
Peter G. Rimbos
PRESTRESS RECOVERY OF STEAM-CURED
PRETENSIONED CONCRETE MEMBERS

FRITZ ENGINEERING
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by

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ABSTRACT

The effect of elevated temperature during curing of prestressed concrete members is an important variable present in the fabrication process. The objective of this research is to determine the permanent loss of prestress, if any, caused by the short-term elevated temperature associated with the steam curing period. A number of small-sized pretensioned specimens were prepared and tested flexurally until a preformed transverse crack opened. The actual prestress force in the specimen was determined from the measured applied moment corresponding to this "crack-opening".

It was found that the apparent thermal recovery of prestress (registered externally by the load cells) accompanying the completion of the curing period is real. For a curing temperature of approximately 66° C (150° F), a net loss of 1.8%, or 23 MPa (3.3 ksi) was observed. These values are comparable to the normally expected relaxation loss for a similar three-day time period without excursion to higher temperature. Consequently, there is no permanent loss in prestress caused by the elevated temperature normally used in steam curing.
1. INTRODUCTION

1.1 Purpose and Scope

The research herein described is part of a six-month investigation into the effect of elevated temperatures present during the steam curing of prestressed concrete members. The purpose of the study is to determine the permanent loss of prestress, if any, caused by the short-term elevated temperature associated with curing.

Pretensioned prestressed concrete specimens were fabricated and subsequently subjected to a 65-70 hour steam cure, during which the strand tensile strains and the specimen temperatures were monitored. The specimens were then tested in bending in order to determine the actual amount of prestress remaining.

In order to fully understand the importance of determining the amount of prestress remaining within a concrete member, the nature of the cure will next be discussed.

Concrete is a heterogeneous material, whose primary constituents are sand, gravel or stone, water and cement. The cement and water combine to form a paste, which bonds the aggregates together. The properties of the concrete change from a plastic mixture to a hard mass by way of hydration, the chemical action between cement and water. The concrete will continue to gain strength, though at an ever-decreasing rate, as long as hydration can properly take place.
However, the rate of hydration will decrease, as evaporation from the exposed surface of the concrete occurs. Consequently, for a period of time after mixing and placing, concrete is cured in a moist environment in order to provide an adequate amount of water for hydration.

Temperature also has a pronounced effect on the rate of hydration. The hydration process can be accelerated by employing a high curing temperature. Consequently, curing by steam causes the concrete to gain strength faster in the early stage.

Prestressed members will generally exhibit concrete creep and shrinkage and steel strand relaxation. However, when accelerated curing methods are employed, the concrete creep and shrinkage will be substantially reduced, thereby increasing the relative importance of strand relaxation.

Tension in the strand decreases during curing due to thermal expansion. Thus, the strand and its stress losses are of major importance when accelerated curing methods are used. The prestress recovery in the strand accompanying the temperature reduction at the end of the curing period is easily determined. The strand stress can be monitored during and after the cure with the aid of load cells mounted on the strands at the dead end of the prestressing bed. As the length of the prestressing bed remains constant during this time, the expansion, contraction and relaxation of the strand will be directly reflected on the load cells.
The background of several theories concerning the recovery and questions raised about some recent research will be presented in the following section.

1.2 Background

A major investigation into prestress losses as they are affected by the type of curing was completed by Hanson in 1964. The three-year study employed the direct measurement of prestress loss in terms of force rather than of strain measurement. Two sizes of post-tensioned concrete prisms were tested in specially designed equipment which would limit the observed losses to those due to concrete creep and shrinkage.

The results demonstrated the beneficial reduction of these losses by accelerated curing methods. Atmospheric steam curing up to $65^\circ C (150^\circ F)$ nearly cut in half the creep, shrinkage and prestress losses observed for normally cured concretes, whereas for autoclave curing up to $175^\circ C (350^\circ F)$ resulted in creep and shrinkage losses which were nearly negligible. However, Hanson's work was centered upon the losses due to creep and shrinkage only, and therefore the prestress recovery was not of major concern.

In 1972, as part of a larger research project into the prestress loss characteristics of in-service highway bridge members, a number of standard PennDOT pretensioned I-beams, 18.3 meters (60 ft.) in length, were fabricated.
Atmospheric steam curing of the beams was incorporated with strand prestress monitored by load cells located at the dead end of the prestressing bed. The observed net loss before prestress transfer was consistent with the amount expected from strand relaxation alone. These observations appeared to indicate that the thermal prestress loss was almost completely recovered after the end of the curing period.

Even though steel prestress was measured with load cells, no further measure of the actual prestress within the members was attempted. In addition, questions were raised concerning the validity of the method of measuring strand prestress external to the members. Observers felt that the prestress within the members would not be comparable to the prestress monitored on the external portions of the strands.

To answer some of these questions a pilot experimental study was conducted in late 1974 as part of a student project at Lehigh University. The test specimens, 10.16 cm square (4 in. x 4 in.) and 3.05 meters (10 ft.) in length containing a metal separation plate at mid-length, were centrally prestressed with one 1.27 cm (1/2 in.) seven-wire stress-relieved pretensioned strand (see Fig. 1). The metal plate would effectively eliminate any tensile stress capacity at the center. Immediately after transfer of prestress to the hardened concrete, direct tension was applied to the strand until separation was achieved at the center of the specimen. Therefore, the load required for separation was, in fact, the "before transfer"
load and not the "after transfer" load. SR-4 strain gages mounted in the center region, along with a clip gage mounted across the metal plate, were used to detect separation.

The sensing devices proved to be sufficiently sensitive in detecting the change of member behavior upon separation. The occurrence of prestress recovery was observed. However, the results from the two pilot tests were not completely consistent. Some difficulties were experienced in positioning and holding the metal plate due to its flexibility. Also, the separation of the specimens was not complete. It was believed that these difficulties contributed to the inconclusive test results.

These pilot tests directly led to the research described herein. However, in order to eliminate the difficulties experienced in the pilot study, and due to the inadequate nature of the direct tension tests, the prestress within the specimens after prestress transfer is determined using a flexure test to open a preformed transverse crack at mid-length. The general experimental program is described in the following section.

1.3 Experimental Program

1.3.1 Fabrication of Specimens

This section will briefly describe the overall program incorporated; more detail can be found in Chapter 2.

Three experiments were performed in order to determine the actual amount of prestress recovery within the concrete specimens.
Each involved the testing of two specimens, 10.2 cm by 15.2 cm (4 in. x 6 in.) in cross section and 3.2 m (10.5 ft.) in length.

The specimens were fabricated within a 6 m long by 2.5 m wide (20 ft. x 8 ft.) steel prestressing frame located in the concrete laboratory of Fritz Engineering Laboratory (see Fig. 1). Two 10.2 cm (4 inch) steel channels and several sections of plywood were used as forms for each specimen. Two specimens were fabricated simultaneously, each pretensioned centrally by one 1.27 cm (1/2 in.) seven-wire stress-relieved prestressing strand of the 270 grade (specified ultimate strength of 1863 MPa or 270 ksi). Load cells were placed at the end of each strand at the "dead end" of the prestressing frame in order to monitor the variation in the strand tension. The strands were stretched with the aid of two 178 kN (40 k) mechanical jacks.

