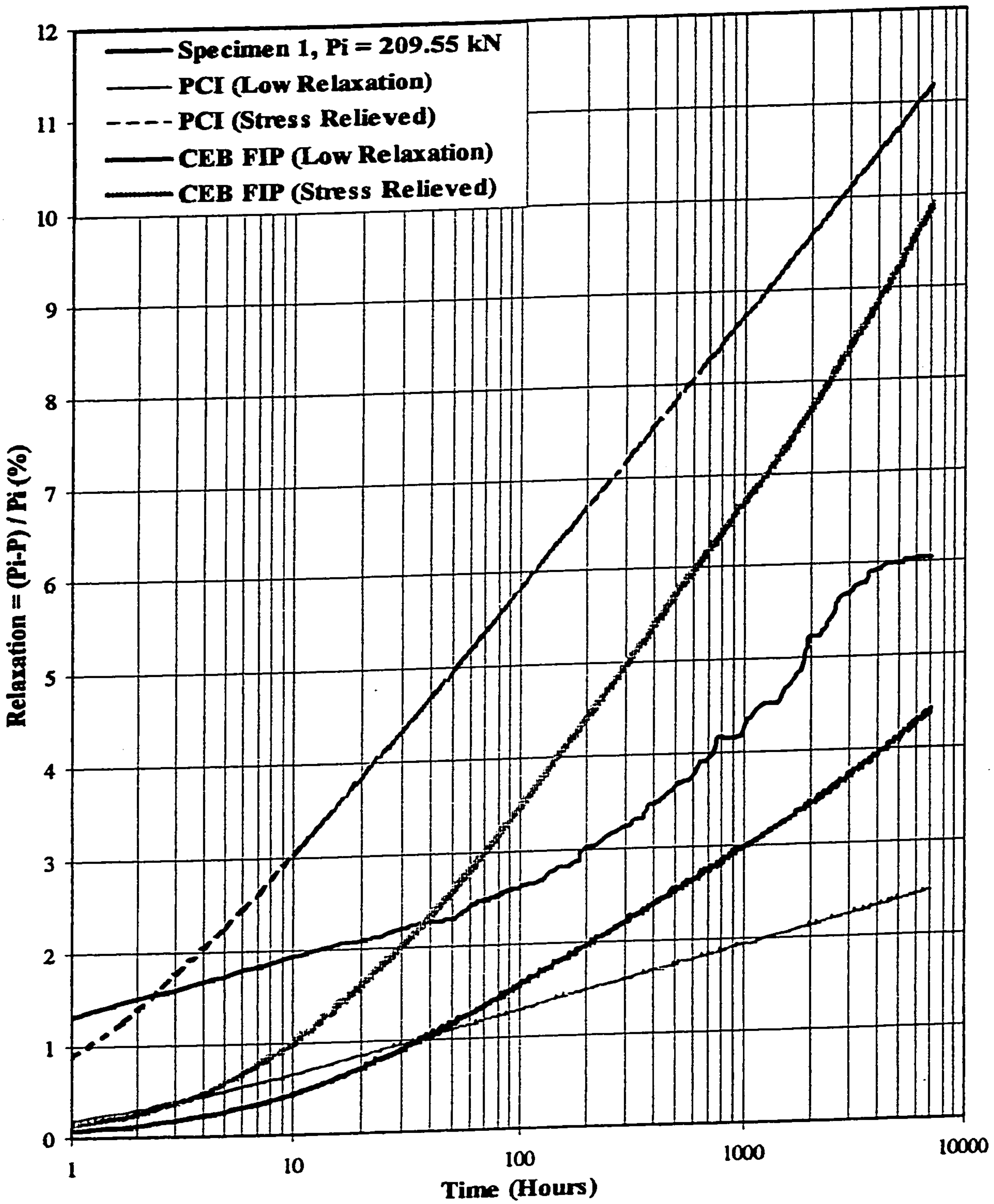


Figure 4.8 – Comparison of Measured Stress Relaxation with Values Calculated Using PCI and CEB-FIP Expressions; ($P_i = 0.80 P_u$).

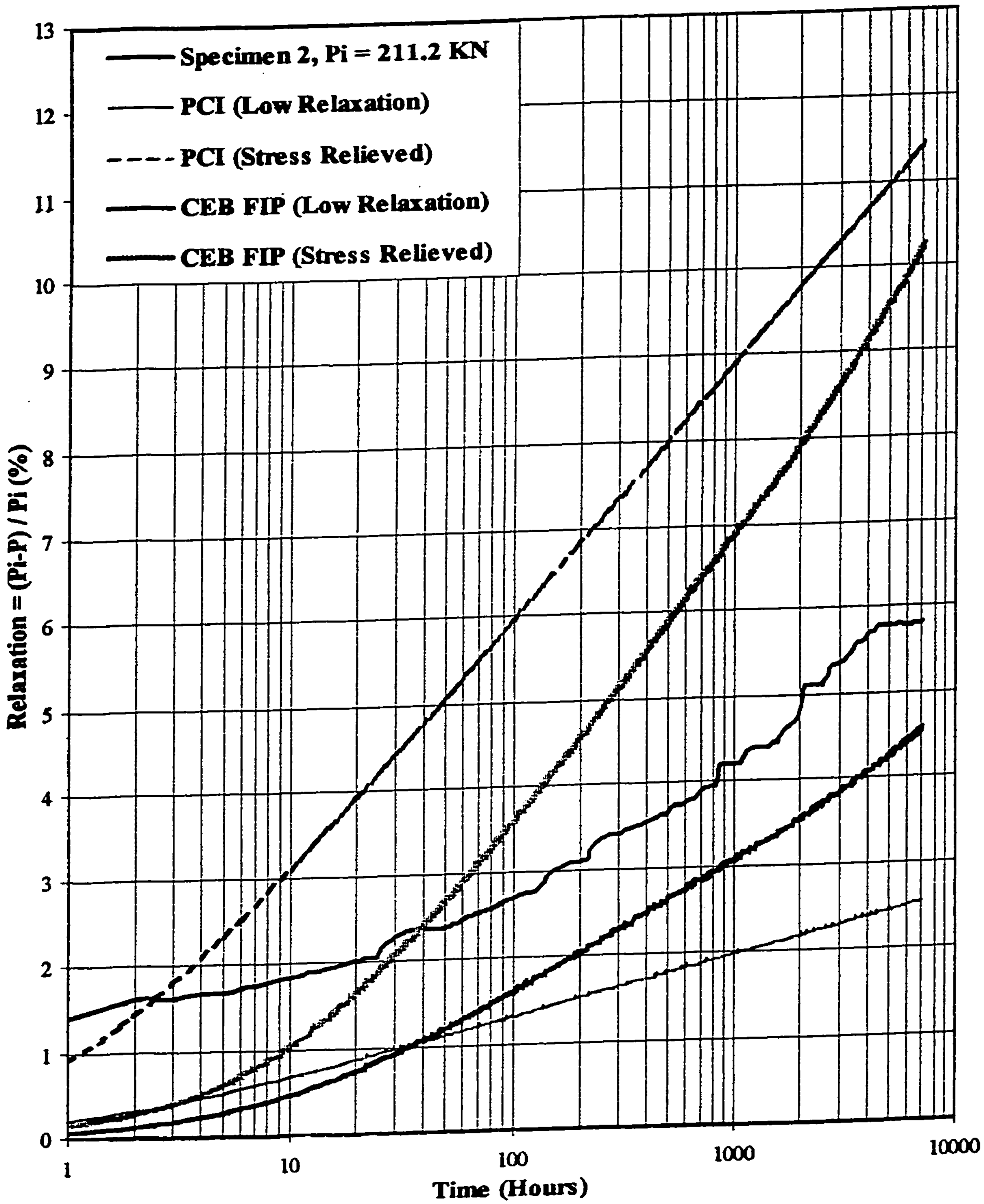


Figure 4.9 – Comparison of Measured Stress Relaxation with Values Calculated Using PCI and CEB-FIP Expressions; ($P_i = 0.80 P_u$).

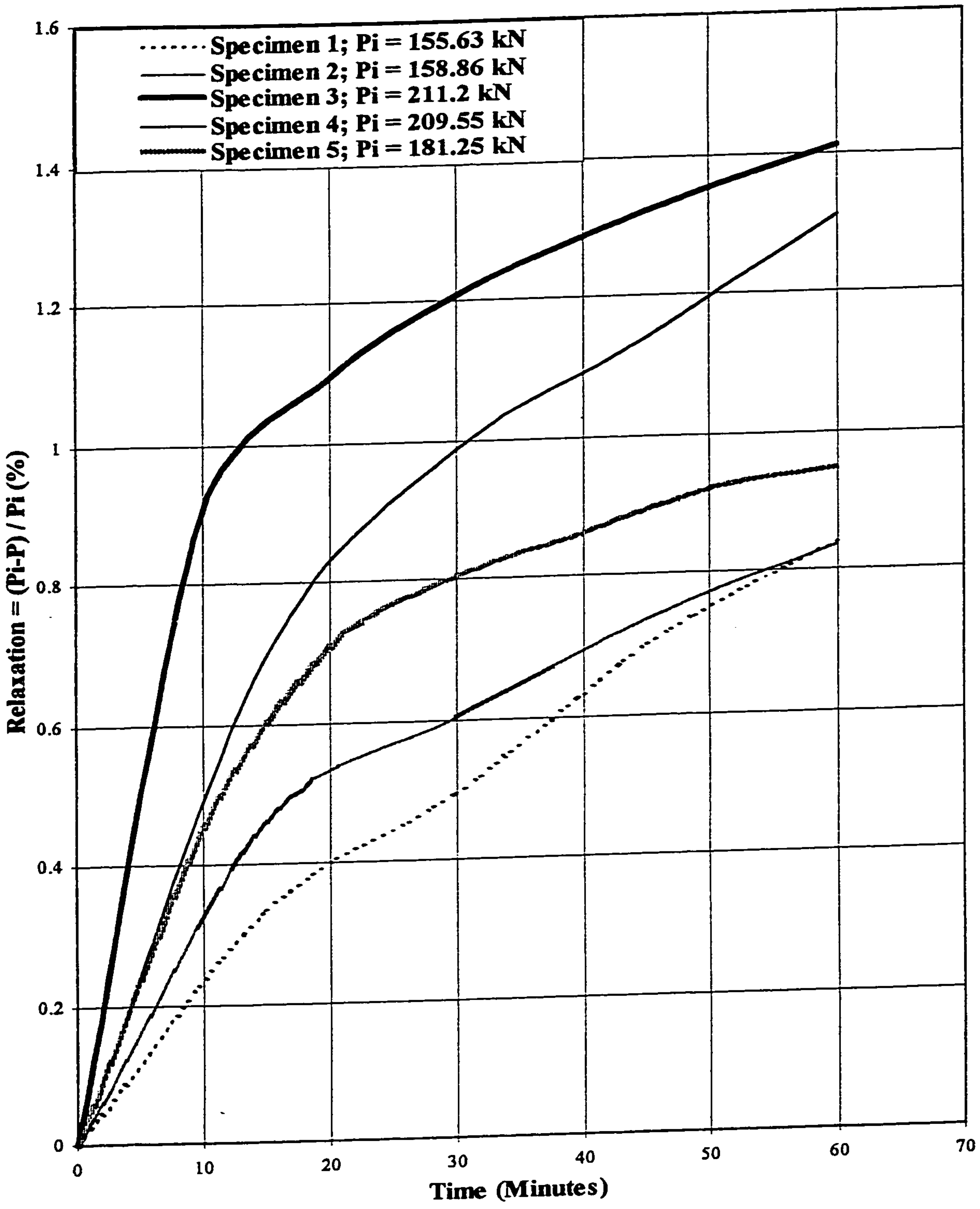


Figure 4.10 – Steel Stress Relaxation values measured experimentally during the first hour after application of the initial force.

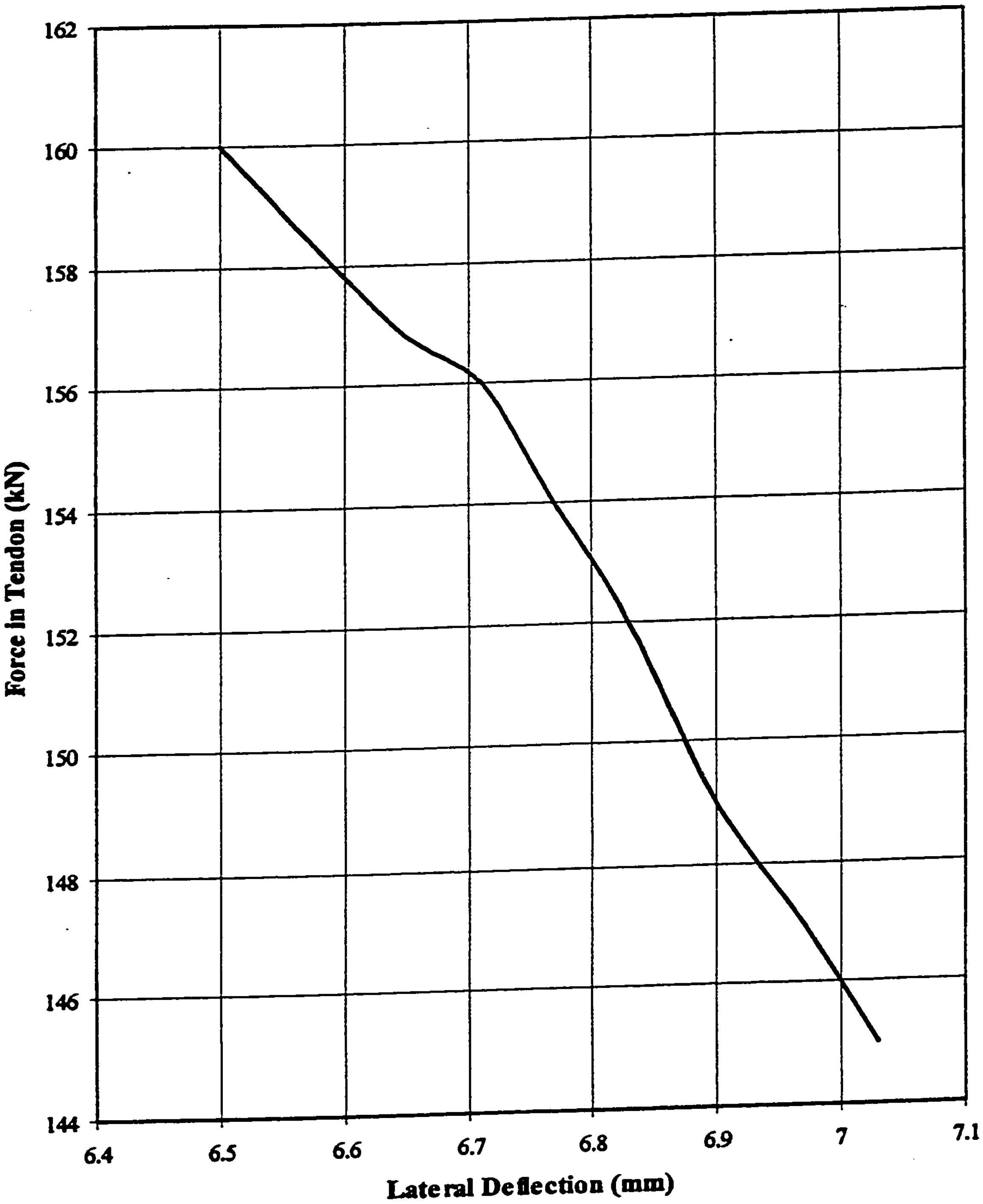


Figure 4.11 – Calibration Curve for Tendon Initially Stressed with Force $P_i = 0.60 P_u$ = 156 kN.

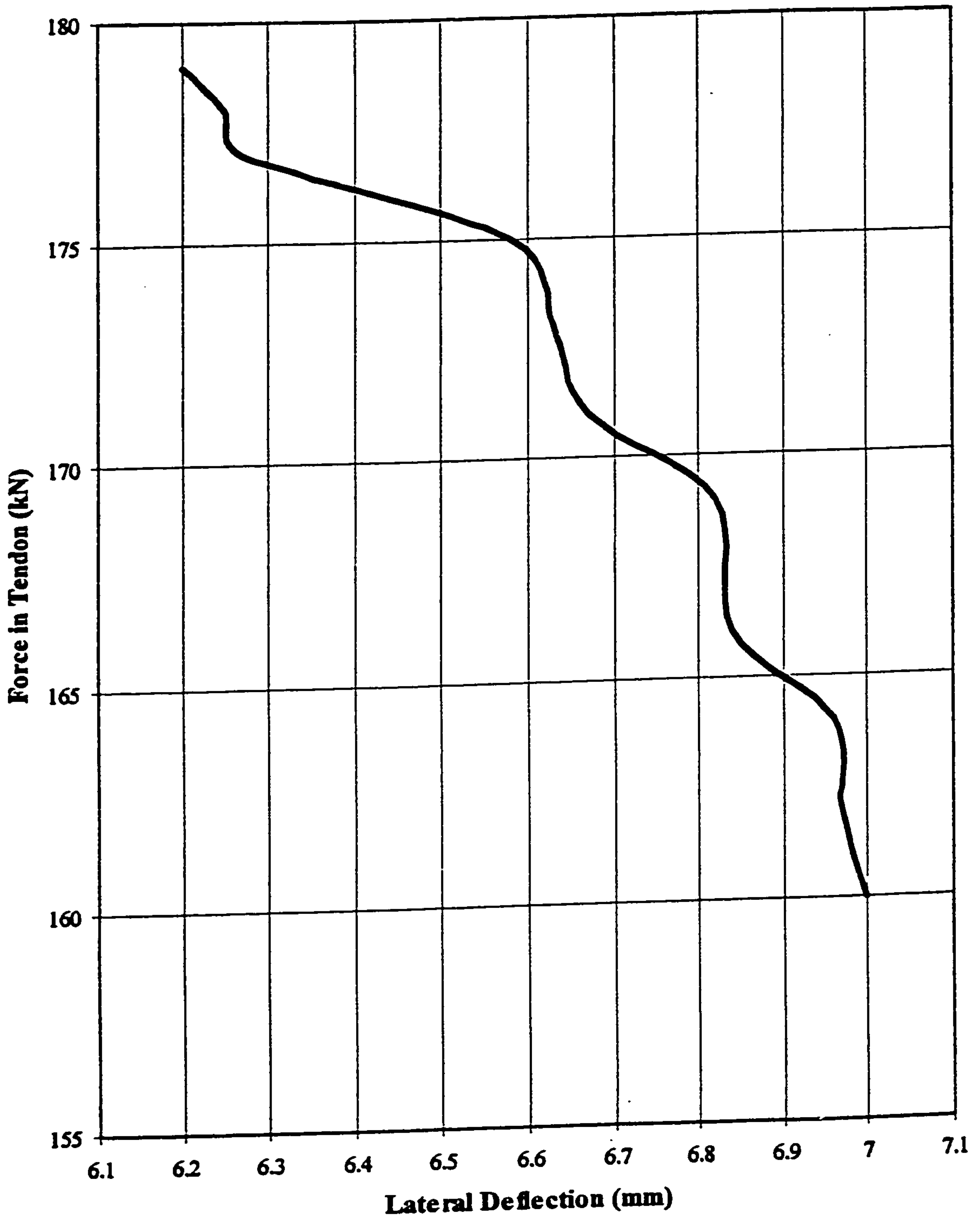


Figure 4.12 – Calibration Curve for Tendon Initially Stressed with Force $P_i = 0.70 P_u = 177.8$ kN.

