RELAXATION OF STEEL CABLES EMPLOYED IN PRE-STRESSED CONCRETE

by

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B. S., Kansas State College of Agriculture
and Applied Science, 1956

A THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Applied Mechanics

KANSAS STATE COLLEGE
OF AGRICULTURE AND APPLIED SCIENCE

1957

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INTRODUCTION

Preliminary

With the increased use of pre-stressed concrete structures, and with greater refinement in its design, it is necessary to have a knowledge of the effect of different time-dependent variables on the characteristics of the structure. One of the important variables is the reduction of the initial pre-stress load. This reduction is generally considered to be caused by three phenomena: Shrinkage of the concrete, creep of the concrete, and relaxation of the steel pre-stressing cable.

Creep can be defined as the time-dependent (anelastic) deformation due to loading. Relaxation is then a special case of creep wherein the sum of the elastic and anelastic deformations is constant.

Creep under constant load best describes the conditions in the concrete portion of a pre-stressed beam in many situations. However, the loading conditions on the cable itself are not so easily determined; the load and the total length of the wire are both functions of the time of loading. In a testing program of this type there are two obvious choices of loading that are easily employed in the laboratory, i.e., constant load or constant cable length. It has been shown that the latter choice is a more accurate description of the cable conditions.

The approximately constant length of the cable is caused by the combination of several actions. After the concrete beam has been cast and the pre-stressing steel freed from restraint, there is elastic reduction of the pre-stressing load. The elongation of the tension fibers in a pre-stressed beam, caused by lateral loading, is usually very small and therefore the elongation of the pre-stressing material is usually small. Concrete shrinkage, concrete creep due to the pre-stressing load, and concrete creep due to lateral loading are of greater importance. The first two of these actions would generally tend to decrease the length of the pre-stressing steel but the third, would usually tend to lengthen the steel. It can be seen that the actual length of the pre-stressing material will be reduced through the various stages of the life of the concrete beam, but this reduction would further decrease the anelastic deformation in the steel. Therefore the actual anelastic deformation would always be less than that found in relaxation tests. This conclusion is the justification for using the term relaxation in describing the action of the cables, and also for using relaxation tests to correlate the loss of pre-stress load to time-dependent characteristics of the steel.

In April of 1956, the Union Wire Rope Corporation of Kansas City, Missouri provided the Applied Mechanics Department of Kansas State College with 3/8 inch 1 by 7, No. TW100R, strand cable to be used in experimental projects. This cable was used throughout this experiment. The primary purpose of the work was to determine the effect of initial stress on the subsequent relaxation. This thesis presents the results to date, and a general survey of the problem.

Purpose and Scope of Investigations

Present pre-stressed concrete design uses a working stress of approximately 55 to 65 percent of the ultimate strength of the wire, and many of the relaxation tests of the steel have been made in this range of stress. However, little investigation has been made of the upper stress levels, 65 to 100 percent of the short-time ultimate strength.

The purpose of this investigation was to determine the relaxation characteristics in these upper stress levels. The primary objective was to determine quantitatively the relaxation of the steel with no prior loading, i.e., no loading other than that required to obtain the desired initial stress. A secondary objective was to determine qualitatively the effect of different loadings prior to the relaxation tests. By these methods the feasibility of the more efficient use of pre-stressing materials (by using higher initial stresses and subsequently fewer cables) could be determined.

Review of Previous Work

The scientific study of creep phenomena probably dates from the work of Phillips. In 1905, he published the results of tests on the elongations of India rubber, glass, and metal wires when subjected to a constant load. The increase of length was related to the time of loading by an empirical equation of logarithmic form. In 1910 and 1914, Andrade made a more detailed investigation of the creep of metal wires. His work had great importance, since it demonstrated that characteristic features existed which were the same for all the pure metals he studied.