Concrete was mixed using Type I cement. The proportions of the mixes incorporated in each of the three experiments are presented in Table 1. Several standard 15 cm by 30 cm (6 in. x 12 in.) cylinders were fabricated along with the beam specimens.

A small hole was made in each specimen in order to insert a temperature sensing device. The specimens and cylinders were covered and insulated using plastic sheets. Some difficulty was encountered in the proper insulation technique and will be discussed in greater detail later.

The time interval from tensioning of strands to the beginning of steam curing was approximately five hours. Once the steam cure commenced, the temperature of the specimens increased until about
60°C (140°F) was attained. About one day after the commencement of the cure the steel channel forms were removed to allow more efficient curing. The curing lasted 65-70 hours, after which the specimens were uncovered and allowed to dry and cool off before detensioning and transfer of prestress. A complete timetable for Experiment III is given in Table 2.

1.3.2 General Testing Program

The beam specimens were placed in a 13,350 MN (300k) machine approximately 20-25 hours after prestress transfer. Strain gages were mounted on the bottom of each specimen. A clip gage was centrally placed between two knife edges attached to the bottom of each specimen half, straddling the center plate. The complete gage setup for the specimens is diagrammed in Fig. 2.

Each beam specimen was tested flexurally using load increments of 445 N (100 lb.) until a preformed transverse crack opened in the center region. The strain gages were used to determine the approximate cracking load. The concrete and steel strains obtained in this manner were analyzed to aid in the prestress force determination. The standard cylinders were later tested to determine the average concrete compressive strength and modulus of elasticity. A segment of prestressing strand was also tested for modulus of elasticity.

Problems were encountered in the first two experiments in the following areas: insulation of the specimens for curing purposes, load cell calibrations, and strain gage data interpretation. Details
of these problems and the remedies used to successfully overcome them will be discussed in later sections.
2. FABRICATION AND TESTING

2.1 Fabrication Program

Three experiments were performed in order to determine the pre-stress recovery accompanying the temperature drop at the completion of the steam curing. These experiments were conducted one month apart, with modifications each time designed to eliminate problems encountered in the preceding experiment in order to achieve improved results. Each experiment involved the fabrication and testing of two centrally pretensioned prestressed concrete specimens, 10.2 cm by 15.2 cm (4 in. by 6 in.) in cross section and 3.2 m (10.5 ft.) in length.

A steel prestressing frame, approximately 6 m long and 2.5 m wide (20 ft. by 8 ft.), was erected on the floor of the concrete laboratory of Fritz Engineering Laboratory, Fig. 1. The prestressing frame, housing the two specimens and several cylinders, was set above the floor on 45.7 cm (18 in.) deep wide-flange-cutoffs.

The specimens were fabricated on their sides with two 10.2 cm (4 in.) steel channels for the sides and several sections of 1.3 cm (1/2 in.) plywood for the bottom and ends serving as forms for each. The channels were placed back to back, 15.2 cm (6 in.) apart, and were bolted to the plywood. A 15.2 cm (6 in.) square sheet metal plate was placed at mid-length between the channels to serve as a separator for each half of the specimen. The plate contained a
1.4 cm (9/16 in.) hole along its centerline, 5.1 cm (2 in.) from the bottom, in order to allow a single prestressing strand to pass through. The forms and plates were well-waxed to prevent adhesion.

A single 1.3 cm (1/2 in.) seven-wire stress-relieved prestressing strand of the $270^k$ grade (specified ultimate strength of 1863 MPa or 270 ksi) was drawn through the frame, the plywood end plates, and the sheet metal separator plate for each specimen. Each strand was approximately 6 m (20 ft.) in length.

At the dead end of the frame a load cell was placed over the end of the strand. Each load cell was calibrated so that readings could be converted to steel stresses in order to monitor the prestress during the curing period.

The load cells used were designed for a previous project at Fritz Engineering Laboratory, Project 339, "Prestress Losses in Pretensioned Concrete Structural Members". They are made of 2014-T6 aluminum alloy, in the shape of a hollow cylinder, with a length of 12.7 cm (5 in.), an inner diameter of 2.2 cm (7/8 in.) and an outer diameter of 4.5 cm (1-3/4 in.). Eight EA-13-125TM-120 type strain gages are mounted on the outside of each cylinder, four in the longitudinal direction, and the other four in the lateral direction. These strain gages are connected to form two independent Wheatstone Bridges. Strain readings are taken from the bridges by a Budd strain indicator.

Some difficulties were encountered during the calibration of the load cells. The load cells were calibrated four or six in series
on a 520 kN (120 k) hydraulic testing machine at Fritz Engineering Laboratory. Two loading runs were performed. The calibrated range at loading was from 18 kN (4 k) to 142 kN (32 k) with readings taken at each multiple of 22 kN (5 k). Though only one bridge is necessary for monitoring strand strain, the calibration was performed using both bridges to obtain complete data for each cell. As a result, calibration factors were obtained which did not agree with those obtained from previous calibrations performed in Project 339 and, in fact, were approximately one-half of those previously obtained. The calibration test was performed again, this time with only one bridge of strain gages connected to the strain indicator. The calibration factor of about $28.5 \mu \text{m/m/kN}$ ($127 \mu \text{in./in/kN}$) obtained agreed very well with those previously obtained. Results of these calibration tests are listed in Table 3.

Pretensioning of strands was accomplished by using a 180 kN (20 ton) mechanical jack on each strand. The stretching force was controlled by readings of the load cells. As a result of the problems encountered with the calibration tests, the initial stress in the strand differs somewhat for the three experiments performed. The initial tensioning stresses can be found in Table 5.

Prior to mixing the concrete, two brass inserts were screwed into the bottom channel of each specimen form. They were placed at mid-length, 2.5 cm (1 in.) each side of the separator plate along the centerline. These were later to be used in the attachment of the knife edges which would hold the clip gage in place during the flexure test (Fig. 2).
The mix proportions initially used in Experiment I closely parallels the one commonly used in many prestressing plants in Pennsylvania. The fresh concrete proved to have a very low workability, probably due to the very dry nature of the fine and coarse aggregate available. The mix proportions were modified for Experiments II and III to compensate for this effect. Table 1 gives a comparison of the mix proportions used in all three experiments. The concrete placed in the specimen forms was well-vibrated. Simultaneously, several standard 15 cm by 30 cm (6 in. by 12 in.) cylinders were fabricated.

A small hole was made in each specimen near the metal separator plate so that a temperature sensing device could be inserted to monitor internal concrete temperature throughout the curing period.