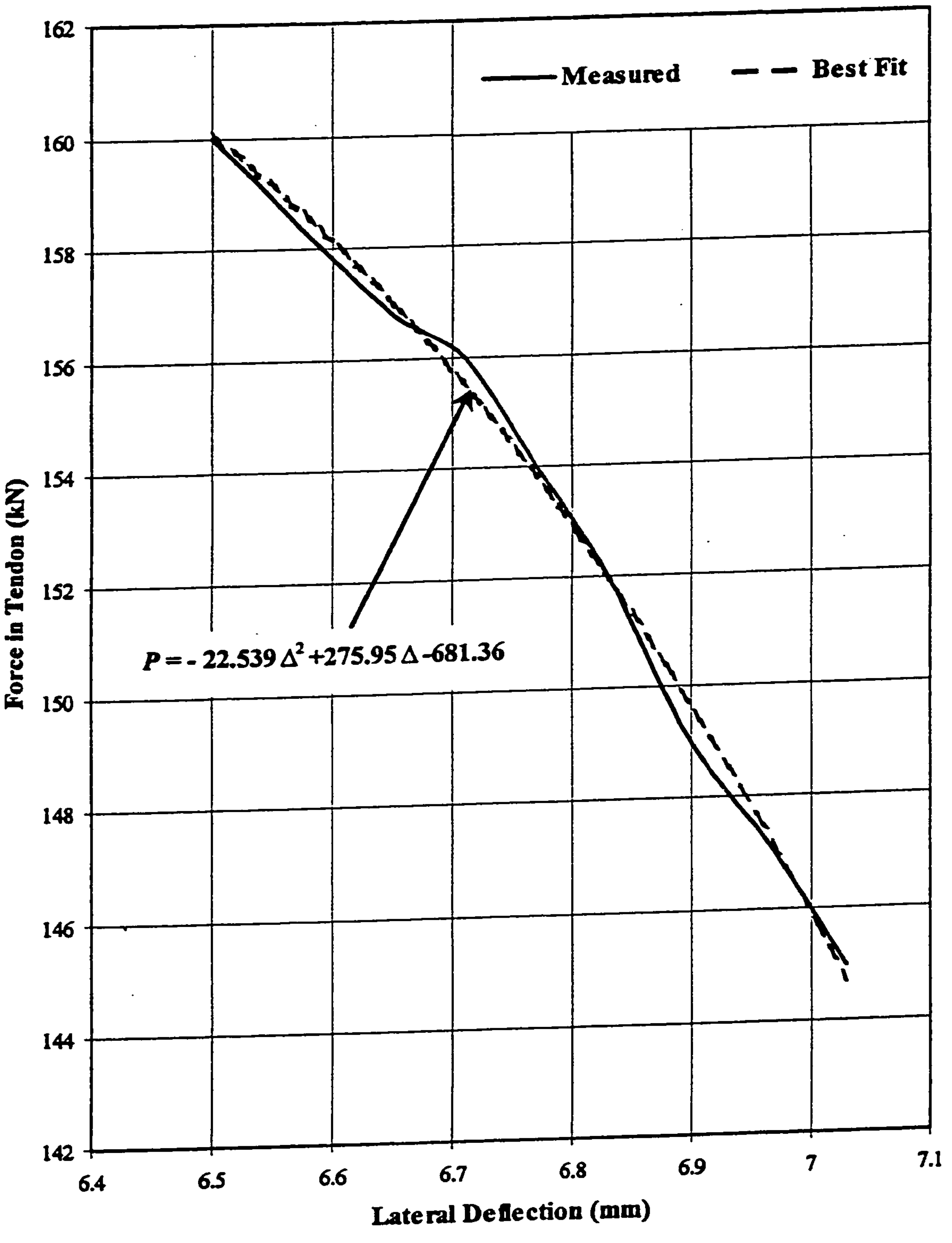


Figure 4.13 – Best Fitting of the Calibration Curve for tendon Initially Stressed with Force $P_i = 0.60\,P_u = 156$ kN.

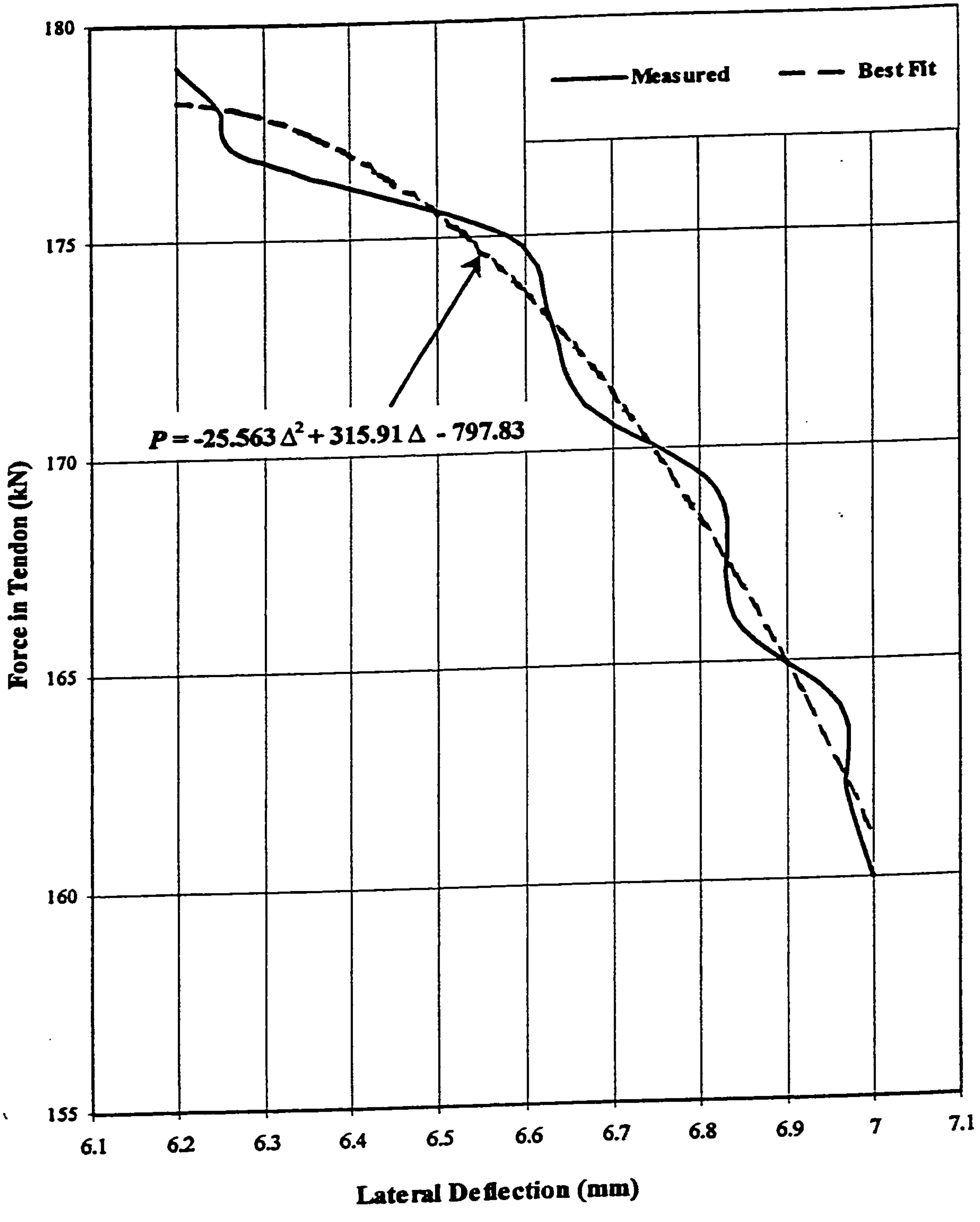


Figure 4.14 – Best Fitting of the Calibration Curve for tendon Initially Stressed with Force $P_i = 0.70\,P_u = 177.8$ kN.

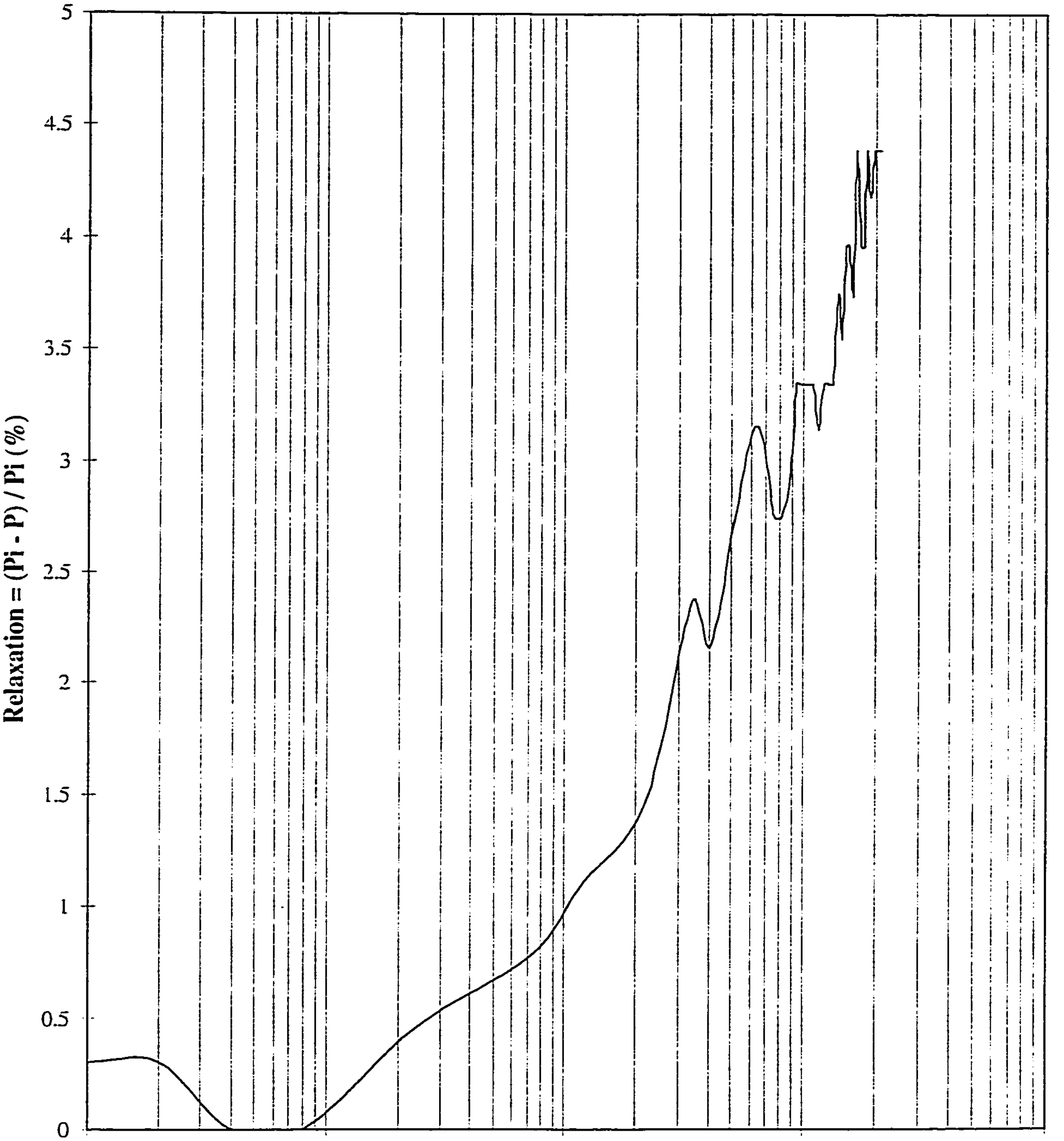


Figure 4.15 – Measured Relaxation in Tendon Initially Stressed with Force P_i = 0.60 P_u = 156 kN Using the Lateral Deflection Test Method.

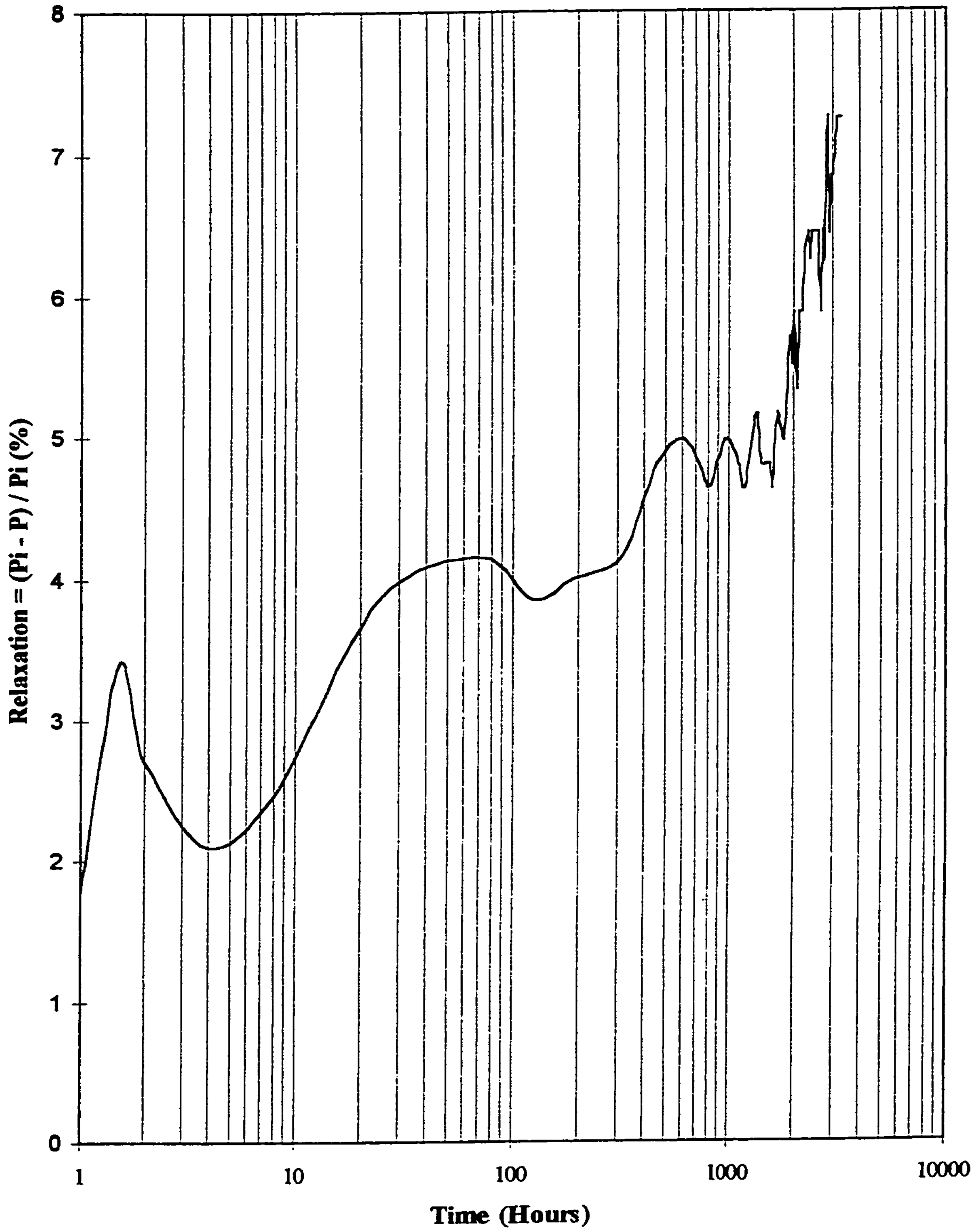


Figure 4.16 – Measured Relaxation in Tendon Initially Stressed with Force $P_i = 0.70\,P_u = 177.8$ kN Using the Lateral Deflection Test Method.

CHAPTER FIVE

DISCUSSION OF TEST RESULTS

5.1 General

In this chapter, the results of the experiments conducted on the stress relaxation of the prestressing steel used in the construction of the Confederation Bridge and presented in Chapter Four are discussed. The test data obtained from the release testing method are used to derive a best fit equation to be used for estimation of the relaxation of prestressed steel. A comparison is made between the results of the proposed equation and the experimental data obtained from both the release testing method and the lateral deflection method.