It was not until Chevenard, in 1919, and Dickenson, in 1922, published the results of their investigations that engineers began to give serious thought to creep, which had been considered to be characteristic of only the softer metals and alloys. Dickenson's results showed conclusively that if stress were sustained for a sufficiently long time, fracture could occur at a stress very much lower than required to cause fracture in a short-term tensile stress at the same temperature, especially at elevated temperatures. As a result of these discoveries, and an increased use of metals in structures operating at elevated temperatures, the study of creep phenomenon and the determination of the creep properties of metals and alloys, over a wide range of temperature, have proceeded during the past thirty years with an increasing utilization of scientific effort (Sully (16)).

Literature discussing metallic creep can be found in the publications of the: American Institute of Mining and Metallurgical Engineers, Hazlett (4), American Society of Mechanical Engineers, Dumont (2), Nadai (11) and (12), American Society for Testing Materials, Marin (7), and McVetty (8) and (9). This merely illustrates the volume of work that has been done; many other sources are available.

However, most of the creep study has developed along two separate paths. First, there has been the practical approach, that of determining the characteristics of specific industrial alloys. This type of information comprises by far the greater part of the literature. Secondly, there has been the academic, theoretical approach. Since the pure metals have more easily measured and understood characteristics, the academic approach has been devoted primarily to the study of these metals. The theoretical approach is being used in an attempt to obtain the understanding of the mechanism of creep, and of the influence of metallurgical factors on creep properties. This understanding has lagged behind the practical studies, but the academic study is increasingly adding to the explanation of creep behavior so that many facets of the subject can be explained. However, there still remains the necessity of programs having the purpose of this thesis; to determine quantitative creep knowledge in a relatively unexplored area.

General Knowledge of Metallic Creep

Since relaxation is a specific form of creep, it would seem necessary to first have a knowledge of the latter before the former could be understood. Creep under constant tensile load has been the most studied aspect, and indeed the knowledge gained from such tests can many times be extrapolated to include other forms of creep. It has been shown by Andrade (Sully (16)) and others that, when creep occurs under constant load there are, in general, after the initial loading, three stages.

During the first stage, called primary or transient creep, there is rapid elongation of the material. This initial high-strain rate rapidly decreases to approximately a constant rate. This stage of constant strain rate has been termed secondary or quasi-viscous creep. When constant load conditions are present, there may occur, after sufficient time, a third stage of increasing strain rate which leads to fracture. This phenomena has been termed tertiary creep.

Creep is generally dependent upon three variables: Stress and stress history, temperature of the metal, and the material which is being tested. Even under constant load conditions these three variables have pronounced effect on the relative importance of the three stages of creep. Therefore extrapolation to other load conditions, such as relaxation, is difficult. However, it is known that for temperatures low in comparison with the metal's melting point, temperature has little effect. Also, tertiary creep has been explained (though not fully) as due to the increased stress caused by area reduction.

Therefore a qualitative prediction of relaxation in steel can be made. During the first stage there would be expected a rapid anelastic deformation which would cause a stress decrease. This stress decrease in conjunction with the expected decrease of anelastic strain rate usually found during secondary creep would cause the transient relaxation rate to rapidly decrease and reach a very low, constant value. It is seen that under these conditions, the initiation of the tertiary stage of creep is unlikely. Also, the temperature of this test is low in comparison with the melting point of steel, so temperature variations would not be expected to have any primary effects on the relaxation characteristics.

TESTING PROCEDURE AND DESCRIPTION OF EQUIPMENT

Test of Short-Term Properties

In order to determine the typical short-term characteristics of the cable, the specimens were attached with commercial cable grips to a hydraulic testing machine. Similarly, Templin grips were used to attach single-strand specimens. A Templin automatic stress-strain recorder was used to measure these two quantities in both situations.

Long-Term Relaxation Tests

In order to determine the long-term relaxation characteristics of the cable, twelve steel pipes with approximately the same dimensions as standard 3-inch pipe were used as loading structures. The pipes were 19½ feet long after being squared on each end. The adjusting end of each pipe was fitted with a steel plate having a concentric hole for the cable. On the outside of the first plate is placed a heavier plate drilled and tapped for six hexagonally placed 3/4-inch bolts. Three of the holes are for adjustment bolts which bear against the first plate, see Plate I. The other three holes are used to connect the jacking apparatus, Plate II. A commercial cable grip held the cable and butted against the second of the first two plates.