The specimens were covered with standard plastic sheets for insulation before the commencement of the steam curing. In the first two experiments the sides of the prestressing frame were also covered in the hope that leakage of steam and heat would be minimized, thereby allowing a constant temperature to be maintained. However, this practice resulted in expansion and contraction of the prestressing frame along with the specimens having a neutralizing effect on the prestress. Consequently, the reference point was changed and the load cell readings became less usable, as the strand stress did not correspond to the situation in real-life fabrication.
Unsatisfactory results, as far as prestress recovery is concerned, were obtained for Experiment I and II. To remedy this the prestressing frame was not covered at all in Experiment III, Fig. 3. As a result, the expected steel stress recovery was observed.

2.2 The Steam Curing

The curing period commenced about 4 to 5 hours after tensioning of the strands. Once the concrete was hard enough to hold the temperature sensing rod in place, the specimens were covered. A steam hose was placed between the specimens at about mid-length and fastened to a cross bar holding the forms off the ground. The other end of the hose was attached to a steam valve approximately 3 m (10 ft.) away.

At first the steam valve was opened all the way and the setup was checked for possible leaks. Once a temperature of about 54 to 60°C (130 to 140°F) was attained (in about 1 to 1-1/2 hours), the valve was closed most of the way in order to maintain a constant temperature. Load cell and temperature readings were recorded periodically, usually every hour during the first day of the curing period.

Approximately twenty hours after the commencement of curing it was interrupted for two hours so that the forms could be removed from both specimens and cylinders to allow more efficient curing. The specimens were again covered with plastic sheets and the steam valve was re-opened. Readings on load cells and temperature sensing devices were taken every 4 to 5 hours during the remainder of the curing period.

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The entire curing process lasted almost three days (65-70 hours). At the end of this period, the specimens were uncovered and allowed to dry and cool off. Then the strands were detensioned with the aid of the mechanical jacks, transferring prestress directly into the concrete. After which the pretensioned beam specimens were moved to the testing area for testing the following day. A timetable depicting tensioning, curing, and detensioning times can be found in Table 2.

2.3 Testing Program

Immediately after detensioning, the excess strands were cut off by grinding. Both specimens were moved to the testing machine area. Two SR-4 strain gages were mounted in the center region of each specimen, Fig. 2. The SR-4 strain gages are designed to give direct values of strain and used to facilitate the determination of the prestress within the specimen.

The remainder of the instrumentation was connected after the specimen had been placed in a Tinius Olsen 1330 kN (300k) testing machine. Two knife edges were attached to the brass inserts in the bottom of the specimen with the use of target point screws. A clip gage was centrally placed between the two knife edges, straddling the center plate, in order to monitor the separation of the two specimen halves during testing, Fig. 2.

The two SR-4 strain gages were individually connected to a Budd strain indicator. In Experiment III this connection was done
in series in order to obtain an averaging effect between the two strain readings. The clip gage was connected to another Budd strain indicator.

Each specimen was flexurally preloaded beyond cracking and then tested until the preformed transverse crack at the center plate opened. A photograph of an actual test is shown in Fig. 3 and the test setup is shown schematically in Fig. 4. During the test loading was performed in increments of 445 N (100 lb.) up to 8900 N (2000 lb.). The approximate cracking load was reached when the SR-4 strain gage readings began to stabilize and remain constant, indicating the complete elimination of concrete pre-compressive strain.

As the cracking load was approached, the clip gage readings began to increase at an ever-increasing rate, also indicating the reopening of the transverse crack at the bottom of the specimen. Since all loads used in the test were within the elastic range of the specimens, the transverse crack opened and closed in the same manner for every loading and unloading cycle. In order to maintain complete control of the applied load on the specimen, the unloading cycle only went down to 2220 N (500 lb.).

After the cracking load is determined from the strain gage behavior, the cracking moment and finally the actual prestress within the member can be easily calculated. It must be re-emphasized here that the prestress determined in this manner directly gives the after transfer prestress. In the Pierce and Hoffman pilot study a direct
tension test was performed which gave only the before transfer pre-
stress. 

Standard ASTM testing procedures were followed in determining
the compressive strengths and moduli of elasticity of the test
cylinders. These characteristics were used in the necessary calcula-
tions.
3. THEORETICAL ANALYSIS

3.1 Preliminaries

3.1.1 Loading Arrangement

The loading arrangement depicted in Fig. 4 will produce a maximum moment within a desired low range. Since the specimen cross-section, 10.2 cm by 15.2 cm (4 in. by 6 in.) is rather small, the smallest loading range, 445 N (100 lb.), on the 1330 kN (300 k) Tinius Olsen testing machine was used (Section 2.3).

3.1.2 Member Properties and Geometry

The material constants and geometric properties of the specimen are:

\[ E_c = \text{modulus of elasticity of concrete} \approx 24,150 \text{ MPa} \]
\[ (3500 \text{ ksi}) \]
\[ E_s = \text{modulus of elasticity of steel} \approx 200,100 \text{ MPa} \]
\[ (29,000 \text{ ksi}) \]
\[ n = \text{modular ratio} = \frac{E_s}{E_c} \approx 8.3 \text{ (as obtained in Experiment III)} \]
\[ A_{ps} = \text{area of single prestressing strand} = 0.987 \text{ cm}^2 \]
\[ (0.153 \text{ in.}^2) \]
\[ A_G = \text{gross area of specimen cross section} = 154.8 \text{ cm}^2 \]
\[ (24.0 \text{ in.}^2) \]
\[ A_N = \text{area of net section} = 153.9 \text{ cm}^2 \text{ (23.85 in.}^2) \]
\[ A_T = \text{area of transformed section} = 162.0 \text{ cm}^2 \]
\[ (25.12 \text{ in.}^2) \]

Due to specimen symmetry and the lack of eccentricity of the prestressing strand \((e = o)\), the following geometric properties exist:

\[ y_t = (y_b) = \text{distance from centroid to top (bottom) fiber} \]
\[ = 7.62 \text{ cm} \ (3.0 \text{ in.}) \]

\[ I = \text{moment of inertia of section} \]
\[ = 2997 \text{ cm}^4 \ (720 \text{ in.}^4) \]

(The above properties are the same for gross, net, or transformed section.)

For such a concentrically prestressed specimen, the dimensionless ratio \(\beta\), which is defined elsewhere,\(^2\) is simplified into a ratio of areas, as follows,

\[ \frac{\beta}{A_{ps}} \left[ \frac{1}{A} + \frac{e^2}{I} \right] = \frac{A}{A_{ps}}, \text{ with eccentricity, } e = o \quad (3-1) \]

Therefore,

\[ \beta_G = \frac{A_G}{A_{ps}} = 156.86 \]
\[ \beta_N = \frac{A_N}{A_{ps}} = 155.86 \]
\[ \beta_T = \frac{A_T}{A_{ps}} = 164.15 \]
3.2 Experimental Analyses

3.2.1 Cracking Moment

In the determination of the cracking moment, $M_{cr}$ of the loaded specimen, the thin metal plate at mid-length prevents transmission of tensile stress and thus none is carried by the concrete. The following expression results,

$$M_{cr} = A_{ps} f_{pb} \left[ \frac{1}{A_t} \right] \left[ \frac{I_T}{y_b} \right] = A_{ps} f_{pa} \left[ \frac{1}{A_N} \right] \left[ \frac{I_T}{y_b} \right]$$