5.2 Discussion of Results

The results obtained by the release testing method have shown negligible fluctuation in the measurements of force in the tested tendon, since readings were taken continuously from the inserted load cell placed at one end of the specimen. The low precision load cells were calibrated using a universal testing machine.

The calibration of each of the low precision load cells was checked against the high precision one. This was done by applying the same force on the high precision load cell and the calibrated low precision one at the same time, and observing the force measurements from both load cells. At the low loading, a deviation between the readings of the two load cells existed. The measurement from the low precision load cell was 1 kN less when the applied force was 5 kN. However, the difference was reduced as the applied force increased and the readings from both load cells were identical once the applied force exceeded 30 kN. Since the forces in the tested specimens were not expected to be less than 120 kN even after all the relaxation losses, the accuracy of the low precision load cell was decided to be the same as the high precision one. The high precision load cell capacity was up to 250 kN and its accuracy was ± 0.1% of the full loading scale.

The lateral deflection method results were less accurate than the release method since force in the tested specimen was indirectly estimated through the magnitude of the lateral deflection at the middle of the specimen. This lateral deflection was induced through the application of a 335 kg.

The marked fluctuation at the first eight hours of the test was due to the fact that the applied lateral deflection disturbed the stressed specimen. The applied strain to the specimen by the initial force caused the steel atomic structure to be unstable. As a defensive reaction, the steel atomic structure rearranged it self to reach a more stable state. The atomic restructuring is a very active process after stress application and slows down as the atomic structure reaches more stable conditions. During this period of stabilization, the applied weight to induce a lateral deflection at the middle of the specimen was another disturbing factor that caused fluctuations in stress measurements.

Lateral deflection measurements for the first specimen that was tested at 70% of the ultimate strength were taken at small intervals especially at the first hour, namely at 10, 15, 25, 45, 60 minutes from applying the initial force. The repeated application of weight in the first hour led to the fluctuation in the readings. As a result, the readings within the first hour were discarded and the reading at the end of the first hour was considered to estimate the stress in the specimen. For the second specimen, the lateral deflection measurements were steadier and more stable since the first measurement was recorded at the end of the first hour. The subsequent readings were recorded on an hourly basis for the first eight hours. In addition, the impact of applying a heavy weight at the middle of the specimen several times affected the steel material. The lateral deflection was an indirect measure to estimate the force in the tested specimen. In general, the indirect testing techniques involve the use of calibration curves, which decreases the accuracy of the results.

The lateral deflection test was conducted to verify the results of the release method. It was decided to choose the same specimen length and loading levels. The specimen length was chosen to be 1.5 m. However, the test results showed that this was not the suitable specimen length to carry out the test and the lateral deflection method required relatively longer specimens compared to the other testing method.

Certain sources of error contributed in reducing the accuracy of the lateral deflection test results on the short specimens. This reduced accuracy is attributed to the following. First, the short specimens required large weight to produce the lateral deflection. The impact of heavy weight applications at the middle of the specimen caused movements at the end anchors. Although these movements were very small, they affected the lateral deflection measurements.

Second, the deflection at the middle of the specimen was high with respect to the specimen length. In order to obtain accurate force measurements using the lateral deflection method, the tested specimen should be maintained as a perfect rope. This requires the angle caused by the lateral deflection between the specimen and the horizontal to be very small. Using longer specimens reduces this angle and produces more accurate results. In this research, the specimens were 1.5 m and the maximum lateral deflection reading was approximately 8 mm. The angel due to this deflection was 0.011 °. This angle was relatively large and did not establish the perfect rope condition, which increased the error in the force measurements.

It is essential to Standardize the lateral deflection test specification. The standardization should include the length of the specimen and the amount of the lateral deflection. Force in the specimen is an important factor that should be taken into consideration to decide the length and lateral deflection. For instance, the higher the tensile force is, the longer the specimen is required. On the other hand, the lateral deflection at the middle of the specimen will require very heavy weight if the specimen is short and the tensile force is high. In general, the trend should be toward using long specimens for the lateral deflection method to increase the accuracy of the test results.

The previous discussion showed that the release test results are more accurate and reliable than the lateral deflection test results. In the next sections, the results of the release testing are adopted to analyze the stress relaxation of steel, and to derive a mathematical equation to estimate the relaxation losses.

5.3 Effects of Various Factors of Relaxation of Steel

The four major factors that affect stress relaxation in steel are the initial stress ratio, time, the temperature and the type of steel. In this section, these factors are analyzed and discussed in accordance with the experimental results and the test conditions. The goal of this analysis is to determine the factors to be used in a mathematical representation of stress relaxation data obtained experimentally in this research.

The initial stress ratio is the initial stress divided by the ultimate strength of the specimen. The ultimate strength is a constant that represents the stress that the specimen would fail at while the initial stress depends on the amount of force applied to the specimen initially. The magnitude of initial stress has a direct effect on the relaxation losses. It is well established that the higher initial stress would lead to higher steel stress relaxation losses. The higher relaxation losses are mainly due to more pronounced flow properties at higher initial stress.

To illustrate the effect of the initial stress on steel stress relaxation with accordance to the experimental results, the relation between the initial stress and relaxation losses at the end of 5000 hour period measured experimentally is plotted in Figure 5.1. This figure indicates that the stress loss increases about 30 MPa by increasing the initial stress from 60% to 70% of the ultimate strength of the steel while the loss increases only about 10 MPa by increasing the initial stress from 70% to 80% of the ultimate strength of steel.

Theoretically, there is a value of initial stress at which no stress relaxation occurs. This initial stress was defined by Oding (1965) as the focal point σ_r. Oding found that beyond a certain time, the relationship between stress losses and the initial stress is linear. Oding also pointed out that the linear relationships for different values of initial stress have different slopes. These slopes have a focal point at a value of $(P_i - P)$ equal to zero thereby defining the relaxation limit. This limit was interpreted to be the maximum stress at which relaxation will not occur. Figure 5.2 shows the relationship between the initial force and the decrease in the initial force due to relaxation after 1 hour, 10 hours, 100 hours, and 250 hours. From this figure, the initial force at which no relaxation losses will take place is 114.5 kN. This value represents 44% of the ultimate strength of steel.

At initial stress of 44% of the ultimate strength, no losses due to steel stress relaxation take place. At initial force of 60% of the ultimate strength, the losses are 4% of the initial force. Increasing the initial force from 60% to 70% of the ultimate strength increases the losses by 2%, and increasing the initial force from 70% to 80% of the ultimate strength increases the losses by 0.7%. This pattern indicates that the steel stress relaxation losses will increase by increasing the initial stress but at a decreasing rate. This behavior can be explained since steel stress relaxation is basically due to the flow properties of steel, which is an atomic restructuring by the material in order to reach a more stable state under the condition of applied stress. The flow properties of steel increase as the applied stress increases but at a decreasing rate. This behavior is similar to the stress-strain curve of steel. The relationship between stress and strain is linear to a certain extent and as the stress approaches the yield point, a noticeable curvature takes place. This curvature means that the rate of increase in specimen stress decreases at higher strains.

The previous discussion leads to the conclusion that the initial stress ratio is a very significant factor that directly affects the value of steel stress relaxation. As a result, this factor had been included in most of the expressions that were derived to estimate stress relaxation and should be included in the any proposed formula. A proposed formula that contains this factor shall be discussed in the next section.

As was discussed in Chapter Two, the steel relaxation is a time dependent phenomenon and the rate of relaxation varies with time; the relaxation starts at a high rate initially and then slows down as time passes. The time is another major factor in any expression or formula to estimate steel stress relaxation.

The type of steel is not considered as a variable in the formula proposed in this chapter to estimate the value of steel relaxation. The reasons for this are the following. First, grade 270, six wire-strand prestressing steel tendon is the mostly used steel in prestressing concrete structures. Thus, the tested steel specimens can be considered to be representative of a high percentage of prestressing steel that is used in the construction industry. Second, examination of the microscopic structure of steel is beyond the scope of this research and therefore no claim of understanding the effect of this factor on the magnitude of stress relaxation of steel can be made. However, different types of steel have different ultimate strengths. Adopting the initial stress ratio $(\sigma_{pi} / \sigma_{pu})$ as a variable in the equation to estimate stress relaxation would take into account part of the effect of the type of steel. As a result, the equation that is proposed according to the experimental data of this research will be generalized to measure stress relaxation of all types of steel and should not be limited to a certain type.

With regard to the effects of temperature, as mentioned earlier, this research was carried out to study the relaxation of prestressed steel in a controlled temperature environment. To meet the ASTM A416-93 specification for the stress relaxation test, the steel stress relaxation was studied under the room temperature in a controlled temperature environment. The relaxation readings were recorded at temperature of 20 °C ± 2. This temperature range meets ASTM A416-93 specification for standard relaxation test. As a result, the temperature did not participate in changing the behavior of steel stress relaxation in this research. The derived formula is considered to predict the behavior of steel stress relaxation under the room temperature.

From the previous discussion, it is emphasized that the effect of temperature and steel type will not be included as variables in equation to estimate the stress relaxation. A proposed equation should expresses the percentage of stress relaxation of steel as a function of both the initial stress ratio and the time. It should be mentioned that the remaining force in the tendon is the point of interest. However, it is obvious that once the amount of prestressing losses is determined, the remaining force in the tendon is the difference between the initially applied force and the amount of loss.

5.4 Equation for Estimate of Steel Stress Relaxation

To obtain a mathematical representation of the experimental results, a trend line and a best fit equation were inserted for each curve of the relaxation values measured experimentally. The trend lines and the best fit equations are shown in Figures 5.3 to 5.5. Each equation represents only the loading level that the specimen was tested at. The goal of this research is to derive a general equation for any initial loading level. As a result, one equation that best represents all the experimental data at the three loading levels is required. The following formula was derived to represent the experimental results obtained by the release testing method:

$$\frac{P_i - P}{P_i} = \frac{(\sigma_{pi}/\sigma_{pu}) - 0.4}{0.55(\sigma_{pi}/\sigma_{pu})} \quad t^{0.22} \tag{5.1}$$

$$\text{for} \quad \frac{\sigma_{pi}}{\sigma_{pu}} > 0.44$$

$$\frac{P_i - P}{P_i} = 0 \quad \text{for} \quad \frac{\sigma_{pi}}{\sigma_{pu}} \leq 0.44 \tag{5.2}$$

where P_i is the initial prestressing force applied to the tendon at time t=0 hour; P is the remaining prestressing force in the tendon at time t; the time t is in hours from the instant of application of the initial force up to the instant of time at which the remaining force in the tendon is required; σ_{pi} is the initially applied stress at time $t = 0$ and σ_{pu} is the ultimate strength of the steel tendon. Steel stress relaxation estimated by equation (5.1) is at a constant temperature of 20 °C ± 2.

To check the validity of equation (5.1), the ratios of the experimentally measured relaxation to the computed values using this equation were calculated. For the six specimens, the mean ratio of the measured to computed relaxation is 1.05 and the average standard deviation is 0.09. On the basis of this statistical analysis, it can be concluded that equation (5.1) represents the experimental results and can be used to estimate steel stress relaxation.

The values of stress relaxation calculated using equation (5.1) are compared with the values of relaxation measured experimentally by using the release method in Figures 5.6 to 5.8. These figures also prove that equation (5.1) can be used to estimate the relaxation of steel at the three initial loading levels, namely, 60%, 70%, and 80% of the ultimate strength of the steel. The use of this equation should not be limited on these three loading levels. Equation (5.1) is proposed to estimate stress relaxation of steel at any initial loading level that is higher than 44% of the ultimate strength of steel.

Assuming that the proposed equation can be used to estimate stress relaxation for extended period of time, say one million hours (about 114 years), Figure 5.9 shows the estimated values of stress relaxation during this period for four different initial stress levels of 60%, 70%, 80% and 90% of the ultimate strength of steel. The estimated stress relaxation of steel at the end of the 114 years period is 11.6%, 14.9%, 17.4% and 19.3% for initial stress levels of 60%, 70%, 80% and 90% of the ultimate strength respectively. The validity of these results can be confirmed by very long-term tests.

As was discussed in the introduction of this chapter, the release test results are used to derive equation (5.1) to estimate the relaxation loss with time, and then the lateral deflection test results will be compared with the proposed equation and the release method results. Figures 5.10 and 5.11 compare the stress relaxation values obtained from the release method, the lateral deflection method and the proposed equation (5.1). The previous discussion of the results of the two testing methods has shown that the results from the release test are more accurate and reliable than the lateral deflection test results. However, despite the fluctuation of stress relaxation values measured using the lateral deflection method, these results support the release test results. Figures 5.10 and 5.11 show that the two testing methods have relatively close results. The close results of the two testing methods support also the proposed equation (5.1).

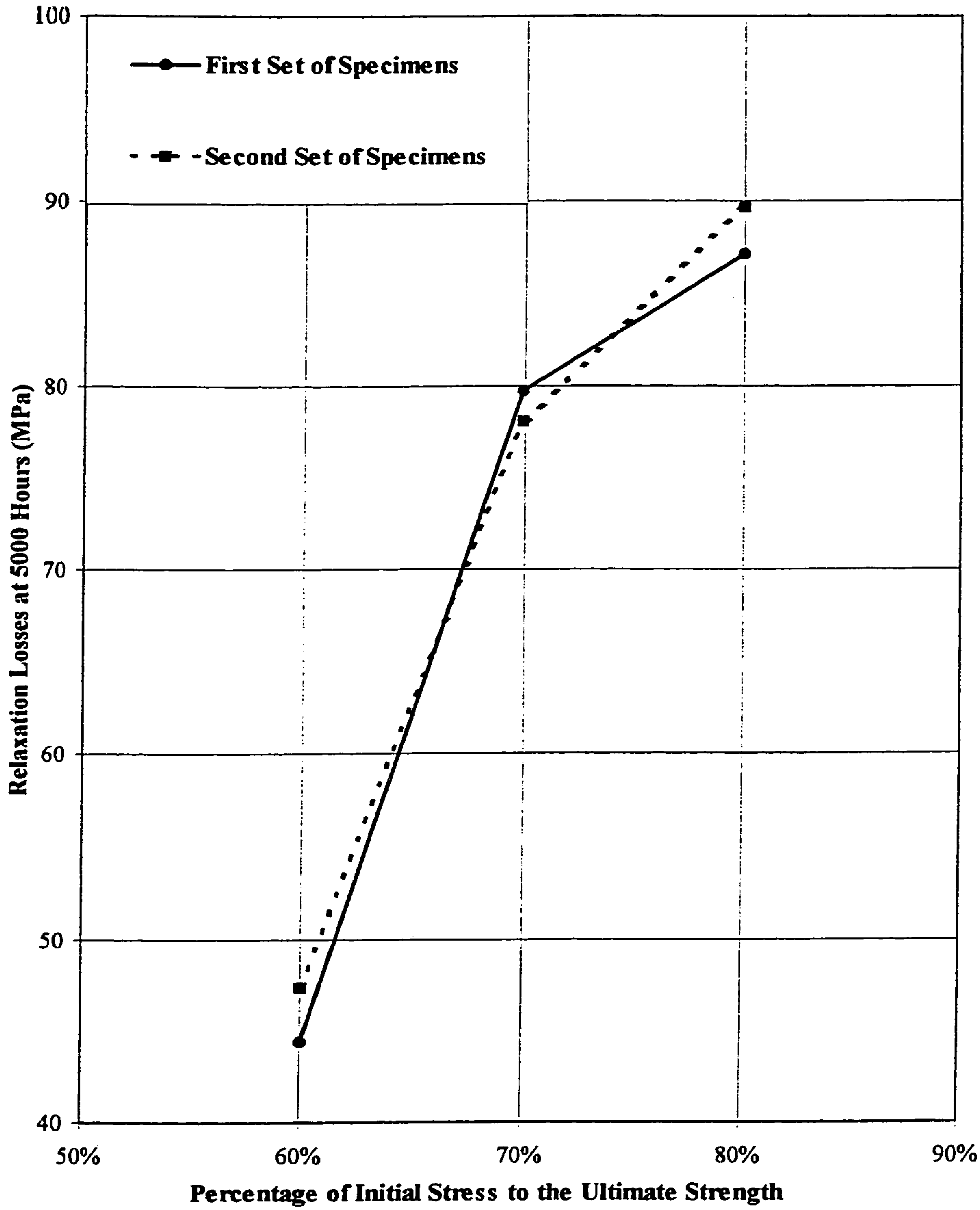


Figure 5.1 – Steel Relaxation Losses at the End of 5000 Hours for Initial Stress Level of 60%, 70%, 80% of the Ultimate Strength of Steel.