Another plate was provided which was drilled for three 3/4-inch bolts, and concentrically drilled and tapped for the jack rod. Three bolts attached this plate to the second plate on which the cable grip bears.

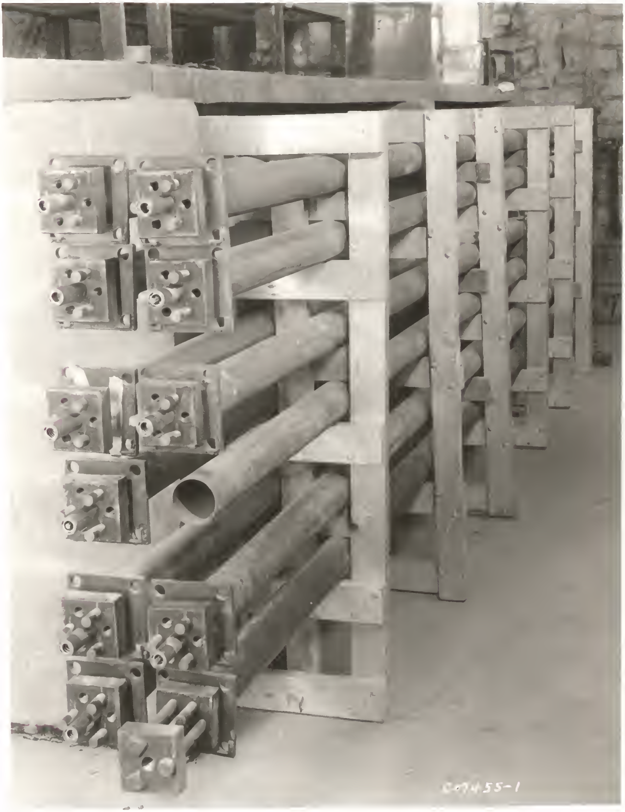
The opposite end of the pipe was fitted with a plate concentrically drilled for the cable. A cable grip butted against this plate. In order that jacking could be done from this end, a cable grip was welded inside a steel collar. The grip and its collar could then be attached to the protruding cable, and with the collar fitted to the jacking rod, loading could be accomplished. The jack was fitted with a bourdon tube pressure gage; the gage readings were correlated with the total load on the jack by direct calibration in a hydraulic testing machine.

The elongation of the cable caused by the desired loads was greater than the adjustment allowed by the adjusting bolts. Because of this elongation it was found necessary to use a step-like procedure in gaining the desired load on the cable. The jack was first attached to the adjusting end of the pipe, and a small initial load placed on the cable. The jack was then attached to the opposite end of the pipe, and a load approximately 350 pounds less than the desired load was placed on the cable. After a cable grip had been positioned against the plate, the jack was released and re-attached to the adjusting end of the pipe. Because some seating movement occurs in the cable grip, and some relaxation occurs during the

EXPLANATION OF PLATE I

Test pipes and fittings used in long-term relaxation experiments.