(3-2)

where,

$$f_{pb} = \text{steel prestress before transfer}$$

$$f_{pa} = \text{steel prestress after transfer}$$

Using equation (3-2) and substituting the previously given geometric parameters, the following expression relating the cracking moment in terms of the before transfer prestress is obtained.

$$M_{cr} = 2.40 f_{pb} \text{[J], with } f_{pb} \text{ in MPa}$$

(3-3)

$$= 0.146 f_{pb} \text{[k-in.], with } f_{pb} \text{ in ksi}$$

The predicted cracking load, $P_{cr}$ is calculated such that together with the dead weight of the beam, it produces the cracking moment, $M_{cr}$. For normal weight concrete, the unit weight is 23.5 kN/m$^3$ (150 pcf), and the midspan bending moment caused by this gravity load is 424 J (3.75 k-in.). Equating the moment caused by $P_{cr}$ and the weight of the beam to $M_{cr}$,
\[ M_{cr} = 0.457 P_{cr} + 424 \, [J], \text{ with } P_{cr} \text{ in N} \]  
\quad (3-4a)
\[ (= 0.018 P_{cr} + 3.75 \, [k-in.], \text{ with } P_{cr} \text{ in lb.}) \]

In general terms, when the cracking moment, \( M_{cr} \) is expressed in terms of the before transfer prestress, \( f_{pb} \), as in equation (3-3),

\[ P_{cr} = 5.24 f_{pb} - 927 \, [N], \text{ with } f_{pb} \text{ in MPa} \]  
\quad (3-4b)
\[ (= 8.12 f_{pb} - 208 \, [lb.], \text{ with } f_{pb} \text{ in ksi}) \]

### 3.2.2 Ultimate Moment

In order to determine the ultimate moment capacity of the specimen, the following expression for the total steel strain is used:

\[ \varepsilon_{ps} = \varepsilon_p \left( \varepsilon_{cp} + \varepsilon_{cs} \right) \]  
\quad (3-5)

where,

\[ \varepsilon_p = \text{steel strain due to prestress} = \frac{f_{pa}}{E_s} \]  
\quad (3-6)

\[ \varepsilon_{cp} = \text{concrete strain at level of steel due to prestress} = \frac{A_{ps} f_{pa}}{A_N E_c} \]  
\quad (3-7)

\[ \varepsilon_{cs} = \text{concrete strain at level of steel at ultimate} = \varepsilon_u = \frac{d - c}{c_u} \]  
\quad (3-8)

where,

\[ \varepsilon_u = \text{concrete strain at top fiber at ultimate} = 0.003 \]

\[ d = \text{distance from level of steel to extreme compression fiber} \]
$c_u =$ distance to neutral axis from extreme compression
fiber under ultimate moment.

Using an interactive procedure and the obtained concrete compres
sive strength of 29.0 MPa (4200 psi) the ultimate moment, $M_u$ is
computed as 6600 J (58.41 k-in.). The corresponding value of the
ultimate load, $P_u$ is equal to 13.51 kN (3037 lb.). The position of
the neutral axis at ultimate is 6.27 cm (2.47 in.) from the top
fiber of the specimen section.

3.2.3 Concrete Fiber Stress at Cracking

The concrete top fiber compressive stress, $f_c$ at initial
cracking and subsequent crack penetration is computed on an elastic
basis using the following parameters:

\[
f_{pc} = \text{concrete stress due to prestress} = \frac{f_{pb}}{\beta_T} = \frac{f_{pa}}{\beta_N} \quad (3-9)
\]

\[
f_{cs} = \text{concrete stress at level of steel} = (\frac{x - d}{x}) f_c \quad (3-10)
\]

where,

\(x\) = depth of uncracked portion of the section

\(d\) = depth to the level of the steel

\(\Delta f_{cs}\) = change in concrete stress at level of steel

\[
\Delta f_{cs} = f_{pc} - f_{cs} \quad (3-11)
\]

\(\Delta f_s\) = change in steel stress = $n \Delta f_{cs}$

\[
\Delta f_s = \text{change in steel stress} = n \Delta f_{cs} \quad (3-12)
\]

\(f_s\) = total steel stress = $f_{pa} + \Delta f_s$

\[
f_s = \text{total steel stress} = f_{pa} + \Delta f_s \quad (3-13)
\]

\(T\) = steel tensile force = $f_s A_p$s

\[
T = \text{steel tensile force} = f_s A_p \quad (3-14)
\]
\[ C = \text{concrete compressive force} = \frac{1}{2} f_c x b \]  

where,

\[ b = \text{width of section} \]

\[ M = \text{moment on section} = T(d - \frac{x}{3}) = C(d - \frac{x}{3}) \]  

(3-16)

Solving for the top concrete fiber stress, \( f_c \), the following relationship involving the depth of the uncracked portion of the section, \( x \) is obtained for the previously computed values:

\[ f_c = \frac{0.1943 f_{pb} x}{x^2 + 1.6104x - 12.271} \text{[MPa], with } x \text{ in cm} \]  

(3-17)

\[ f_c = \frac{0.0765 f_{pb} x}{x^2 + 0.634x - 1.902} \text{[psi], with } x \text{ in in.} \]

The corresponding moment is,

\[ M = 1.6926 (22.86 - x) f_c x \text{[J], with } f_c \text{ in MPa} \]  

(3-18)

\[ M = \frac{9 - x}{1500} f_c x \text{[k-in.], with } f_c \text{ in psi} \]

This analysis was performed in order to determine how far the crack could penetrate while the concrete still behaved elastically. A crack depth of about 5 cm (2 in.) was obtained. (See Table 4 for a complete tabulation.)
3.3 Analysis of Gage Data

3.3.1 SR-4 Strain Gages

The SR-4 strain gages are direct reading strain measuring devices used to monitor the variation in concrete compressive strain as load is gradually applied to the specimen. The slope of the load versus strain curve can be easily predicted using elastic theory.

The change in the concrete fiber stress, $\Delta f_c$, is equal to:

$$\Delta f_c = \frac{\Delta M}{S} = \frac{\Delta Pa}{2S} = E_c \Delta \epsilon_c$$  \hspace{1cm} (3-19)

where

$\Delta M =$ change in moment

$S =$ section modulus

$\Delta P =$ change in loads applied by the testing machine

$= \text{twice each load applied to the specimen at two load points}$

$a =$ distance from end of specimen to load point.

$E_c =$ modulus of elasticity of concrete

$\Delta \epsilon_c =$ change in concrete compressive strain as read from SR-4 strain gages.

Rearranging terms of equation (3-19) the slope of the load versus strain curve is obtained:

$$SL = \frac{\Delta P}{\Delta \epsilon_c} = \frac{2E_cS}{a} = \frac{2(24,150 \text{ MN/m}^2)(0.0003933 \text{ m}^3)}{0.9144 \text{ m}}$$  \hspace{1cm} (3-20)

$$= 20.77 \text{ MN-m/m} \ (4667 \text{ k-in./in.})$$
For each $\Delta P = 445$ N (100 lb.), the corresponding change in concrete strain, $\Delta \varepsilon_c$, is anticipated to be 0.0000214.