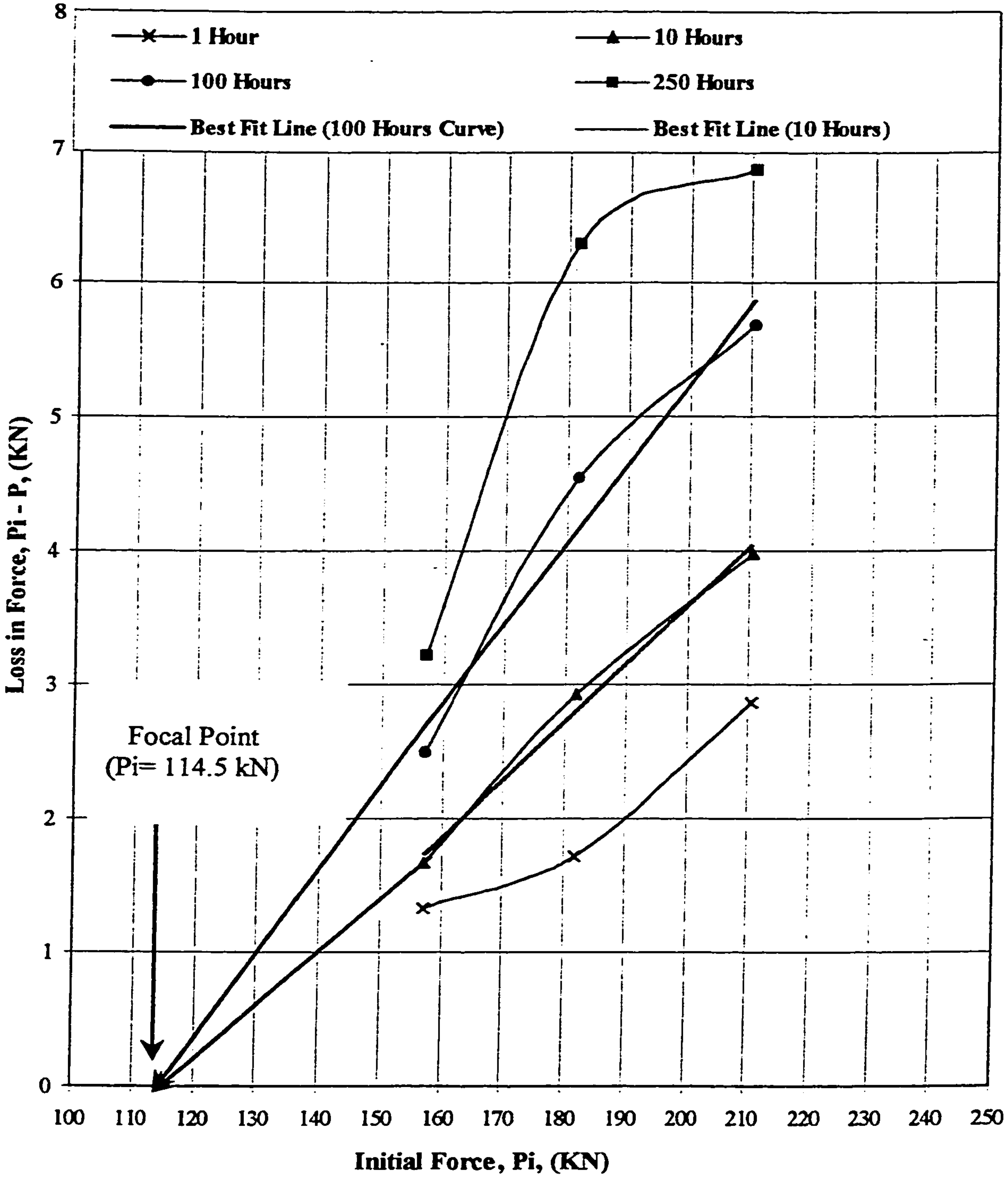


Figure 5.2 – The relationship between Initial Stress and Steel Stress Relaxation.

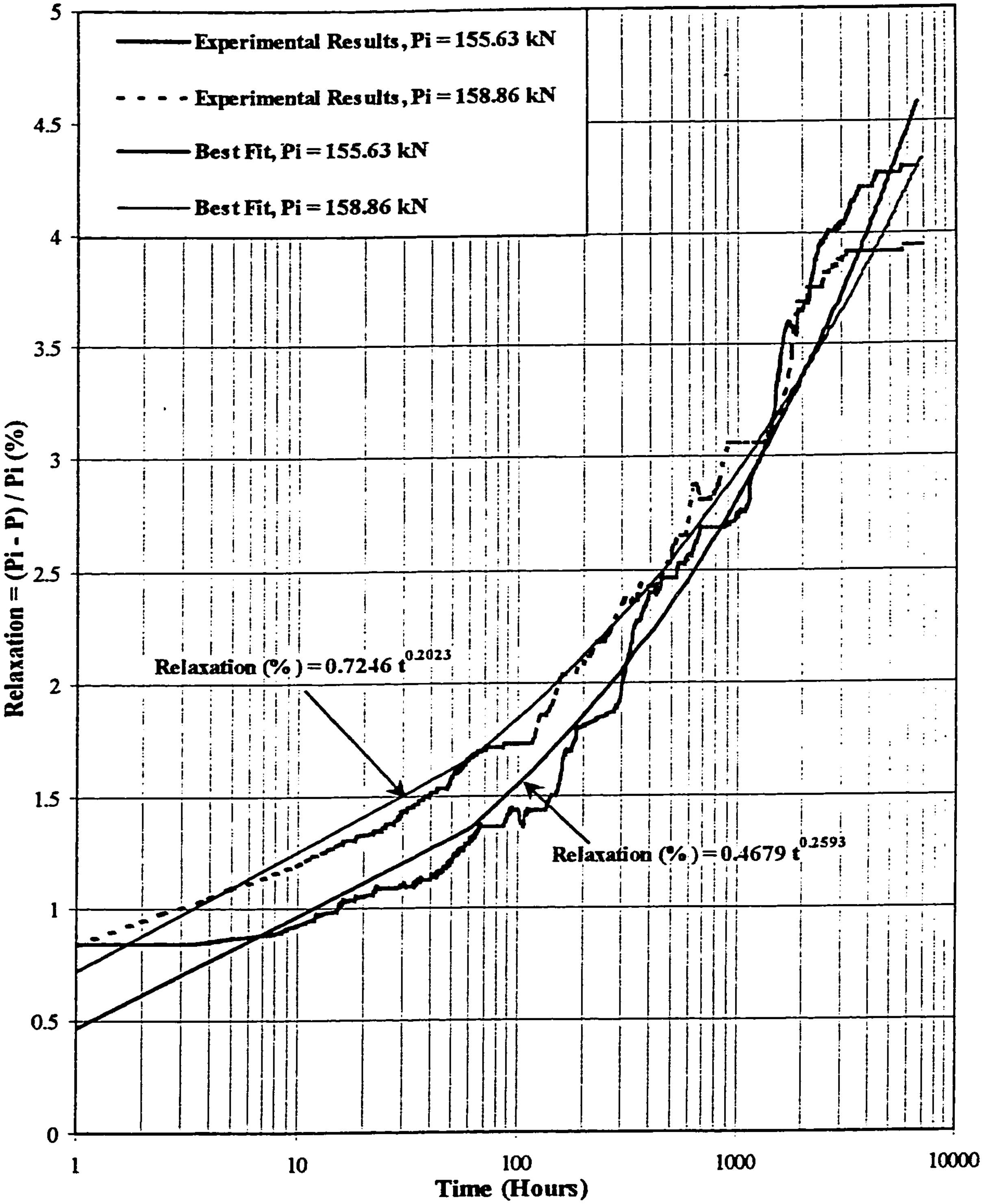


Figure 5.3 - Best Fit Equation of the Experimental Results; $P_i = 0.60P_u$.

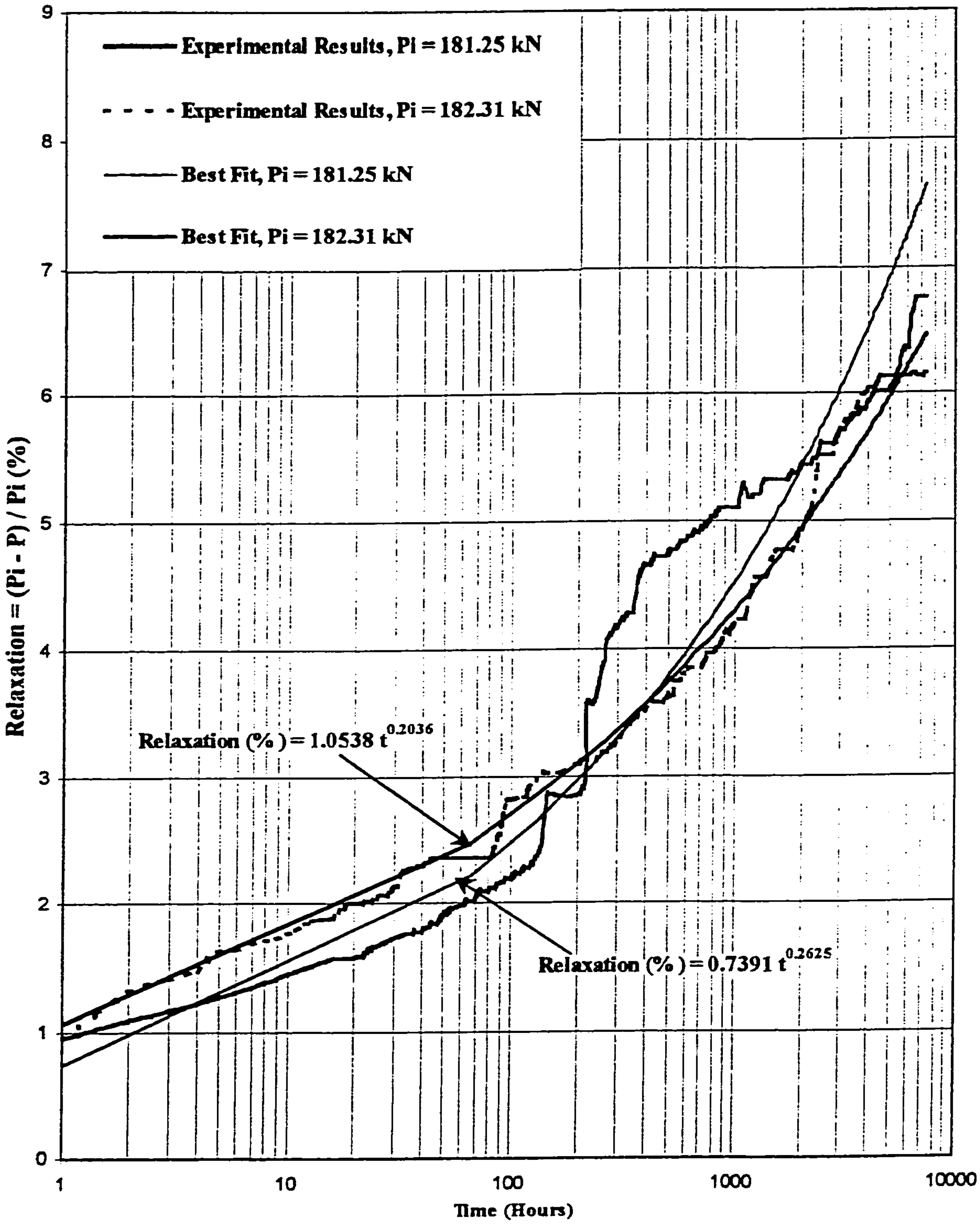


Figure 5.4 - Best Fit Equation of the Experimental Results; $P_i = 0.70P_u$.

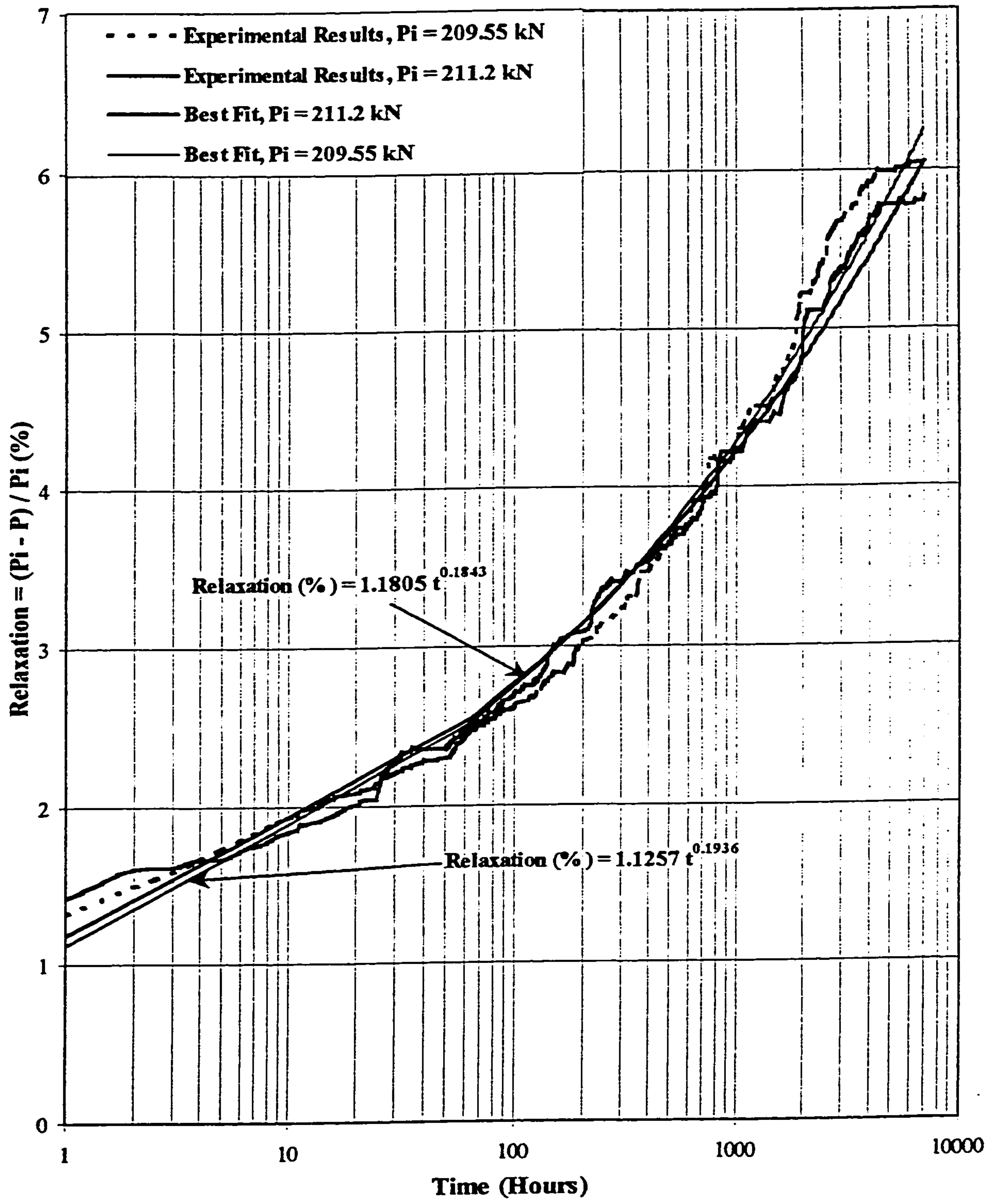


Figure 5.5 - Best Fit Equation of the Experimental Results; $P_i = 0.80P_u$.

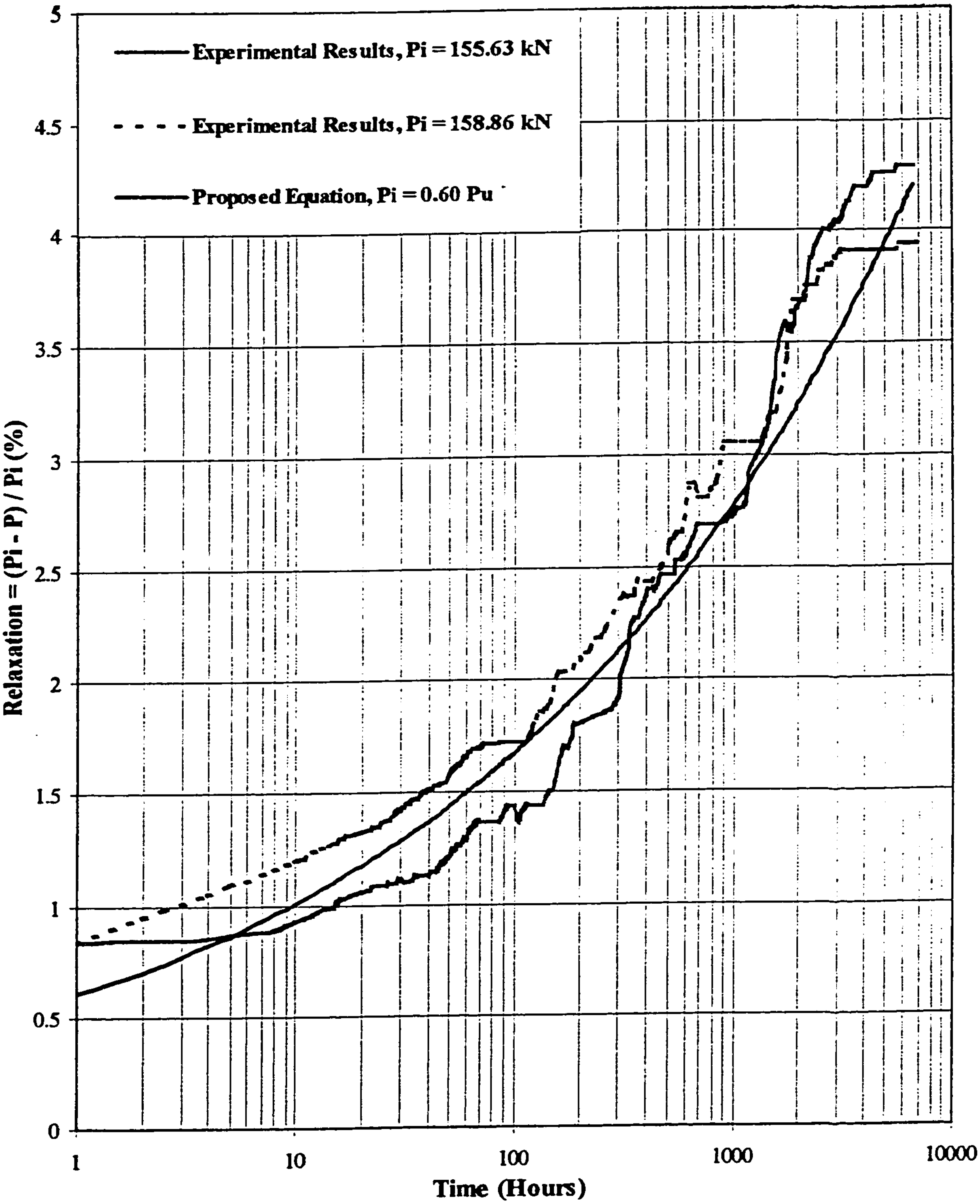


Figure 5.6 – Comparison between Steel Stress Relaxation Values Measured Experimentally and Estimated Using Equation 5.1 for $P_i = 0.60P_u$.