PLATE I



EXPLANATION OF PLATE II

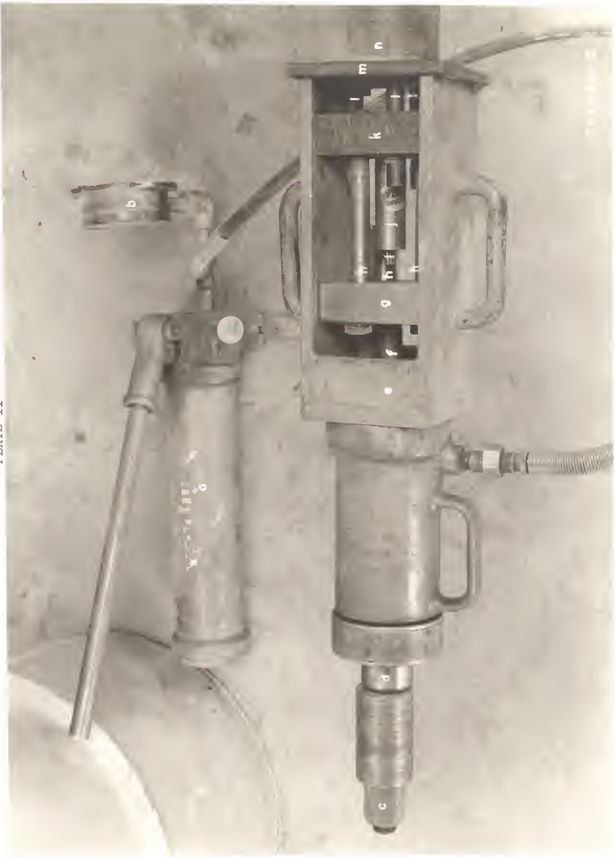
Jacking apparatus used for loading and load measurement in test pipes.

The components of the apparatus are,

a.	Hydraulic pump	h.	Connecting bolts
b.	Pressure gage	i.	Cable
c.	Jack-rod nut	j.	Cable grip
d.	Jack piston	k.	Adjustable head
e.	Jack frame	l.	Adjusting screws
f.	Jack rod	m.	Butt plate
g.	Connecting head	n.	Pipe

Load is measured when the adjusting screws are finger loose.

PLATE II



positioning of the jacking apparatus, the cable load was reduced approximately 3000 pounds. The desired load is then placed on the cable from the adjusting end. The load was determined by reading the jack gage the instant the adjusting bolts are finger loose.

It was originally planned to obtain relaxation curves with two cables at each of the following initial stresses: 65, 75, 80, 85, and 95 percent of the short-term ultimate stress. However, cable failure occurred when loading to the 95 percent level. Therefore the cables were loaded to give initial stress as follows:

Table 1. Initial stress in long-term relaxation tests.

Pipe Number	Initial Stress	Percent of Short-Term Ultimate
4 and 5	241,000 psi	89.3
1 and 2	225,000	83.5
7 and 8	216,000	79.6
9 and 10	204,000	75.5
3 and 6	188,000	69.5
11 and 12	174,000	64.5

Short-Term Relaxation Tests

In order to determine qualitatively the effect of different loadings prior to the relaxation conditions, a series of short-term tests were made in conjunction with similar long-term tests in the pipes. The short-term tests were made in a large mechanical screw-type testing machine equipped with a balance-type load indicator. Because of the massiveness of the screws, heads and columns, it was considered that once the cable was loaded, there could be no further movement of the heads.

After the original long-term relaxation tests had progressed for several months, it was obvious that the results of the pairs of cables were consistent enough that one of each of the pairs could be removed. This meant that there would remain only one cable to determine the continued relaxation, but it was felt that this would be sufficiently accurate.

The pipes thus freed were used in determining the effects of prior loading on subsequent relaxation. Four pipe tests and four machine tests were used to determine these effects. The stress immediately after the pre-loading, at the inception of the relaxation conditions, is termed the initial stress. The amount the pre-loading stress is greater than the desired initial stress is termed the pre-load.

Table 2. Initial stress and pre-stressing conditions of short-term relaxation tests.

Test Device	Initial Stress psi	Pre-load psi	Time of Pre-load
Machine	174,000	8,500	5 minutes
Pipe	174,000	17,000	5 minutes
Machine	174,000	8,500	1 day
Machine	174,000	17,000	1 day
Pipe	204,000	15,500	5 minutes
Machine	204,000	31,000	5 minutes
Pipe	204,000	15,500	1 day
Pipe	204,000	31,000	1 day

Movement of the cable through the cable grip would be of primary importance in a relaxation experiment of this type. Therefore this variable was investigated during two of the short-term relaxation tests in the screw type machine. Small plates were attached to the free ends of the cable, and movement of the plates relative to the testing heads was measured with dial indicators.