### 3.3.2 Clip Gages

The clip gage readings are indirect measurements of the movement of the tips of the gage. A calibration factor $CF$ was experimentally determined to relate the reading to the travel of the tips. As the load is increased, the gage tips move farther apart. The change in length of the tips of the clip gage, $\Delta \ell$, is computed from,

$$\Delta \ell = \frac{\Delta R}{CF}$$  \hspace{1cm} (3-21)

where $\Delta R = \text{change in clip gage reading for the corresponding load increment}$.

The corresponding change in concrete strain, $\Delta \varepsilon_c$, as recorded by the clip gage is,

$$\Delta \varepsilon_c = \frac{\Delta \ell}{GL}$$  \hspace{1cm} (3-22)

where $GL = \text{gage length (between anchor points)}$.

The slope of the load versus strain curve is obtained by combining equations (3-21) and (3-22):

$$SL = \frac{\Delta P}{\Delta \varepsilon_c} = \frac{\Delta P}{\Delta R} (CF)(GL)$$  \hspace{1cm} (3-23a)

For Experiment III: $CF = 0.027 \text{ units/cm (0.069 units/in.)}$;

$$GL = 5.1 \text{ cm (2 in.)}$$

$$SL = \frac{0.0614 \text{ kN}}{\Delta R} \left( \frac{0.0138 \text{ k}}{\Delta R} \right), \text{ with } \Delta P = 0.445 \text{ kN (0.1 k)}$$  \hspace{1cm} (3-23b)
4. TEST RESULTS AND DISCUSSION

4.1 General

The test results described in this chapter are those of Experiment III (January 1976). Results from Experiments I and II were inconclusive as were described in section 2.1 and as such will not be discussed here.

The major features of Experiment III that differ from the first two experiments are:

(1) During the curing period the concrete specimens were encased in a plastic "housing", keeping as much of the prestressing frame as possible external to the steam environment (see Fig. 3).

(2) The two SR-4 strain gages attached to each specimen were connected in series in order to obtain an "averaging" effect. This method of connection also eliminated the need for switching channels at test time and consequently eliminated the errors arising from imperfect switching contacts. The SR-4 strain gages were mounted on the bottom face of each specimen on opposite sides of the plate (see Fig. 2). These positions of the strain gages were selected, instead of on the sides of the specimen near the bottom face, in order to obtain a better indication of the change in bottom fiber concrete strains during loading.
(3) Prior to testing, three preloading cycles were performed on each specimen in order to assure the formation of the preformed crack at the plate, and to eliminate any non-linear behavior in the concrete. Preloading cycles for specimen No. 1 were to 6.7 kN (1500 lb.) and for specimen No. 2 to 8.9 kN (2000 lb.). The preloading cycles for specimen No. 2 induced a calculated top fiber concrete stress of approximately 20.4 MPa (2950 psi), which is safely within the elastic range (see section 3.2.3 and Table 4 for further details).

4.2 Observations During Fabrication

The monitoring of the curing temperature was accomplished by incorporating two temperature sensing devices, the tips of which were placed within each concrete specimen. The temperature was regulated by means of a steam valve with a steam hose used to feed the steam under the plastic housing (Fig. 1).

Tensioning of the prestressing strands took place at 8:30 a.m., Friday, January 23, 1976. By 10:00 a.m. the concrete was in place. Just before the commencement of the curing period, at 1:30 p.m., readings indicated that specimen No. 1 had suffered a 1.7% loss of prestress, or 22 MPa (3.2 ksi). Similar loss occurred in specimen No. 2 (see Table 6). This five-hour loss prior to the commencement of curing represents the initial relaxation loss in the strands. These values agree very well with expected pure relaxation loss.
values for a similar time period. Figure 7 depicts the variation of steel stress, as obtained from the load cells, versus time.

At 1:30 p.m. the curing period commenced with the temperature inside of the concrete specimens reaching a high of 70\degree C (159\degree F), within approximately an hour (see Table 2 and Fig. 8). The steam valve was closed somewhat, in order to reduce the curing temperature, so that it would stabilize in the vicinity of 54\degree C (130\degree F). Complete stabilization of the temperature was very difficult to achieve, and some fluctuation of temperature remained. At noon of the following day, the steam valve was closed for form-removal. This marked the end of the first portion of the curing period, approximately 24 hours in length. The average losses for the two specimens, based on the stresses obtained at the start of the curing period, were about 4.8\%, or 59 MPa (8.6 ksi) (see Table 6). At 2:00 p.m., just prior to recommencement of curing, load cell readings showed a thermal recovery of 40 MPa (5.8 ksi) for specimens No. 1 and No. 2. The average temperature drop during the two-hour recovery period was 24\degree C (44\degree F). Based on a steel thermal coefficient of 0.0000117 per \degree C (0.0000065 per \degree F) and a steel modulus of 200 100 MPa (29,000 ksi), a stress change of 57 MPa (8.2 ksi) is obtained, which does not correspond too well with the observed values. This discrepancy will be explained later. Nevertheless, if the observed thermal recovery is "real", then the net loss during the first portion of the curing period, including the recovery period, would average to 1.5\%, or 19 MPa (2.7 ksi).
At 8:00 a.m., Monday, just prior to the completion of the second portion of the curing period, load cell readings indicated a loss for the second portion of 81 MPa (11.7 ksi) for specimen No. 1 and 75 MPa (10.8 ksi) for specimen No. 2. After the steam valve had been closed, and just prior to detensioning at 2:15 pm., the load cell indicated a stress recovery of 75 MPa (10.8 ksi) for specimen No. 1 and 73 MPa (10.6 ksi) for specimen No. 2.

The average temperature drop during the recovery period was 30°C (55°F). The correlation between the temperature and stress changes is better than for the first portion, giving a stress change of 71 MPa (10.3 ksi) during the recovery period. One reason for the discrepancy during the first recovery period was believed to be its being only two hours long, thereby not allowing sufficient time for the temperature and stress to stabilize throughout the specimen length. To provide a further check, values were computed for the first two hours of the second recovery period. An observed partial stress recovery of 36 MPa (5.2 ksi) and a calculated thermal stress change of 59 MPa (8.6 ksi) were obtained very nearly the same as those for the first recovery period.

The apparent net loss for the second portion of curing plus the recovery period, approximately 48 hours in length, was 0.5% for specimen No. 1 and 0.1% for specimen No. 2.