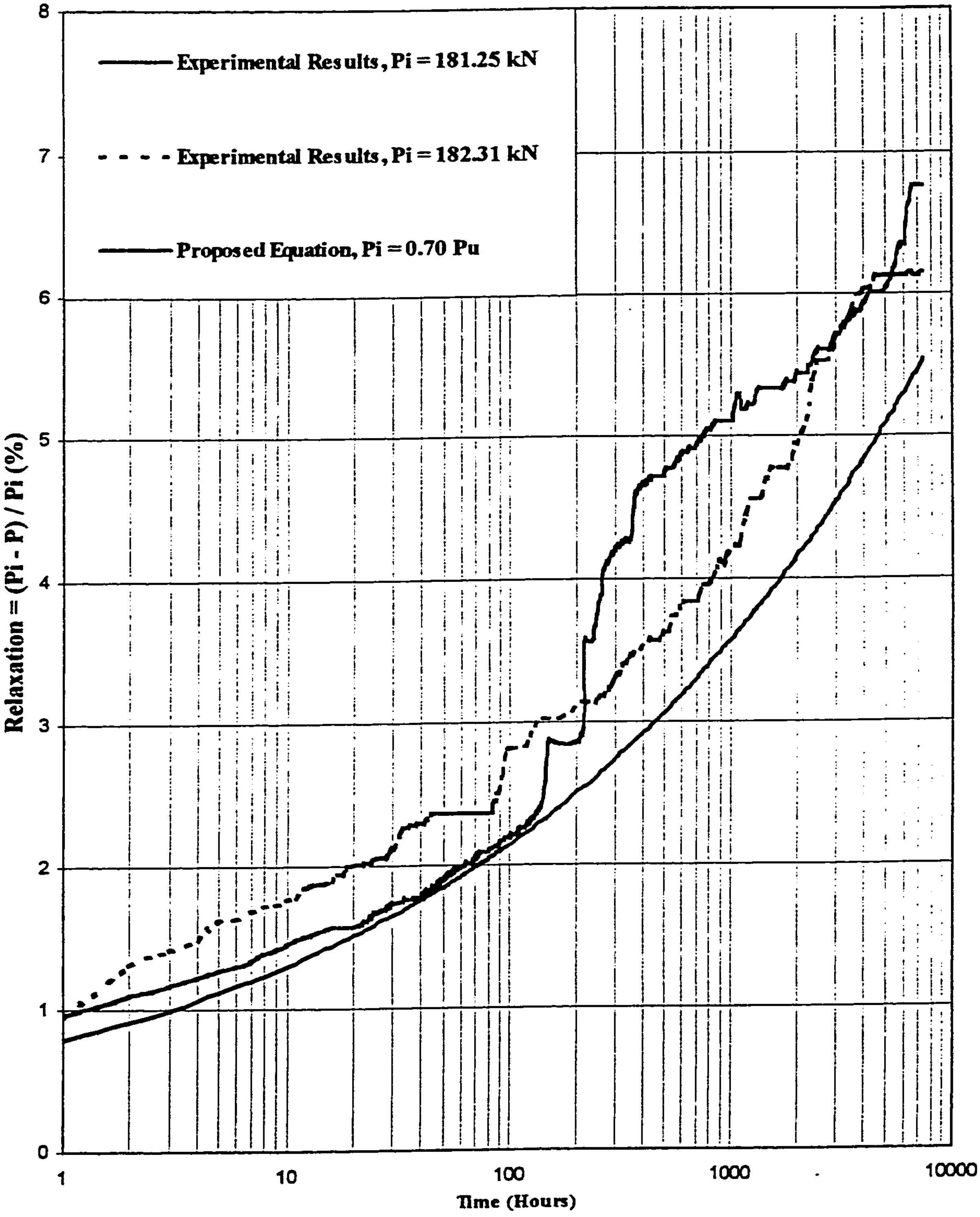


Figure 5.7 – Comparison between Steel Stress Relaxation Values Measured Experimentally and Estimated Using Equation 5.1 for $P_i = 0.70P_u$.

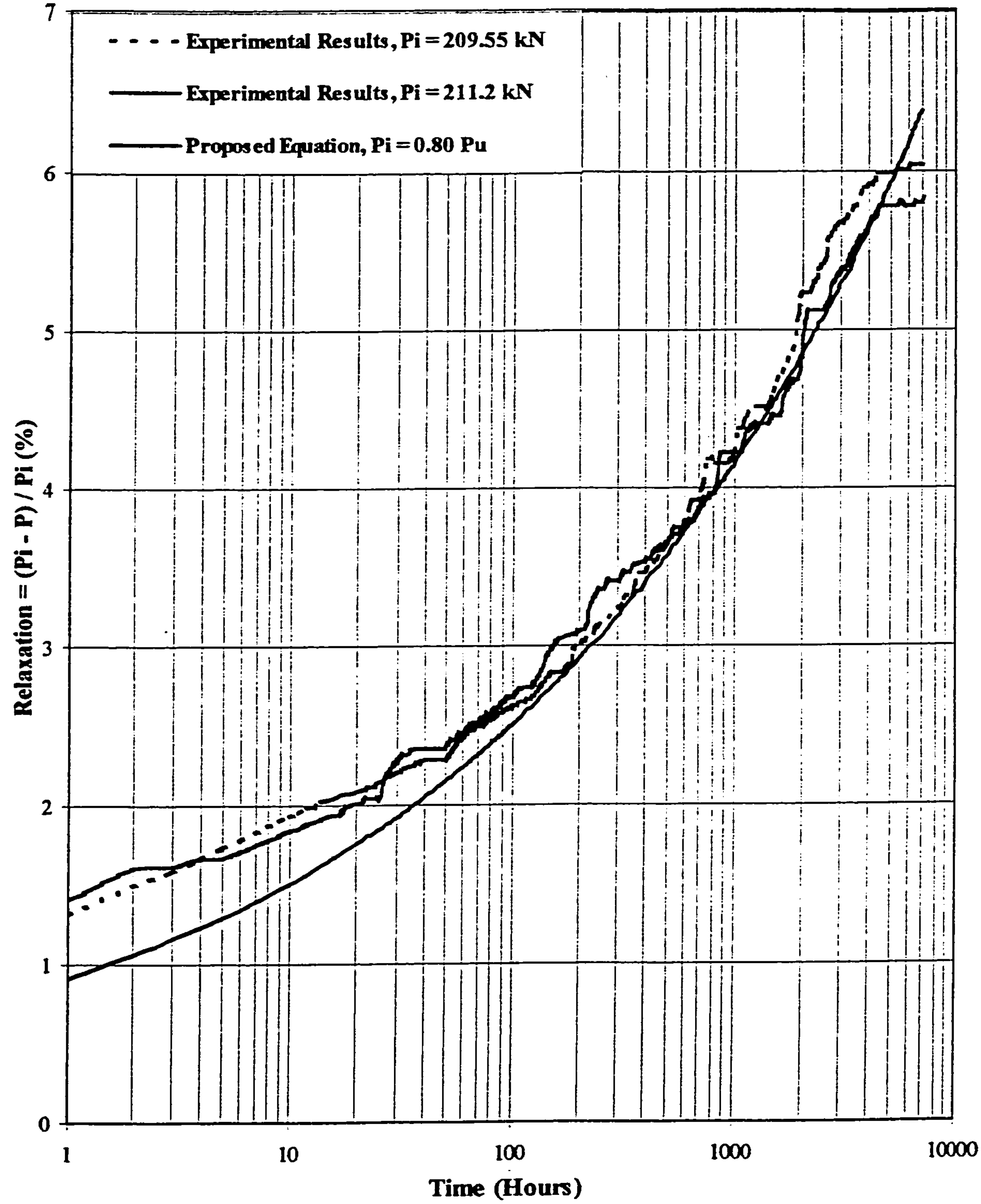


Figure 5.8 – Comparison between Steel Stress Relaxation Values Measured Experimentally and Estimated Using Equation 5.1 for $P_i = 0.80P_u$.

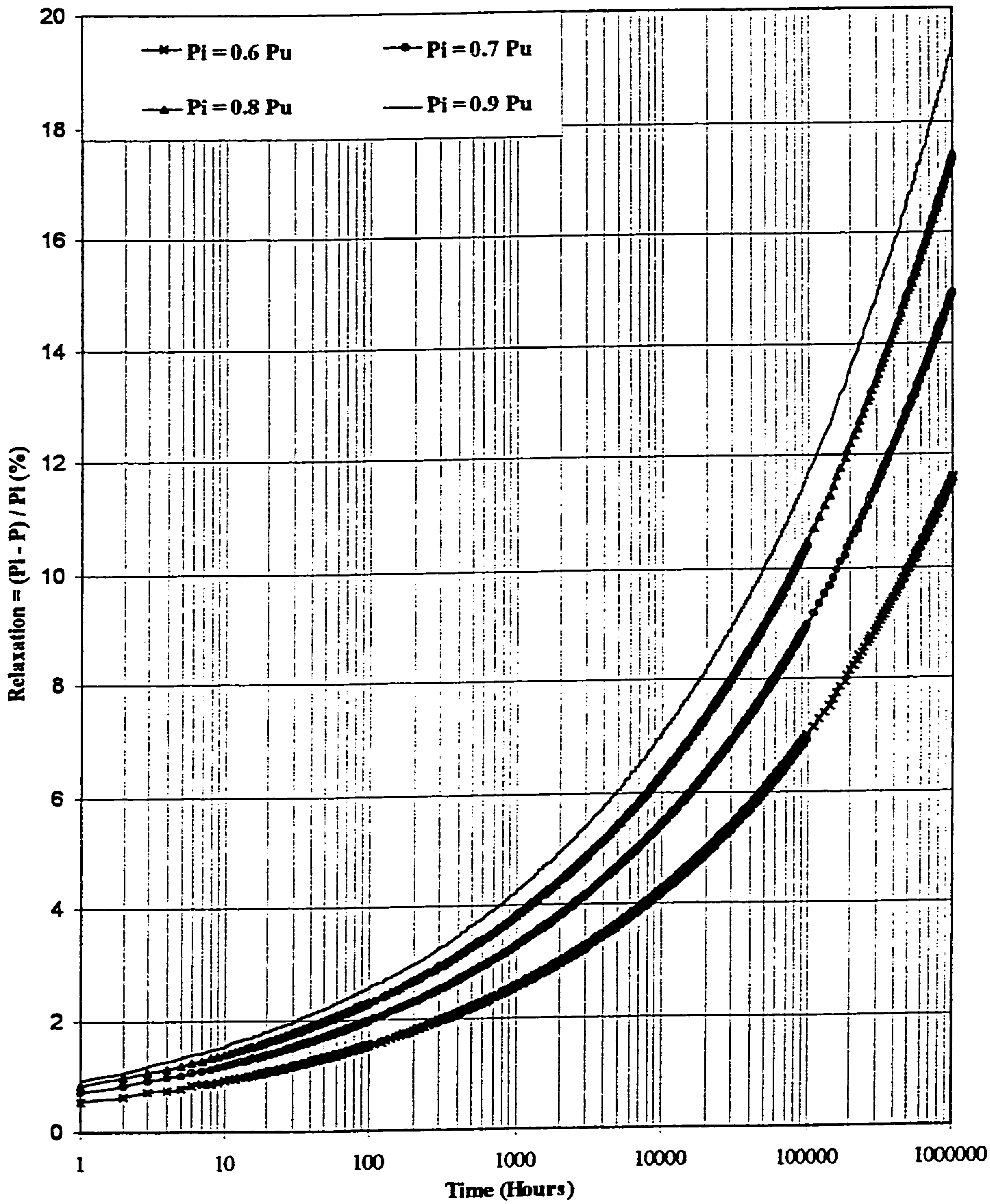


Figure 5.9 – Variation of Steel Stress Relaxation with Time According to Proposed Equation 5.1.

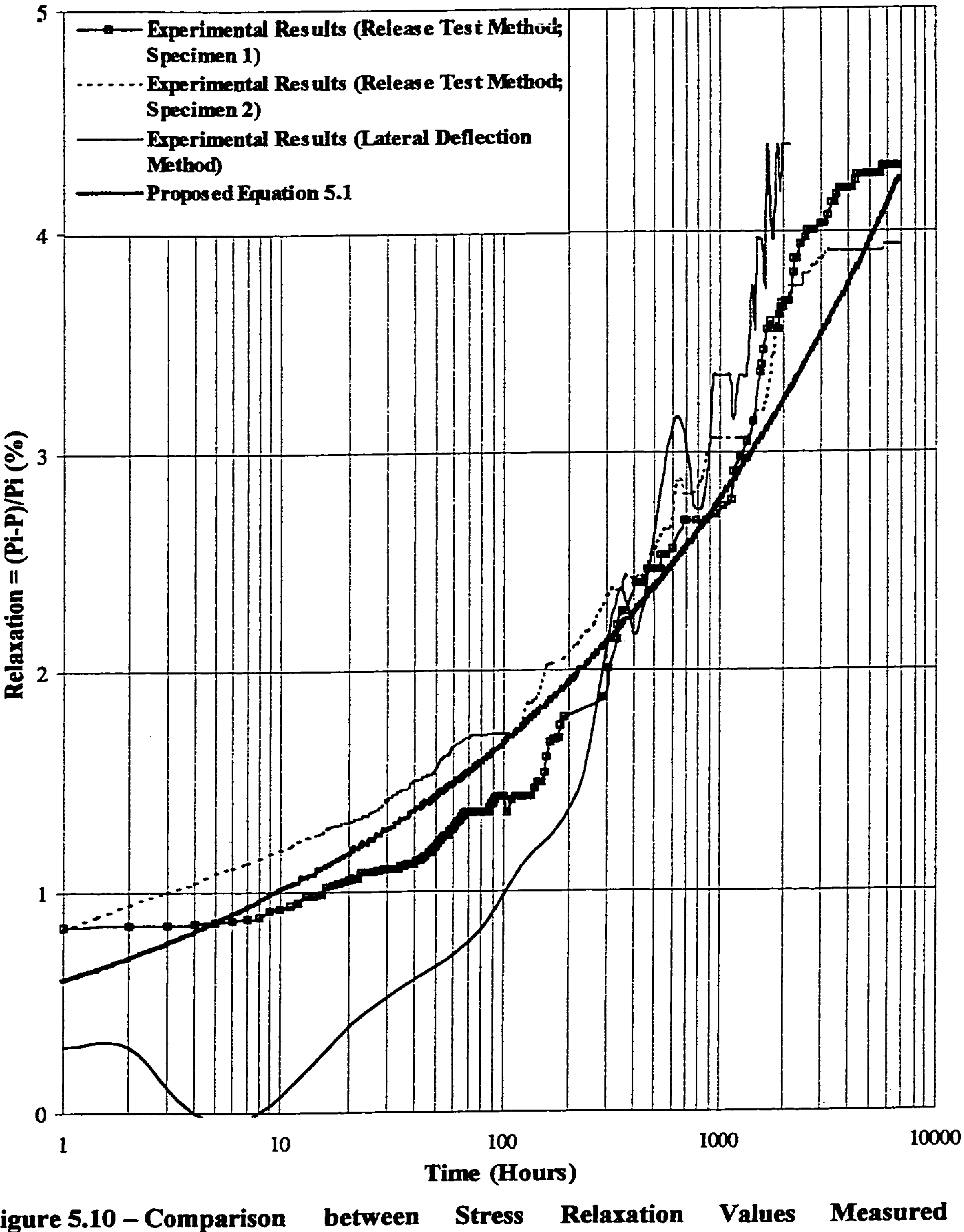


Figure 5.10 – Comparison between Stress Relaxation Values Measured Experimentally Using the Lateral Deflection Test and the Release Test, and the Calculated Using the Proposed Equation 5.1; $P_i = 0.6P_u$.