DISCUSSION OF ACCURACY

In the relaxation tests made in the pipes, the greatest inaccuracy was due to the limited sensitivity of the pump gage. Pressure reading could be estimated to the nearest 25 psi. This corresponds to a jack load of 160 pounds, or a cable stress of 2000 psi. This latter figure probably represents the accuracy of the relaxation data.

Temperature variations were not considered to be of great importance. The primary effects of varying the actual relaxation characteristics of the cable would be negligible. The secondary effects of the expansion or contraction of the cable in comparison with the pipe would be of importance if the pipe were not steel. However, since both materials would have approximately the same coefficient of thermal expansion, and since the temperature variation at the time of reading was small (approx. $50^{o}F.$), temperature would not be an important variable.

Little creep of the pipes is expected because of the low stresses in the pipe. With a load of 20,000 pounds, and the area being 1.44 square inches, p/a becomes 15,000 psi which is considered to be too small to cause appreciable creep. However, the elastic elongation of the pipe during the reduction of load due to wire relaxation cannot be ignored.

It is believed that the small corrections involved do not affect the trends appreciably; i.e., the same results would be obtained if a constant length structure were available. It is easily calculable that the elastic elongation of the pipe due to anelastic deformation is equal to 5.26 percent of the anelastic stress decrease; i.e., it is necessary to add 0.0526 times cable stress decrease to determine what the actual cable stress decrease would be if the cable were held at constant length.

RESULTS

Short-Term Properties

The following quantities were determined with the loading rate producing ultimate strength in approximately three minutes. A single cycle of loading was used.

The short-term cable properties were:

Ultimate Tensile Strength - Full Cable ----	21,575 lb.,	270,000 psi
Single Strand,	3,200	280,000
Yield Strength - Full Cable, 0.2% off-set,	18,800	235,000

Ultimate Elongation in 15 inches, 5.5%

Metal Area - Full Cable, 0.0799 sq. in.

Modulus of Elasticity - Full Cable, 30.5×10^6 psi

In order to determine the effect of cyclic loading, such as encountered in the step-like loading in the pipes, the following data was obtained. In each case the reversal load indicated is the maximum of the cycle; the minimum load was nearly zero. After the indicated number of reversals, the wire was loaded to failure. Time of each cycle was approximately two minutes.

Table 3. Ultimate strengths following cyclic loading.

No. of Reversals	Reversal Stress	Ultimate Strength
5	226,000 psi	272,000 psi
5	226,000	270,000
5	244,000	267,000
5	244,000	272,000

Comparing the ultimate strengths after this cyclic loading, it would seem that cyclic load has little effect on the short-term ultimate strength, if the maximum cyclic stress is not greater than 244,000 psi and the number of reversals is small.

Cable Failure in Pipes

During the initial loadings of the cables in the pipe tests the cable fractured at a stress of approximately 243,000 psi, a stress equal to 90 percent of the short-term ultimate. Summarizing the results of the step-like loading procedure is this table.

Table 4. Cable failure in pipes.

Cable No.	1	2	3
Stress of initial seating	2,500 psi	2,500 psi	2,500 psi
Secondary loading stress	248,000	248,000	230,000
Stress after secondary loading	215,000	215,000	200,000
Ultimate stress	243,000	243,000	241,000

Note: Stresses other than ultimate are very approximate.

The cause of this "premature" failure is not completely understood; however, it may be explained by the impact loading caused by the pumping of the jack. Although the cause may be unknown, the phenomenon was consistent and caused the lowering of the initial stresses in the long-term relaxation tests as noted before.

Long-Term Relaxation Tests

Results are presented here by relaxation curves, as shown by Figs. 1 through 6.

Short-Term Relaxation Tests

Results are also presented by curves as found in Plates III and IV. It was also verified during tests in the screw-type machine that there was no movement of the cable through the cable grip after loading. Movement during loading was found to be approximately 0.4 inches through each grip.