The total loss during the entire curing period, approximately 72-1/4 hours in length, as indicated by the load cells, was 98.7 MPa.
(14.3 ksi) for specimen No. 1 and 94.5 MPa (13.7 ksi) for specimen No. 2. Assuming the thermal recovery described in the preceding paragraph is real, the net loss suffered by specimen No. 1 would be 1.9%, or 24 MPa (3.5 ksi). Specimen No. 2 would have experienced a net loss of 1.7%, or 21 MPa (3.1 ksi). These net losses correspond well to the losses due to relaxation during a similar time period. Consequently, according to the load cell readings, there is an almost complete recovery of prestress after the completion of the curing period, save for the loss due to relaxation. In order to provide a check upon the load cell readings, a flexure test was performed on the specimens (as described in section 2.3) to determine the actual prestress within the specimen. The flexure test results are described in the next section, 4.3.

4.3 Flexure Test Results

The flexure test was performed in order to determine the "after transfer" prestress in each specimen by obtaining the cracking load. As described earlier (section 2.3) each specimen was flexurally preloaded beyond the calculated cracking load and then tested through several loading cycles to determine the load at which the preformed transverse crack at the center plate opened.

The occurrence of cracking was indicated by two sets of strain gages attached to each specimen. Two SR-4 strain gages were connected in series to directly measure the change in concrete strain caused by the applied bending moment. The clip gage indirectly measured the
same strain by measuring the change in length between the gage tips, thereby indicating the separation of the two halves of the specimen.

The SR-4 strain gages and the clip gage measured the same strain until the cracking load was reached, after which, however, each type of gage gave different information. The SR-4 strain gages, being near the "free" crack surface, would record no further change in strain. Their readings would tend to stabilize and nearly remain constant, thereby indicating elimination of the pre-compressive strain in the specimen. However, the clip gage was mounted across the crack, and the opening of the crack would be directly measured. Therefore, readings from the clip gage would increase faster after cracking, as can be seen in Figs. 5 and 6.

The SR-4 strain gages give a clear indication of the cracking load by the abrupt change in slope of the load versus strain curve. For specimen No. 1 the apparent cracking load is in the vicinity of 7.1 kN (1600 lb.), while that for specimen No. 2 is only 5.3 kN (1200 lb.). The reason for this discrepancy in the cracking loads for the two specimens is not clear. At first it was thought that the higher preload for specimen No. 2 could be the cause of the smaller cracking load. However, as can be seen in Table 4, a load of 9.8 kN (2200 lb.) induces only a top concrete fiber compressive stress of 22.5 MPa (3260 psi), still less than the tested compressive strength of the cylinders.
The clip gages used were not as sensitive as expected. In addition, the load versus strain curves for the clip gages were relatively smooth, and thus impractical to use in the determination of the cracking load. Consequently, the clip gages were used as a check on the SR-4 strain gages.

To provide a check on the strain readings, the slopes of the load versus strain curves prior to cracking have been determined. The slopes for the SR-4 strain gages are computed directly from the graph. To determine the slopes for the clip gage, equation (3-23b) is used to convert the readings to direct strain measurements, similar to the SR-4 strain gages.

When determining the slopes of the load versus strain curves, it must be realized that the gages are very sensitive to even small changes in load and any scattering of the data will be amplified in the differentiation process. Consequently, a large tolerance of error must be allowed in the slopes thus calculated.

In section 3.3.1 an elastic analysis was used to compute a slope up to the occurrence of cracking of 20.77 MN-m/m (4667 k-in/in). The slopes of the load versus strain readings for the actual test are given in Table 7. Of particular interest are the slopes for the SR-4 strains. As is apparent from Figs. 5 and 6, the SR-4 strain gages indicate a much greater "stiffness" than expected. In addition, the SR-4 strain readings for specimen No. 2 show nearly twice the stiffness of those for specimen No. 1. All three loading cycles show similar results.
The determination of the slopes of the load versus clip gage reading curves presents an even greater problem due to the gradual, smooth change along the curve. The cracking load is not readily apparent. Table 7 shows the method incorporated in determining the slopes given. The three loading cycles show very similar results with the average slopes being 23.0 MN-m/m (5170 k-in/in) and 17.9 MN-m/m (4030 k-in/in) for specimens No. 1 and No. 2, respectively. These values straddle the computed slope of 20.77 MN-m/m (4667 k-in/in).

Although the slopes of the load versus clip gage reading curves provide a good check on the validity of the readings as a method of determining the cracking load; nevertheless, it must be emphasized that they are highly dependent upon the method of analysis employed in evaluating the data obtained from the curves.

4.4 Comparisons

The difficulties in the analysis of the strain gage data in the determination of the cracking load have been described in section 4.3. The approximate nature of the cracking loads so obtained necessitates that they not be used directly to determine the prestress remaining in the specimens. Instead, the calculations are reversed, so that the before transfer prestress values obtained from the load cells (see Table 5) are used to determine the cracking loads, which are then compared with the experimental values.
The load cell readings just prior to detensioning indicated $f_{pb}$ values of 1221 MPa (177.0 ksi) and 1218 MPa (176.5 ksi) for specimens No. 1 and No. 2, respectively. Substituting into equation (3-4b), the corresponding cracking loads, $P_{cr}$, are 5.47 kN (1229 lb.) and 5.45 kN (1225 lb.), respectively. The corresponding values of cracking moment, $M_{cr}$, as obtained from equation (3-3) are 2930 J (25.9 k-in) and 2920 J (25.8 k-in), respectively.

The cracking loads, as obtained from the before transfer prestress, agree fairly well with those so obtained from the flexure test and strain gage readings. Therefore, the before transfer values of prestress are considered as accurate representations of the prestress remaining in the specimens at the completion of the fabrication stage. Consequently, the thermal recovery, as shown by the load cells, must be taken as real, indicating an almost complete prestress recovery, save for the relaxation loss suffered by the strands during the curing period.
5. CONCLUSIONS AND RECOMMENDATIONS

The findings of Experiment III along with observations from the first two experiments lead to the following conclusions:

(1) The prestress within the specimen is comparable to that measured externally.

(2) The apparent thermal recovery of prestress (as shown by the load cells) accompanying the completion of the steam curing period is real.

(3) There is essentially no permanent loss in prestress caused by the short-term elevated temperature up to approximately 66° C (150° F) associated with the steam curing period.

(4) The average net loss in prestress during the curing period is only 1.8%, or 23 MPa (3.3 ksi). This value corresponds well with the relaxation loss for a similar three-day period.

(5) The SR-4 strain gages used to directly measure the change in concrete strain caused by the applied bending moment of the flexure test pinpoint the cracking load well. On the other hand, the clip gage which indirectly measures the same strain by indicating the separation of the two halves of the specimen does not pinpoint the cracking load well.
Observations from the overall experimental program lead to the following recommendations:

(1) A better way of inserting the temperature sensing device into the specimen is needed; possibly a holding device could also be incorporated.

(2) A device similar to a thermostat should be used to regulate the steam intake and therefore the temperature during the curing period.

(3) Water tends to collect on the floor surrounding the prestressing frame. A good drainage system should be available or a collection device used.

(4) The calibration of the clip gage should be performed for a range comparable to that used in the test. In the experiments, the calibration range (and steps) was too large, and the resulting test data were difficult to interpret.