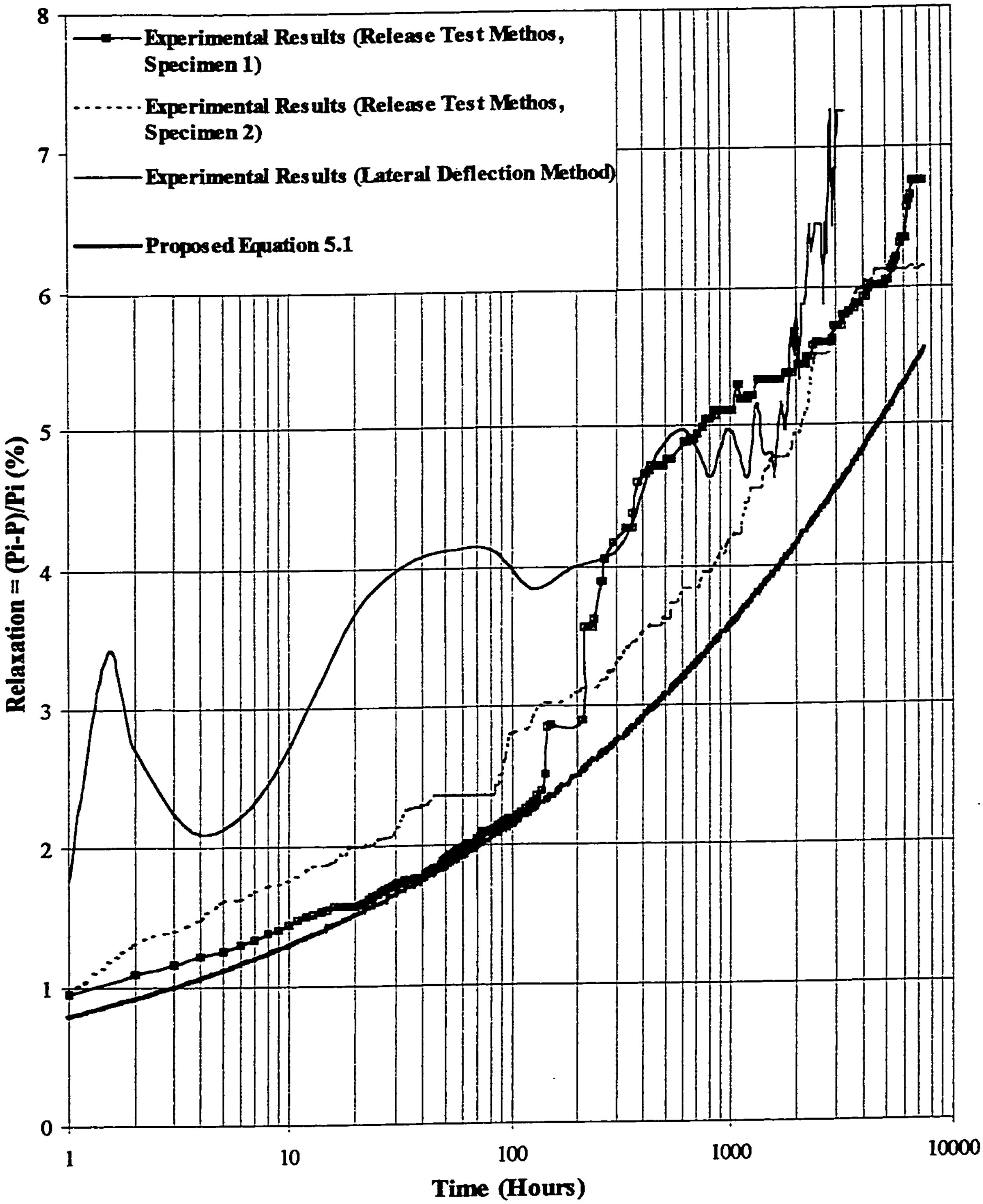


Figure 5.11 – Comparison between Stress Relaxation Values Measured Experimentally Using the Lateral Deflection Test and the Release Test, and the Calculated Using the Proposed Equation 5.1; $P_i = 0.7P_u$.

CHAPTER SIX

SUMMARY, CONCLUSION AND RECOMMENDATIONS

6.1 Summary

As a part of the comprehensive research program to study the performance of the Confederation Bridge, the relaxation of force in steel tendons used for concrete prestressing was experimentally investigated in this research. Steel stress relaxation is the decrease with time in the initial prestressing force applied to the steel tendon. Experimentally, steel stress relaxation is measured by monitoring the decrease in stress with time while holding the steel specimen at a constant extension. Stress relaxation measured experimentally is termed the *intrinsic relaxation*. However, prestressed concrete members shorten due to the effect of creep and shrinkage of concrete. This shortening decreases the initially applied prestressing force. Since stress relaxation of steel decreases by decreasing the initial prestressing force, the value of intrinsic relaxation should be reduced to account for the effect of creep and shrinkage of concrete.

Theoretically, there are several empirical formulas to estimate stress relaxation of steel. However, most of the available formulas were obtained from old and relatively short periods experimental tests results. The PCI expression and the CEB FIP Code equation are most commonly used in estimating stress relaxation of steel. These equations adopt the two most important factors affecting the amount of steel stress relaxation, namely, the time and the initial prestressing ratio as variables. All the available equations to estimate stress relaxation establish the following two main facts: 1)

Steel stress relaxation starts initially at a high rate then the rate decreases with time. 2) Steel stress relaxation increases by increasing the initial stress.

Experimentally, there are several testing methods. Two of them were adopted in this research. First, the release method in which the test was carried out by measuring the force in the tested specimen by means of a load cell while keeping the specimen at the same extension that it reached due to the initially applied force. The release testing method can be considered as one of the most effective methods since the remaining force in the tendon is measured directly by the load cell. Using the release method, two specimens were tested at each of the following loading levels: 60%, 70% and 80% of the ultimate strength of steel.

Second, the lateral deflection testing method. In this method a known weight was used to measure the lateral deflection at the middle of a stressed specimen that was kept at a constant extension. The amount of lateral deflection was converted to force in the tested specimen by means of a pre-prepared calibration curve that relates the deflection at the middle of the specimen to the force in the specimen. Two specimens were tested using the lateral deflection testing method at initial stress of 60% and 70% of the ultimate tensile strength.

The experimental results of this research were analyzed and used to derive a formula to estimate steel stress relaxation. This formula has two variables that are the time and the initial stress ratio, $(\sigma_{pi} / \sigma_{pu})$.

6.2 Conclusions

The conclusions of this research are based on experimental results of tests conducted on eight high strength, seven-wire strand, prestressing steel specimens. Six specimens were tested using the release method; two specimens were tested at each of the following initial loading levels: 60%, 70% and 80% of the steel ultimate strength. Two specimens were tested using the lateral deflection method at initial loading levels of 60% and 70% of the steel ultimate strength.

The main conclusion of this study is that the available equations to predict stress relaxation of steel underestimate its values. The comparisons between stress relaxation of steel measured experimentally and calculated from the PCI and the CEB FIP Code expressions presented in Chapter Four, support this conclusion.

It is a well established fact that stress relaxation of steel increases by increasing the initial force. The PCI expression states that stress relaxation of steel increases by increasing the initial force at a constant rate. The CEB FIP Code expression states that stress relaxation of steel increases by increasing the initial force at an increasing rate. However, the results of this study prove that stress relaxation of steel increases by increasing the initial force at a decreasing rate. This finding was adopted in the proposed equation (5.1) to estimate stress relaxation of steel.

The fact that decreasing the initial stress will decrease the relaxation losses leads to the existence of theoretical initial stress ratio at which no steel stress relaxation will take place. The analysis of the experimental results of this research have shown that at 44 % initial stress ratio ($\sigma_{pi} / \sigma_{pu}$) or less, steel stress relaxation will be zero.

Stress relaxation of steel can be represented in the form of a mathematical equation. The power equation was found to be the best form to represent the stress relaxation values measured experimentally.

The lateral deflection testing method is not recommended to be conducted on short specimens since the error will be significant. The trend should be toward using long specimens. The test specimen should be at least 3 meters in order to obtain accurate results.

The results obtained from the two different testing methods are relatively different. This is due to the different accuracy level for each method. The results obtained from the release testing method are accurate since the force in the tested specimen was directly measured by means of a load cell. However, different sources of errors participated in reducing the accuracy of the lateral deflection method since the force in the specimen was indirectly estimated.

6.3 Recommendations for Future Work

In this research, two testing methods were adopted to study steel stress relaxation, namely, the release method and the lateral deflection method. A future study on high strength, 1.5 meter steel specimens can be conducted using the vibration method and the lever arm method in order to compare results from different testing methods. Carrying out the relaxation test using the different methods can give a better understanding of the advantages and disadvantages of these testing methods

This research was intended to be a standard relaxation test. The test was carried out in a controlled temperature environment of approximately 20 °C. Research work can be carried out to study stress relaxation of steel under changing temperature conditions.

In addition, the effect of prestretching on steel stress relaxation can be investigated. Prestretching is an operation in which the stress in the specimen is increased to a level higher than the required initial stress level, and held for a certain time period. At the end of this time period, the stress level is reduced to be the required initial stress level and the standard relaxation test is conducted. To compare with the results of this research, similar specimens can be prestretched before carrying out the same relaxation test. For example, the effect of applying a certain stress level, say 20% higher than the required initial stress, for a certain time period, say 3 hours, on steel stress relaxation can be studied.

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APPENDIX A

Tensile Strength Test Results

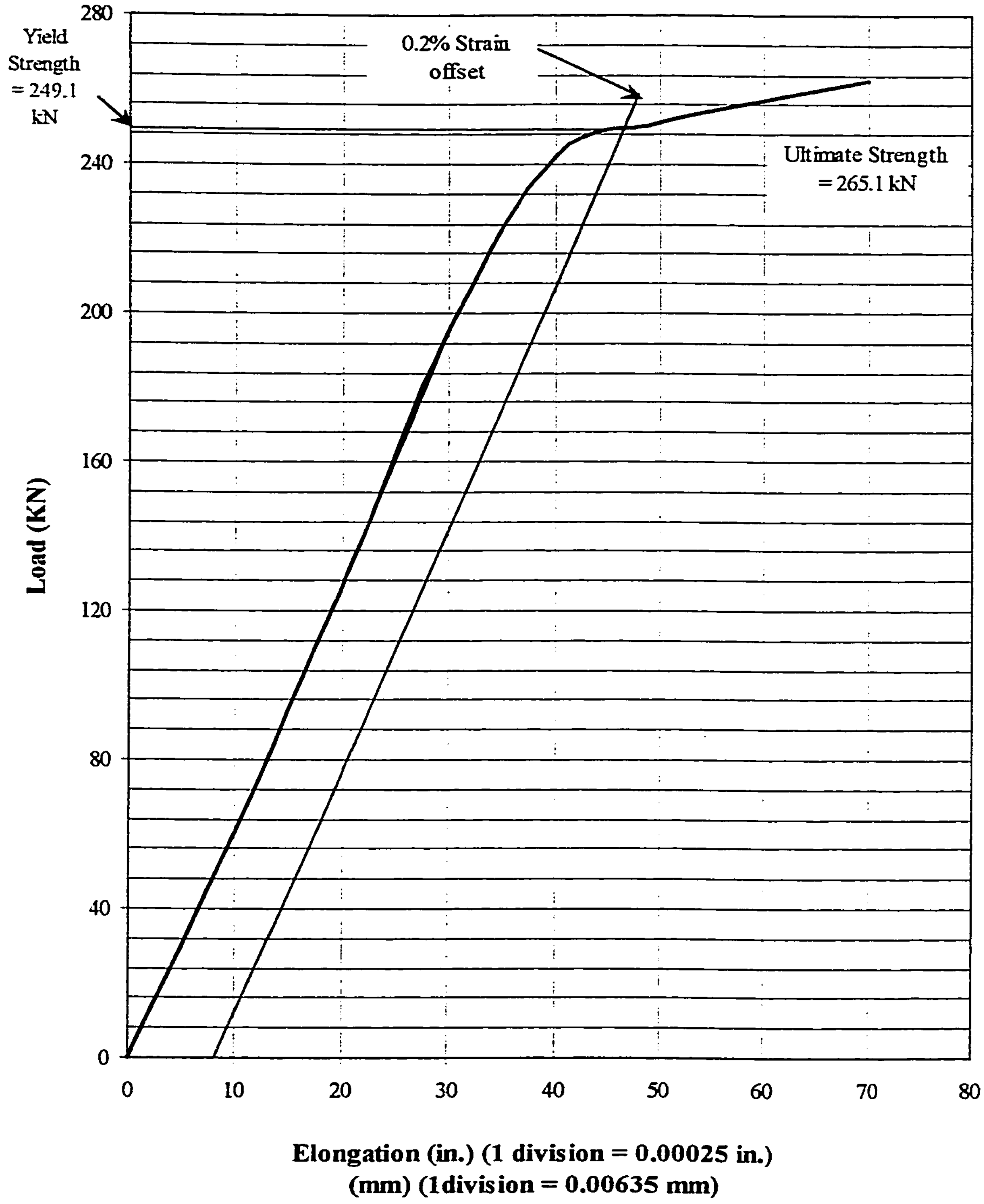


Figure A.1 - Load-Elongation Diagram of the Tested High Strength Steel Specimen.

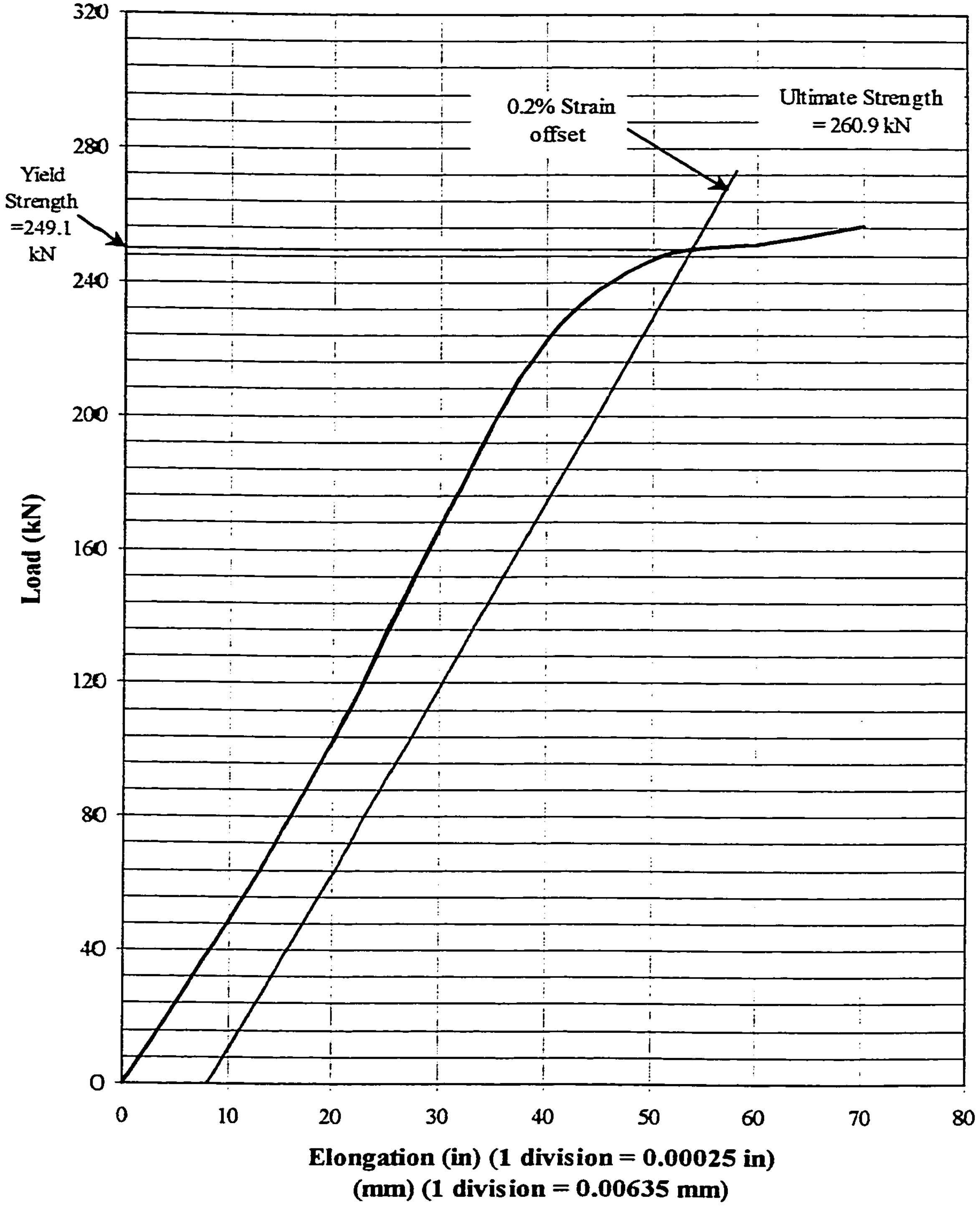


Figure A.2 - Load-Elongation Diagram of the Tested High Strength Steel Specimen.