ANALYSIS OF RESULTS

Empirical Formula

Various investigators have suggested the following forms for creep under constant stress and temperature. Although they are not directly applicable to relaxation phenomena, they are indicative of types of equations that could be considered:

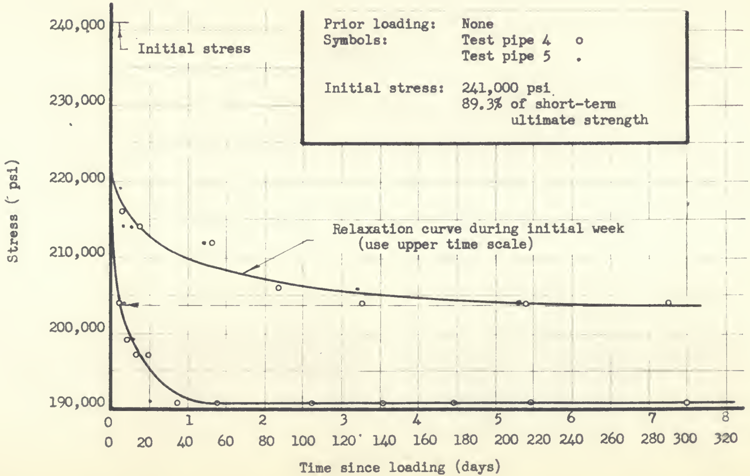


Fig. 1. Relaxation curves for specimen with no prior loading.

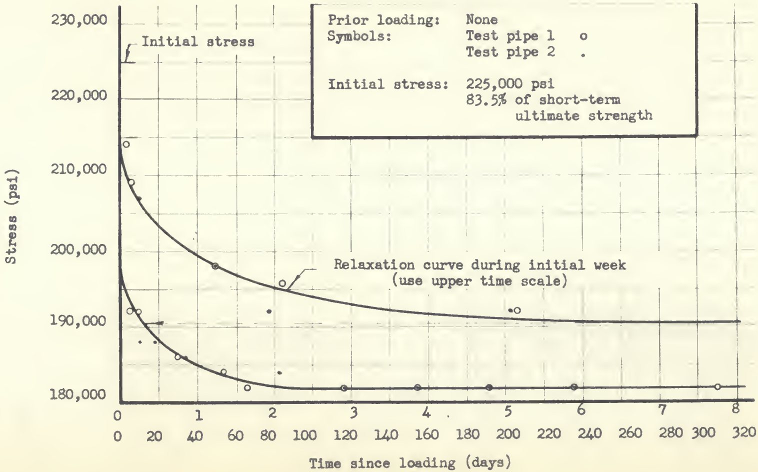


Fig. 2. Relaxation curves for specimen with no prior loading.

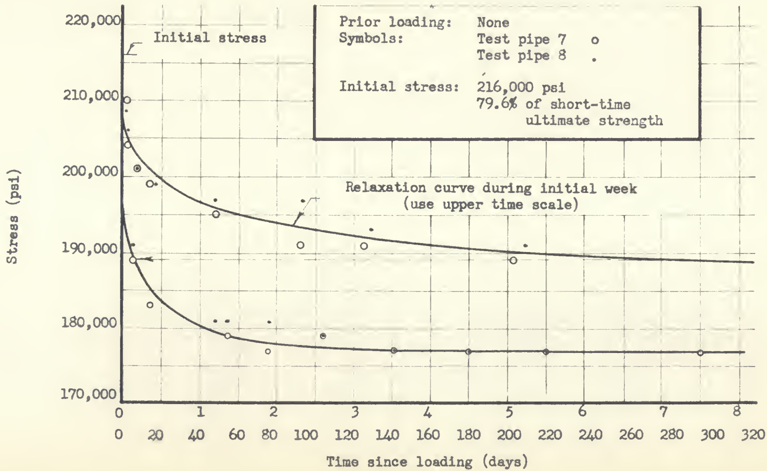


Fig. 3. Relaxation curves for specimens with no prior loading.