(5) If a smaller loading range on the test machine is possible it should be used to give a better indication of the cracking load.
<table>
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<th>Experiment</th>
<th>I*</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
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<tr>
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<td>Amount (kN)</td>
<td>Amount (lb.)</td>
<td>% by Weight</td>
</tr>
<tr>
<td>Cement</td>
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<td>150.5</td>
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<td>Fine Aggregate</td>
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<tr>
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<td>100.0</td>
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*Only 4 cylinders were made in Experiment I, whereas 8 cylinders were made for each of the other two experiments (II, III).*
### TABLE 2  TIMETABLE OF SPECIMEN NO. 1 FOR EXPERIMENT III

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<th>Time</th>
<th>°C</th>
<th>°F</th>
<th>MPa</th>
<th>(ksi)</th>
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<td></td>
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<td></td>
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<td></td>
<td></td>
<td>9:20</td>
<td>48</td>
<td>(118)</td>
<td>1159</td>
<td>(168.0)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10:00</td>
<td>51</td>
<td>(123)</td>
<td>1183</td>
<td>(171.4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10:45</td>
<td>39</td>
<td>(102)</td>
<td>1199</td>
<td>(173.7)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12:00</td>
<td>31</td>
<td>(89)</td>
<td>1209</td>
<td>(175.2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12:45</td>
<td>27</td>
<td>(81)</td>
<td>1216</td>
<td>(176.2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13:30</td>
<td>26</td>
<td>(78)</td>
<td>1220</td>
<td>(176.8)</td>
</tr>
<tr>
<td></td>
<td>Detensioning</td>
<td>14:00</td>
<td>25</td>
<td>(76)</td>
<td>1221</td>
<td>(177.0)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14:15</td>
<td>18</td>
<td>(64)</td>
<td>--</td>
<td>( -- )</td>
</tr>
</tbody>
</table>

* High temperature readings due to insertion of sensing device too far into opening on specimen side.
### TABLE 3  LOAD CELL CALIBRATION FACTORS (units\(^{\text{kip}}\))

#### Test 1 (December 12, 1975)

<table>
<thead>
<tr>
<th>Load Cell Identification No.</th>
<th>Run No.</th>
<th>#103</th>
<th>#104</th>
<th>#110</th>
<th>#113</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>48.9</td>
<td>57.9</td>
<td>68.7</td>
<td>59.5</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>47.2</td>
<td>58.5</td>
<td>68.5</td>
<td>61.2</td>
<td></td>
</tr>
</tbody>
</table>

#### Test 2 (January 9, 1976)

<table>
<thead>
<tr>
<th>Load Cell Identification No.</th>
<th>Run No.</th>
<th>#103</th>
<th>#104</th>
<th>#110</th>
<th>#113</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>126.7</td>
<td>128.2</td>
<td>126.8</td>
<td>127.6</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>127.2</td>
<td>128.3</td>
<td>126.4</td>
<td>127.7</td>
<td></td>
</tr>
</tbody>
</table>

#### Test 3 (February 2, 1976)

<table>
<thead>
<tr>
<th>Load Cell Identification No.</th>
<th>Run No.</th>
<th>#104</th>
<th>#110</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>130.8</td>
<td>130.7</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>132.0</td>
<td>131.0</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Load Cells Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>#103, 104</td>
</tr>
<tr>
<td>II</td>
<td>#110, 113</td>
</tr>
<tr>
<td>III</td>
<td>#104, 110</td>
</tr>
</tbody>
</table>

Note: 1 unit\(^{\text{kip}}\) = 0.22472 unit/kN
TABLE 4   DEPTHS OF CRACK PENETRATION

<table>
<thead>
<tr>
<th>Depth of Cracking</th>
<th>Moment, M</th>
<th>Top Concrete Fiber Compressive Stress, $f_c$</th>
<th>Load on Specimen, P</th>
</tr>
</thead>
<tbody>
<tr>
<td>cm (in.)</td>
<td>J (k-in.)</td>
<td>MPa (psi)</td>
<td>kN (lb.)</td>
</tr>
<tr>
<td>0 (0)</td>
<td>2910 (25.7)</td>
<td>14.8 (2140)</td>
<td>5.43 (1220)</td>
</tr>
<tr>
<td>2.54 (1)</td>
<td>3880 (34.4)</td>
<td>17.8 (2580)</td>
<td>7.57 (1770)</td>
</tr>
<tr>
<td>5.08 (2)</td>
<td>4910 (43.4)</td>
<td>22.5 (3260)</td>
<td>9.80 (2200)</td>
</tr>
<tr>
<td>7.62 (3)</td>
<td>6120 (54.2)</td>
<td>31.1 (4510)</td>
<td>12.5 (2800)</td>
</tr>
</tbody>
</table>

for $f_{pb} = 1221$ MPa (177 ksi)
TABLE 5  STRESSES AND TIMES FOR ALL EXPERIMENTS

<table>
<thead>
<tr>
<th>Exper. No.</th>
<th>Beam No.</th>
<th>Initial Tension</th>
<th>Stress at Start of Steam Curing</th>
<th>Prestress Before Transfer</th>
<th>Total Times (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MPa (ksi)</td>
<td>MPa (ksi)</td>
<td>MPa (ksi)</td>
<td>Tensioning</td>
</tr>
<tr>
<td>I</td>
<td>1</td>
<td>1291 (187.1)</td>
<td>1261 (182.8)</td>
<td>1154 (167.2)</td>
<td>74-1/2</td>
</tr>
<tr>
<td>I</td>
<td>2</td>
<td>1291 (187.1)</td>
<td>1255 (181.9)</td>
<td>1179 (170.9)</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>1</td>
<td>1044 (151.3)</td>
<td>1016 (147.2)</td>
<td>946 (137.1)</td>
<td>75</td>
</tr>
<tr>
<td>II</td>
<td>2</td>
<td>975 (141.3)</td>
<td>958 (138.8)</td>
<td>907 (131.4)</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>1</td>
<td>1268 (183.7)</td>
<td>1245 (180.5)</td>
<td>1221 (177.0)</td>
<td>77-3/4</td>
</tr>
<tr>
<td>III</td>
<td>2</td>
<td>1263 (183.1)</td>
<td>1239 (179.6)</td>
<td>1218 (176.5)</td>
<td></td>
</tr>
</tbody>
</table>
## TABLE 6  PRESTRESS RECOVERY RESULTS FOR EXPERIMENT III

<table>
<thead>
<tr>
<th>Comments</th>
<th>Time</th>
<th>Day</th>
<th>Specimen No. 1</th>
<th>Specimen No. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>MPa  ksi</td>
<td>MPa  ksi</td>
</tr>
<tr>
<td>Tensioning</td>
<td>8:30 am</td>
<td>Friday</td>
<td>1266 (183.7)</td>
<td>1263 (183.1)</td>
</tr>
<tr>
<td>1st Start of Curing Period</td>
<td>1:30 pm</td>
<td>Friday</td>
<td>1245 (180.5)</td>
<td>1239 (179.6)</td>
</tr>
<tr>
<td>Portion Steam off (Forms off)</td>
<td>Noon</td>
<td>Saturday</td>
<td>1188 (172.1)</td>
<td>1179 (170.8)</td>
</tr>
<tr>
<td>2nd Steam on</td>
<td>2:00 pm</td>
<td>Saturday</td>
<td>1228 (177.9)</td>
<td>1219 (176.7)</td>
</tr>
<tr>
<td>Portion Steam off</td>
<td>8:00 am</td>
<td>Monday</td>
<td>1147 (166.2)</td>
<td>1145 (165.9)</td>
</tr>
<tr>
<td>Detensioning</td>
<td>2:15 pm</td>
<td>Monday</td>
<td>1221 (177.0)</td>
<td>1218 (176.5)</td>
</tr>
</tbody>
</table>