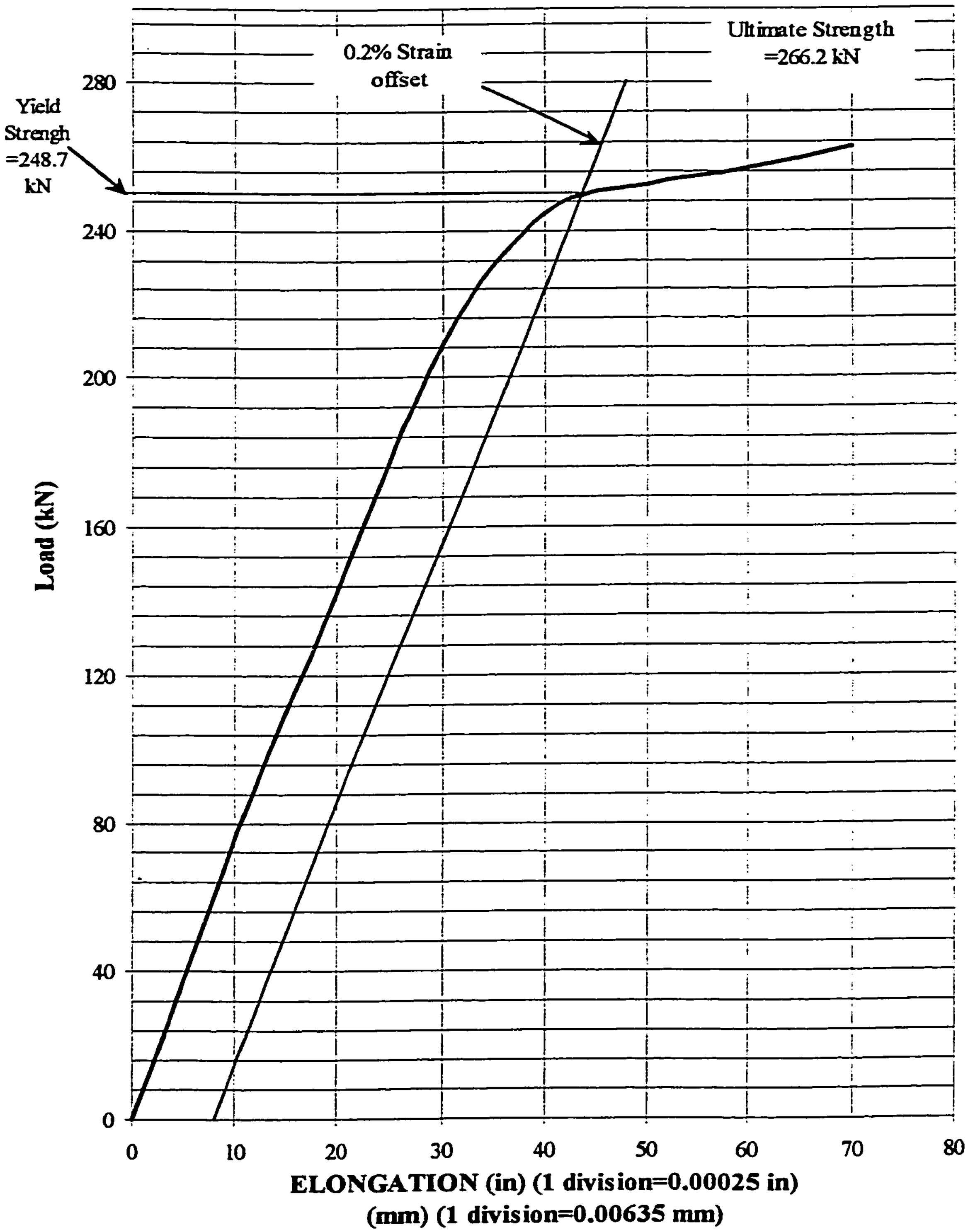
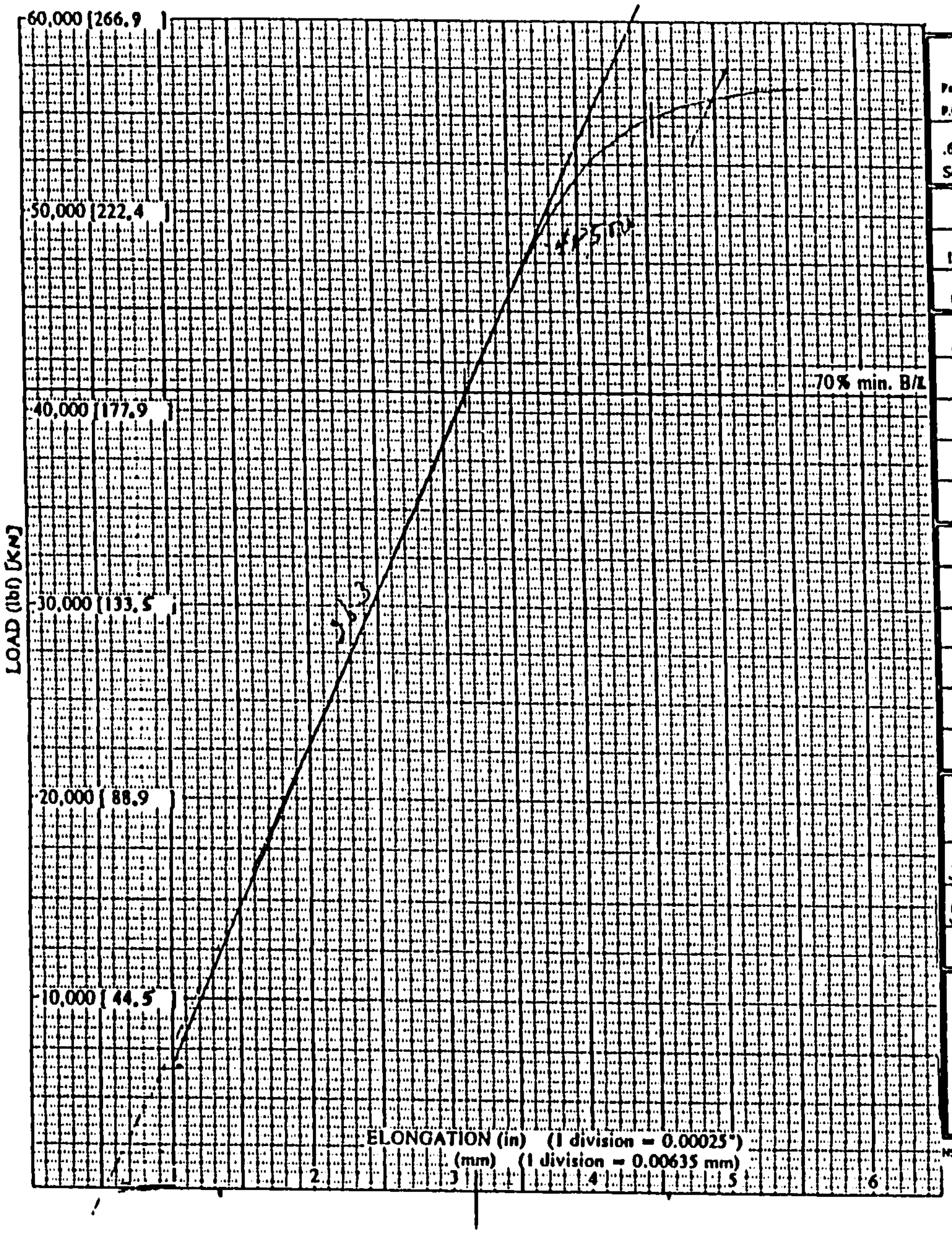


Figure A.3 - Load-Elongation Diagram of the Tested High Strength Steel Specimen.

APPENDIX B

High Strength Steel Properties Provided by the Manufacturer



STELWIRE Parkdale Works, Strathearne Ave. N. P.O. Box 2030, Hamilton, Ont. L8N - 3T1	DATE: 8-22-96 REEL # N518684.

.600 Inch, 15.24 mm, Grade 270 K Low Relaxation
Seven-Wire Strand For Prestressed Concrete.

INDIVIDUAL WIRE DIAMETERS

Inch	$.205^{5}$	.198	.198	.198	$.198^{5}$	$.198^{5}$	$.198^{5}$
mm	5.22	5.03	5.03	5.03	5.04	5.04	5.04

Area in²: .218	Area mm²: 140.6
B/Load lbf: 61600	B/Load KN: 274.0
UTS psi: 282,567	UTS MPa: 1948.8
Load at 1 % Ext (lbf): 54900	Load at 1 % Ext KN: 244.2
Yield lbf: 55900	Yield KN: 248.7

E Modulus X 10⁶ psi: 28.6

E Modulus GPa: 197.2

Extension (70 % Min. B/Load) in/in: .00658

Extension (70 % Min. B/Load) mm/mm: .1670

Elongation in 24" (%): 6.5

Visual Examination: OK

Heat	C (X 100)	Mn (X 100)	Si (X 100)	P (X 1000)	S (X 1000)
532142	81	89	52	28	16
532146	81	82	47	25	14

This is to certify that the strand pake produced from this reel, covered by this report meet the requirements of the following specifications: CSA G279 - M, ASTM A416.

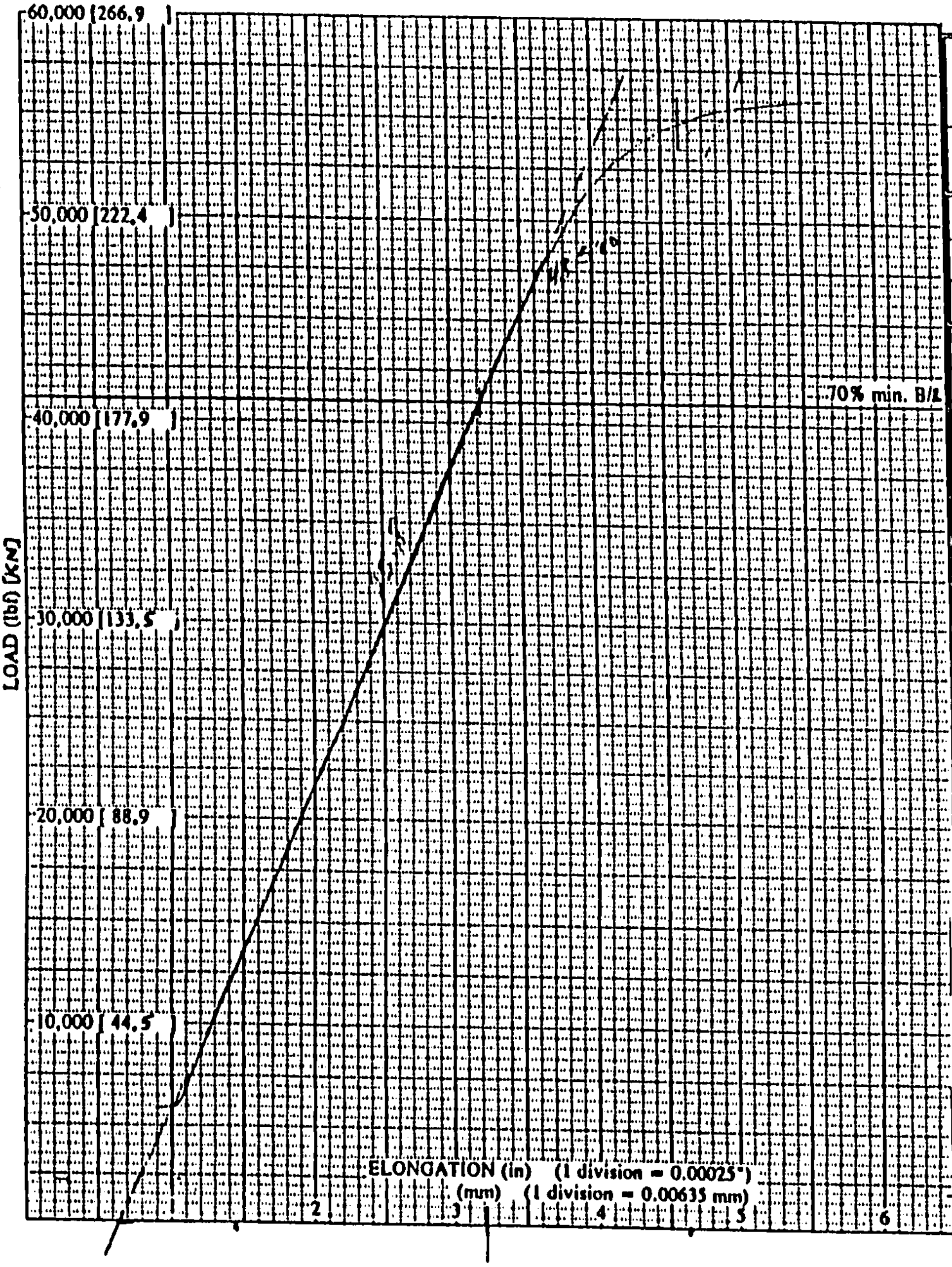
J. K. Whittaker

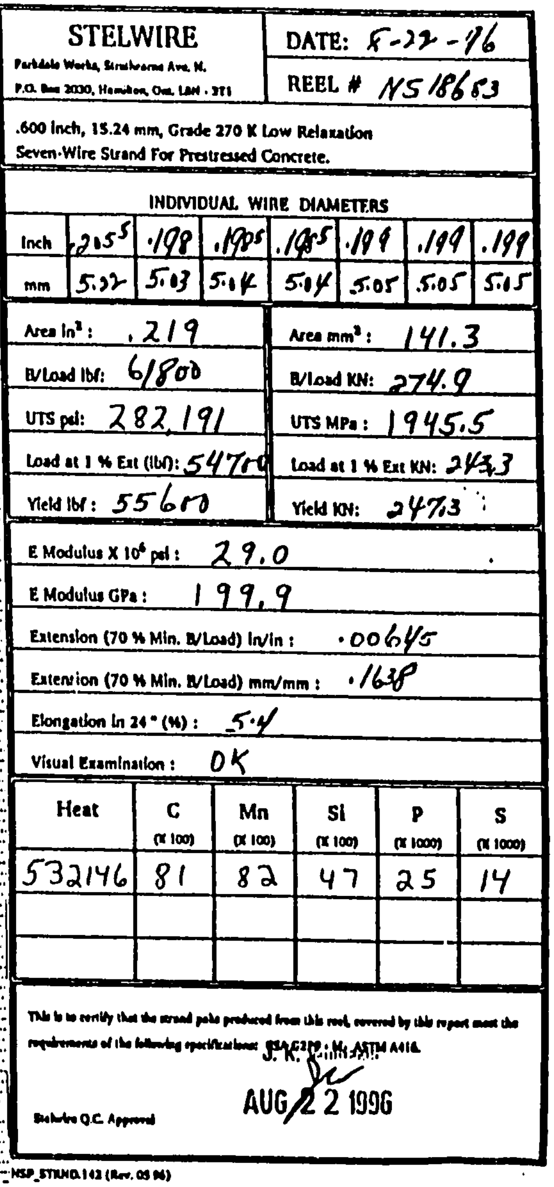
Stelwire Q.C. Approval

AUG 23 1996

NSP_STRND.142 (Rev. 05 96)

Figure B.1 – Load-Elongation Diagram Provided by the Manufacturer of Steel.





STELWIRE

Parkdale Works, Strathearne Ave. N.
P.O. Box 2030, Hamilton, Ont. L8N 3T1

DATE: 8-22-96

REEL # NS18683

.600 Inch, 15.24 mm, Grade 270 K Low Relaxation Seven-Wire Strand For Prestressed Concrete.

INDIVIDUAL WIRE DIAMETERS

Inch	.2055	.198	.1985	.1985	.199	.199	.199
mm	5.22	5.03	5.04	5.04	5.05	5.05	5.05

Area in²: .219	Area mm²: 141.3
B/Load lbf: 61800	B/Load KN: 274.9
UTS psi: 282,191	UTS MPa: 1945.5
Load at 1 % Ext (lbf): 54700	Load at 1 % Ext KN: 243.3
Yield lbf: 55600	Yield KN: 247.3

E Modulus X 10⁶ psi: 29.0

E Modulus GPa: 199.9

Extension (70 % Min. B/Load) In/in: .00645

Extension (70 % Min. B/Load) mm/mm: .1638

Elongation In 24" (%): 5.4

Visual Examination: OK

Heat	C (X 100)	Mn (X 100)	Si (X 100)	P (X 1000)	S (X 1000)
532146	81	82	47	25	14

This is to certify that the strand pole produced from this reel, covered by this report meet the requirements of the following specifications: CSA G279 - M, ASTM A416.

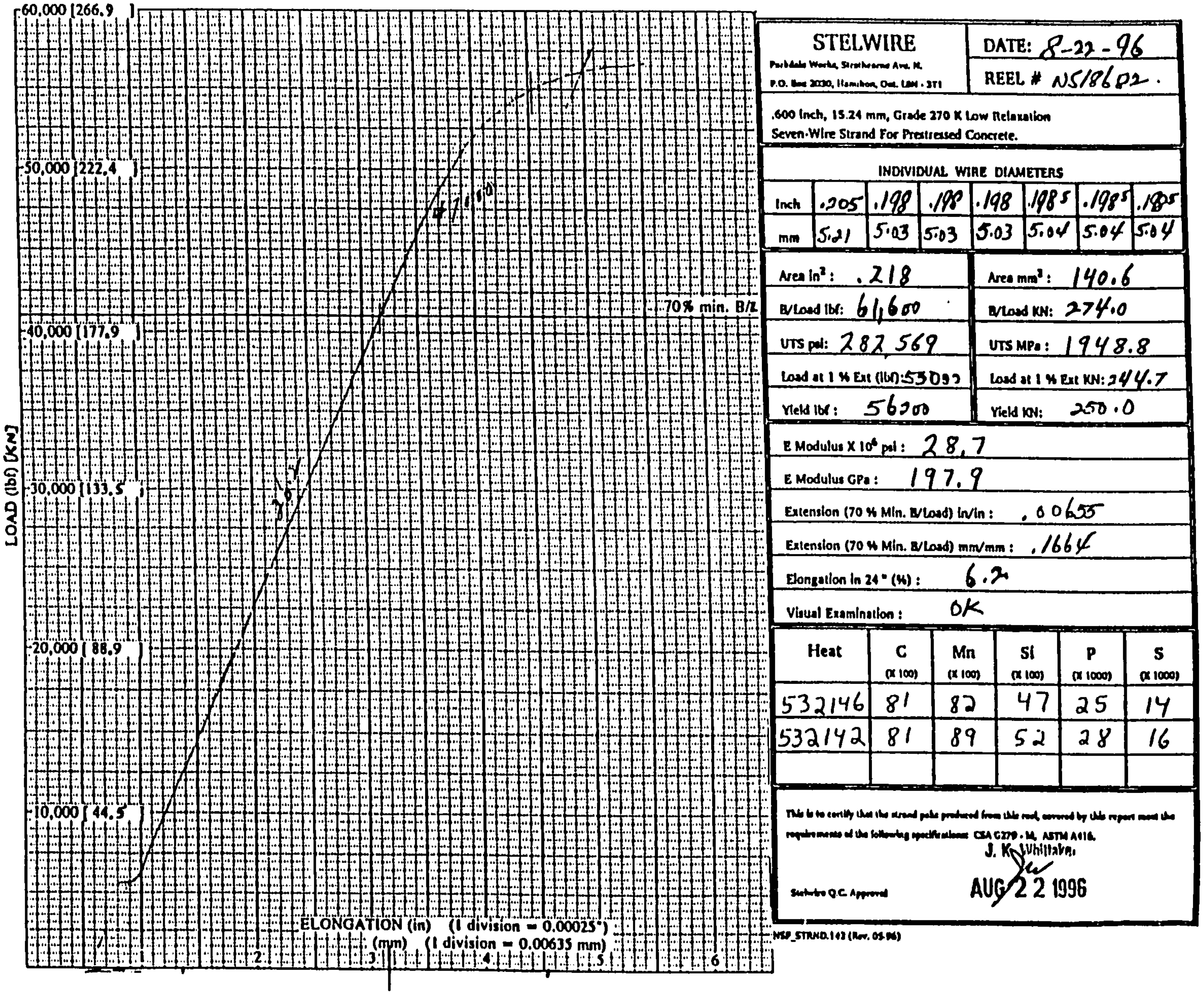
J. K. [illegible]

Stelwire Q.C. Approval

AUG 2 2 1996

NSP_STRND.142 (Rev. 05 96)

Figure B.2 - Load-Elongation Diagram Provided by the Manufacturer of Steel.