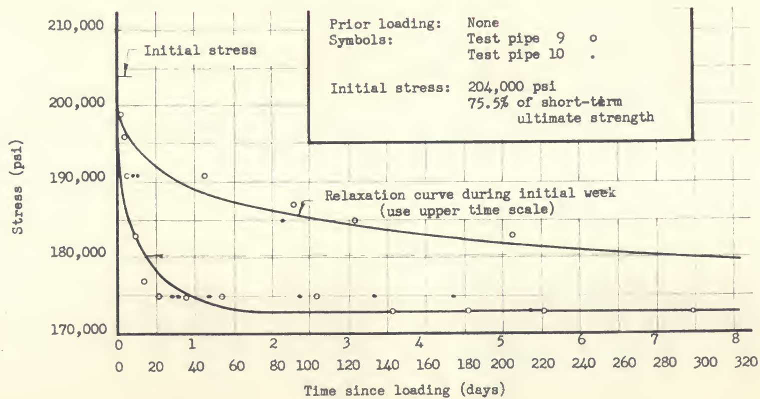


Fig. 4. Relaxation curves for specimens with no prior loading.

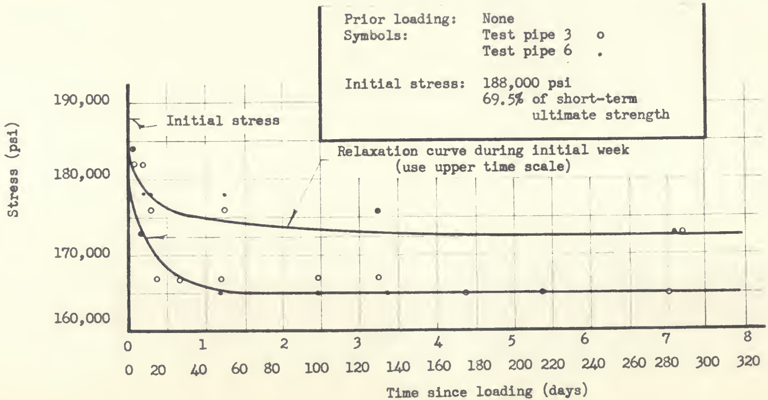


Fig. 5. Relaxation curves for specimens with no prior loading.

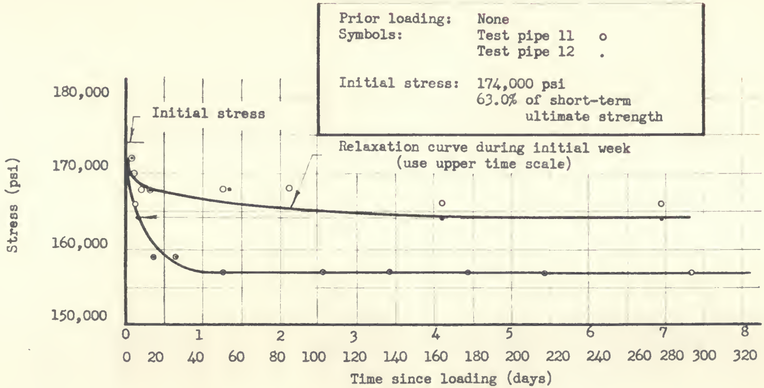


Fig. 6. Relaxation curves for specimens with no prior loading.

EXPLANATION OF PLATE III

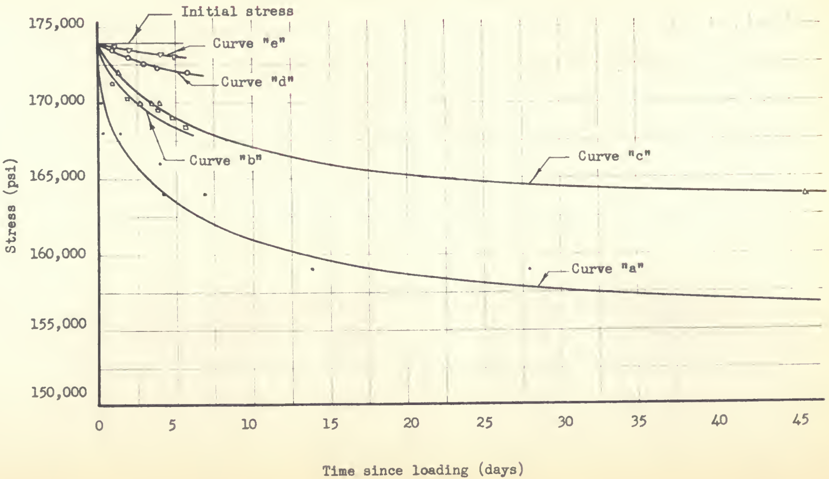
Effect of prior loading on subsequent relaxation