**Prior to Curing Period**

<table>
<thead>
<tr>
<th>Initial Relaxation Loss (5 hours)</th>
<th>Specimen No. 1</th>
<th>Specimen No. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>22 (3.2)</td>
<td>24 (3.5)</td>
</tr>
<tr>
<td></td>
<td>1.7%</td>
<td>1.9%</td>
</tr>
</tbody>
</table>

*All percentages refer to the start of the curing period except for those occurring prior to the curing period.*
TABLE 6 PRESTRESS RECOVERY RESULTS FOR EXPERIMENT III (continued)

<table>
<thead>
<tr>
<th>Specimen No. 1</th>
<th>Specimen No. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MPa</td>
</tr>
<tr>
<td><strong>First Part of Curing Period</strong></td>
<td></td>
</tr>
<tr>
<td>Total Loss</td>
<td>58</td>
</tr>
<tr>
<td>Thermal Recovery</td>
<td>40</td>
</tr>
<tr>
<td>Net Loss</td>
<td>18</td>
</tr>
<tr>
<td><strong>Second Part of Curing Period</strong></td>
<td></td>
</tr>
<tr>
<td>Total Loss</td>
<td>80.7</td>
</tr>
<tr>
<td>Thermal Recovery</td>
<td>74.5</td>
</tr>
<tr>
<td>Net Loss</td>
<td>6.2</td>
</tr>
<tr>
<td><strong>Entire Curing Period</strong></td>
<td></td>
</tr>
<tr>
<td>Total Loss</td>
<td>98.7</td>
</tr>
<tr>
<td>Thermal Recovery</td>
<td>74.5</td>
</tr>
<tr>
<td>Net Loss</td>
<td>24</td>
</tr>
</tbody>
</table>

*All percentages refer to the start of the curing period except for those occurring prior to the curing period.*
## TABLE 7 SLOPES OF LOAD VERSUS STRAIN CURVES UP TO CRACKING FOR EXPERIMENT III

<table>
<thead>
<tr>
<th>Specimen</th>
<th>LC</th>
<th>SR-4 Strain Gages</th>
<th>Clip Gage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Obtained by: MN-m/m</td>
<td>k-in/in</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>$\frac{1.2 - 0.5}{130 - 55} \times 10^6$</td>
<td>41.5 (9330)</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>$\frac{1.1 - 0.5}{127 - 67} \times 10^6$</td>
<td>44.5 (10,000)</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>$\frac{1.1 - 0.5}{130 - 70} \times 10^6$</td>
<td>44.5 (10,000)</td>
</tr>
<tr>
<td>Avg.</td>
<td></td>
<td></td>
<td>43.5 (9780)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specimen</th>
<th></th>
<th>Obtained by: MN-m/m</th>
<th>k-in/in</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>$\frac{0.8 - 0.3}{61 - 28} \times 10^6$</td>
<td>67.4 (15,150)</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>$\frac{0.8 - 0.5}{61 - 45} \times 10^6$</td>
<td>83.4 (18,750)</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>$\frac{0.8 - 0.5}{60 - 43} \times 10^6$</td>
<td>78.5 (17,650)</td>
</tr>
<tr>
<td>Avg.</td>
<td></td>
<td></td>
<td>76.5 (17,180)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specimen</th>
<th></th>
<th>Obtained by: MN-m/m</th>
<th>k-in/in</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>$\frac{1.0 - 0.0}{32 - 0.0} \times 138,000$</td>
<td>19.2 (4310)</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>$\frac{0.9 - 0.5}{33 - 19} \times 138,000$</td>
<td>17.6 (3940)</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>$\frac{1.0 - 0.5}{39 - 21} \times 138,000$</td>
<td>17.1 (3830)</td>
</tr>
<tr>
<td>Avg.</td>
<td></td>
<td></td>
<td>17.9 (4030)</td>
</tr>
</tbody>
</table>
Fig. 1 Fabrication and Curing Set Up
Fig. 2 Gage Set Up on Specimen for Experiment III
Fig. 3  Specimen Insulation and Test Set Up
Cross-Section Of Specimen

Loading Arrangement

Fig. 4 Schematic of Test Set Up
Fig. 5 Load versus Strain for Specimen No. 1, Experiment III (Three Loading Cycles)
Fig. 6 Load versus Strain for Specimen No. 2, Experiment III (Three Loading Cycles)
Steel Stress MPa

January 23-26, 1976

Fig. 7 Steel Stress versus Time (Hours) for Experiment III
Fig. 8 Temperature versus Time (Hours) for Experiment III
8. REFERENCES

1. Hanson, J. A.
PRESTRESS LOSS AS AFFECTED BY TYPE OF CURING,
Journal of the Prestressed Concrete Institute,
Vol. 9, No. 2, April 1964.

2. Huang, T.
PRESTRESS LOSSES IN PRETENSIONED CONCRETE STRUCTURAL
MEMBERS, Fritz Engineering Laboratory Report
No. 339.9, Lehigh University, August 1973.

3. Huang, T. and Tansu, J.
SOME OBSERVATIONS ON THE PRESTRESS LOSS BEHAVIOR OF
BEAMS IN AN EXPERIMENTAL BRIDGE, Fritz Engineering
Laboratory Report No. 382.2, Lehigh University,
April 1974.

4. Pierce, M. A. and Hoffman, B.
AN INVESTIGATION OF LOSS IN PRESTRESS IN A PRESTRESSED
CONCRETE MEMBER DUE TO STEAM CURING, A Pilot Study,
Lehigh University, December 1974.
VITA

Peter George Rimbos was born on October 25, 1953 in Queens, New York, the only son of George and Cecelia Rimbos. In 1966 his family moved to New City, New York, where he attended high school. In September 1971 he enrolled at Lehigh University, Bethlehem, Pennsylvania, where he received his Bachelor's Degree in the Department of Civil Engineering in December 1974.

In January 1975 he was married to Naomi Karen Olster of Mt. Penn, Pennsylvania. At this time he joined the research staff of Fritz Engineering Laboratory, Department of Civil Engineering, at Lehigh University. He was associated with the research project "Prestress Losses in Post-Tensioned Members" in the Structural Concrete Division of the Fritz Engineering Laboratory. In July 1976 he is expecting to receive his Master's Degree in the Department of Civil Engineering. He expects to find work in consulting or industry.