STELWIRE Parkdale Works, Strathearne Ave. N. P.O. Box 2030, Hamilton, Ont. L8N - 3T1	DATE: 8-22-96 REEL # NS18602.

.600 Inch, 15.24 mm, Grade 270 K Low Relaxation
Seven-Wire Strand For Prestressed Concrete.

INDIVIDUAL WIRE DIAMETERS

Inch	.205	.198	.198	.198	.1985	.1985	.1985
mm	5.21	5.03	5.03	5.03	5.04	5.04	5.04

Area in²: .218	Area mm²: 140.6
B/Load lbf: 61,600	B/Load KN: 274.0
UTS psi: 282,569	UTS MPa: 1948.8
Load at 1 % Ext (lbf): 53097	Load at 1 % Ext KN: 244.7
Yield lbf: 56200	Yield KN: 250.0

E Modulus X 10⁶ psi: 28.7

E Modulus GPa: 197.9

Extension (70 % Min. B/Load) in/in: .00655

Extension (70 % Min. B/Load) mm/mm: .1664

Elongation in 24" (%): 6.2

Visual Examination: OK

Heat	C (X 100)	Mn (X 100)	Si (X 100)	P (X 1000)	S (X 1000)
532146	81	82	47	25	14
532142	81	89	52	28	16

This is to certify that the strand pak produced from this rod, covered by this report meet the requirements of the following specifications: CSA G279 - M, ASTM A416.

J. K. Whittaker

Stelwire Q.C. Approved

AUG 22 1996

NSP_STRND.143 (Rev. 05-96)

Figure B.3 – Load-Elongation Diagram Provided by the Manufacturer of Steel.

APPENDIX C

Pictures of the Experimental Setup

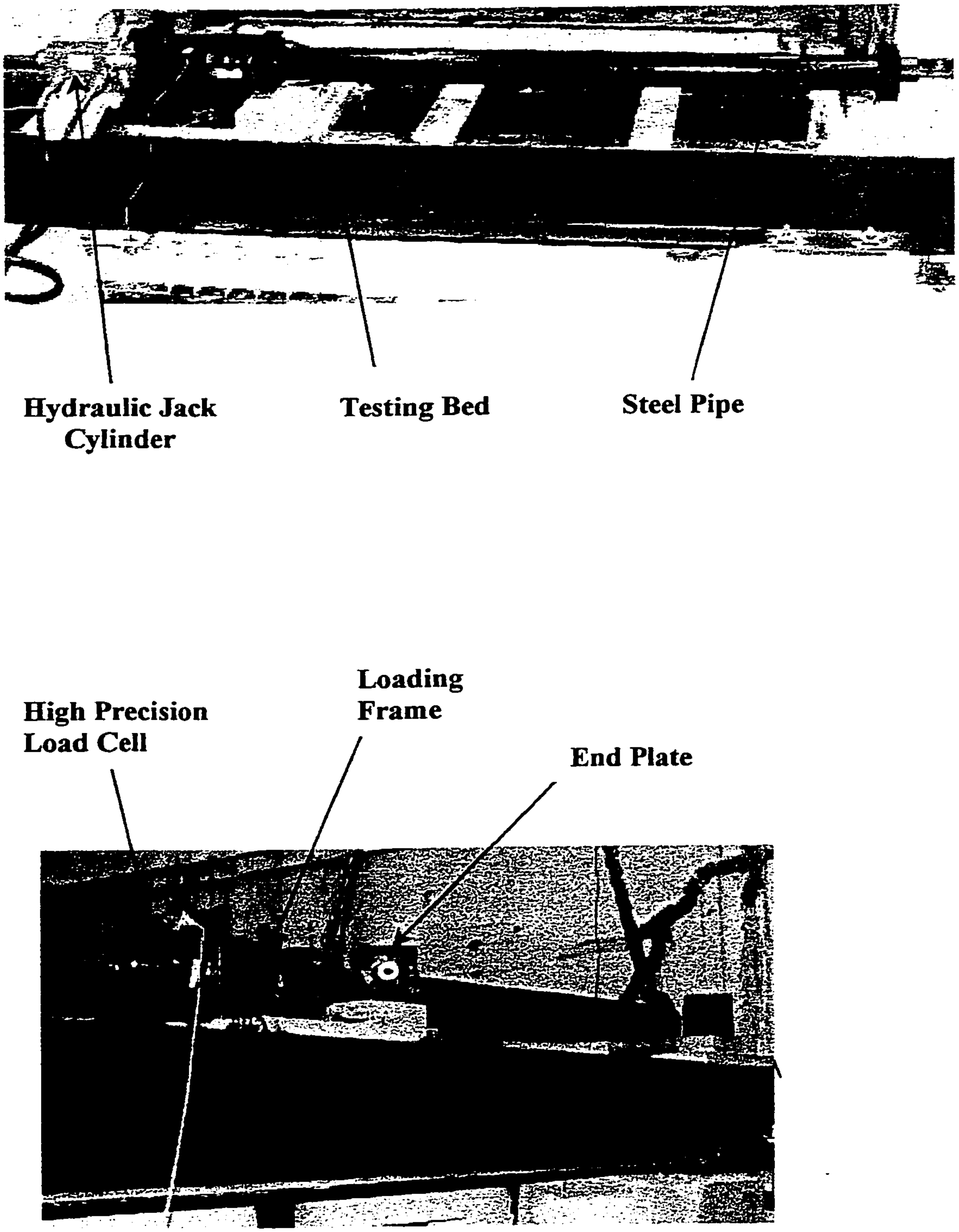


Figure C.1 – Steel Relaxation Test Setup (Release Testing Method).

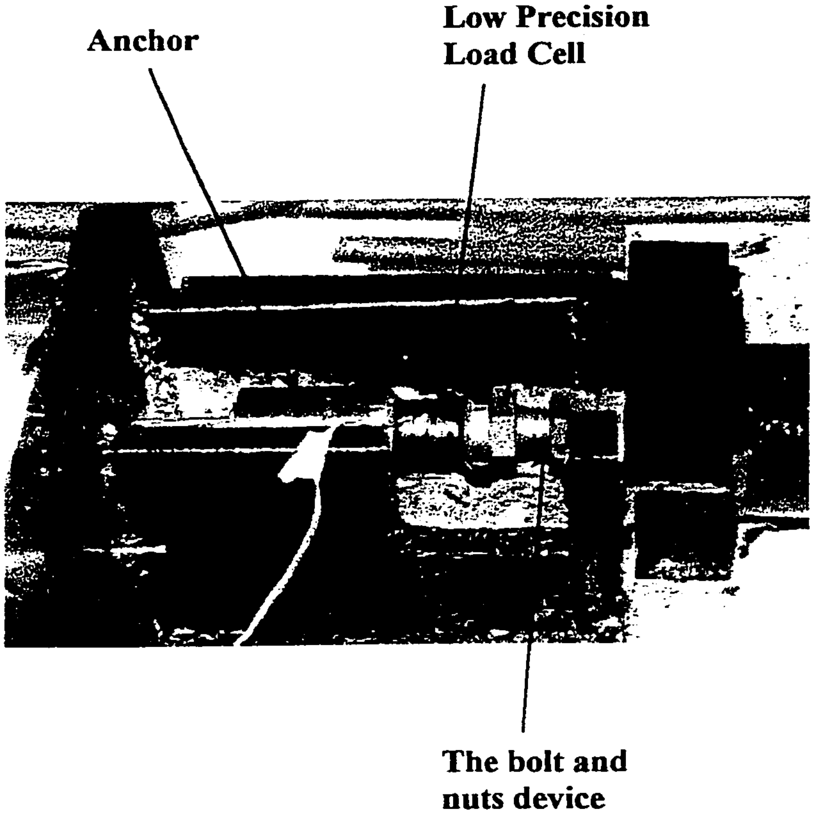


Figure C.2 – The Loading Frame Used to apply the Initial Prestressing Force (Release Testing Method).

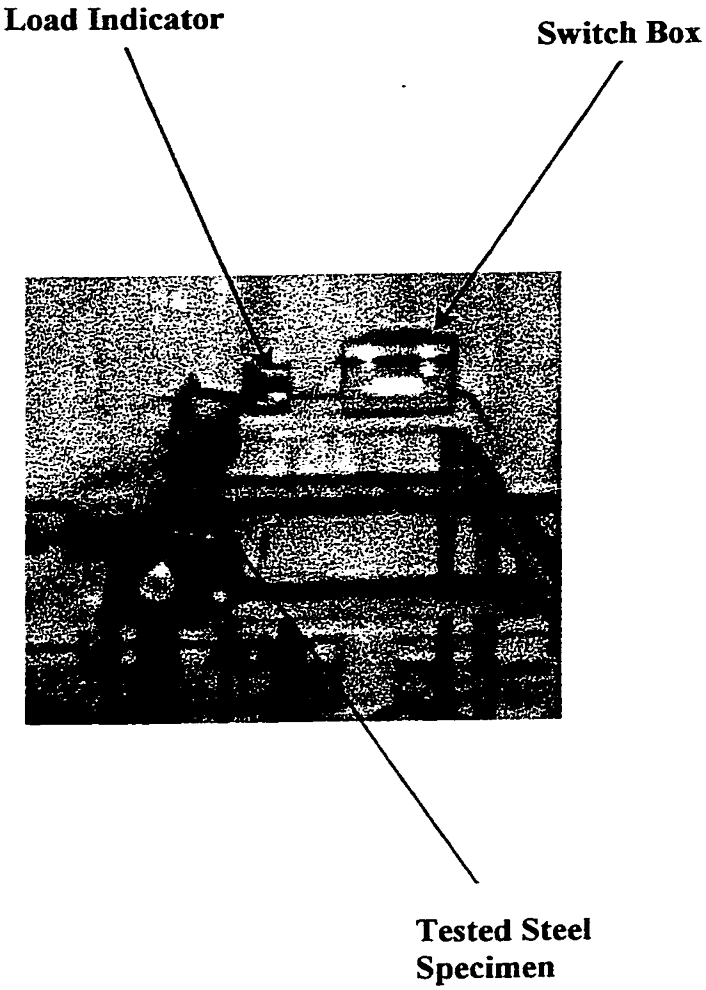


Figure C.3 – Long Term Relaxation Test (Release Testing Method).

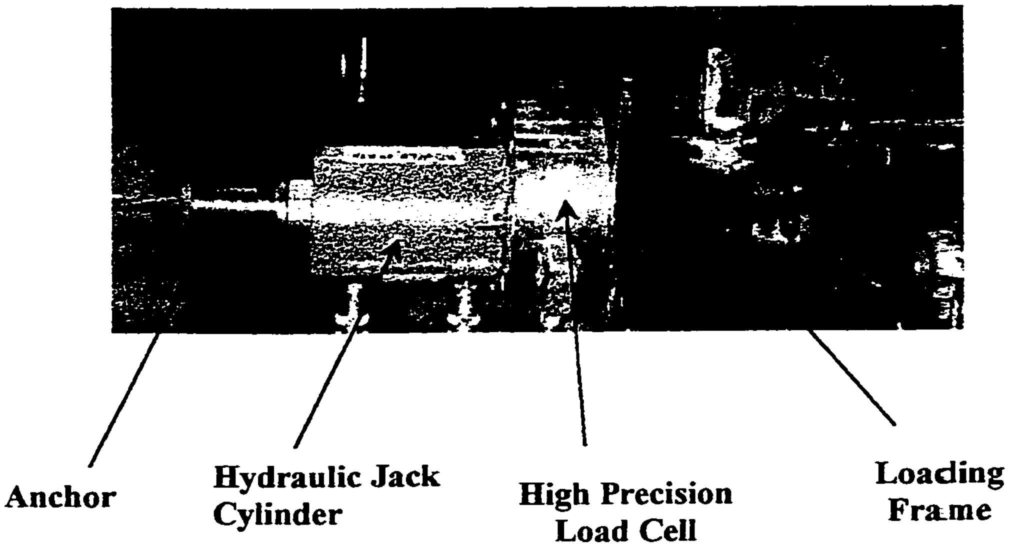


Figure C.4 - Loading Frame at Time of Load Application (Lateral Deflection Method).

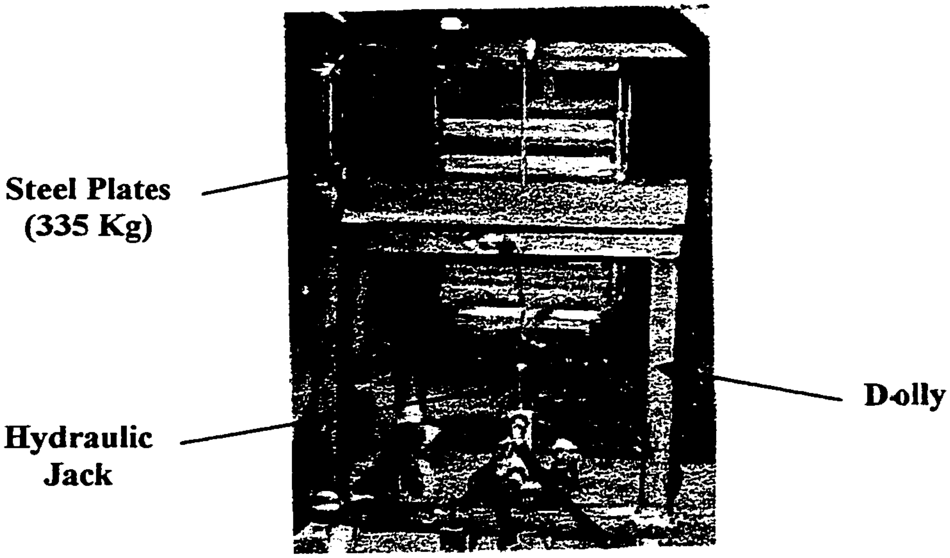


Figure C.5 - Setup Used to Apply the Lateral Deflection to the Tested Specimen

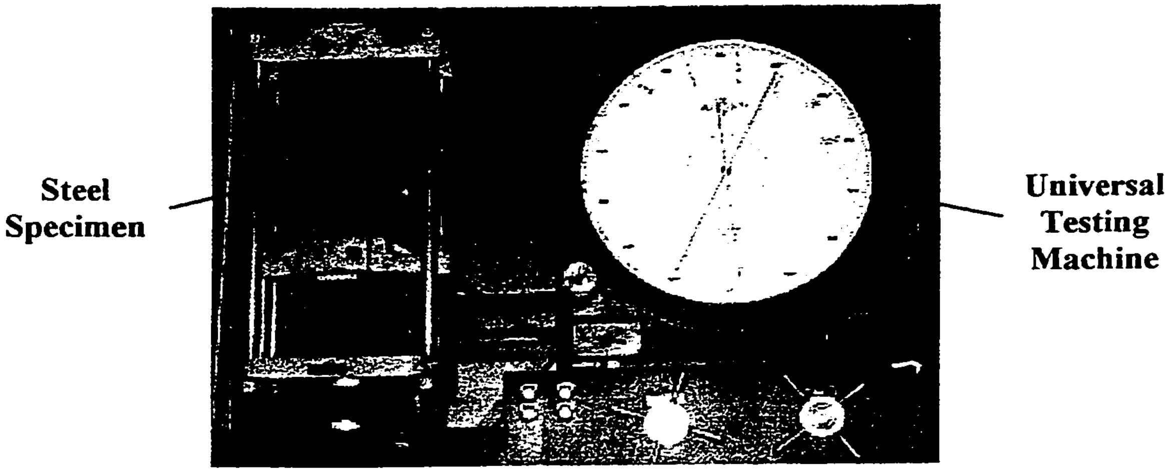


Figure C.6 - The Tensile Test.

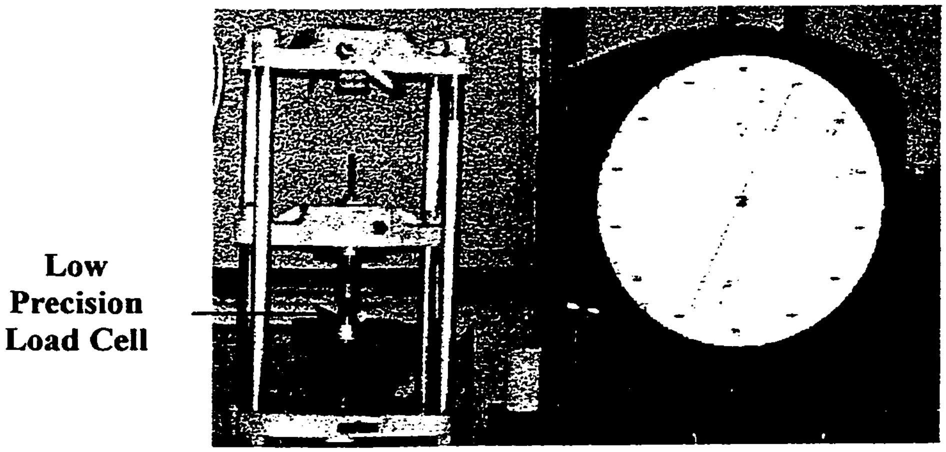


Figure C.7 – The Calibration Test.