Symbol	Curve	Test device	Pre-load	Time of pre-load
•	a	pipe	0 psi	0
□	b	machine	8,500	5 minutes
△	c	pipe	17,000	5 minutes
○	d	machine	8,500	1 day
▽	e	machine	17,000	1 day

The amount the pre-loading stress is greater than the initial stress, is termed the pre-load.

The initial stress, at the inception of the relaxation conditions, was 174,000 psi, which is 63.0 percent of the short-term ultimate strength.

PLATE III


Initial stress
Curve "e"
Curve "d"
Curve "b"
Curve "c"
Curve "a"
175,000
170,000
165,000
160,000
155,000
150,000
Stress (psi)
0
5
10
15
20
25
30
35
40
45
Time since loading (days)

EXPLANATION OF PLATE IV

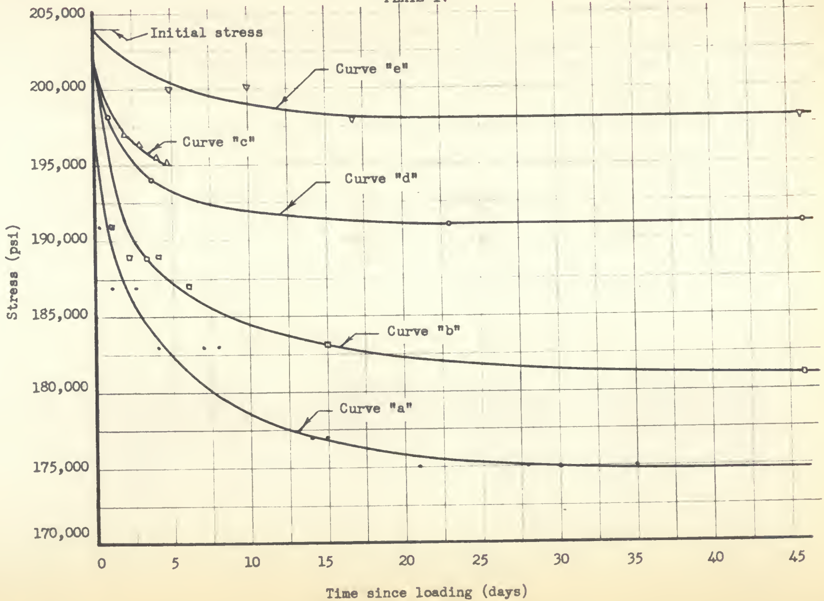
Effect of prior loading on subsequent relaxation

Symbol	Curve	Test device	Pre-load	Time of pre-load
•	a	pipe	0 psi	0
□	b	pipe	15,500	5 minutes
△	c	machine	31,000	5 minutes
○	d	pipe	15,500	1 day
▽	e	pipe	31,000	1 day

The amount the pre-loading stress is greater than the initial stress, is termed the pre-load.

The initial stress, at the inception of the relaxation conditions, was 204,000 psi, which is 75.5 percent of the short-term ultimate strength.

PLATE IV


Initial stress
Curve "e"
Curve "c"
Curve "d"
Curve "b"
Curve "a"
205,000
200,000
195,000
190,000
185,000
180,000
175,000
170,000
Stress (psi)
0
5
10
15
20
25
30
35
40
45
Time since loading (days)

Phillip's Formula (16),

$$L = a + b \log t \tag{1}$$

Andrade's Formula (16),

$$L = L_o \ (L + Bt \ ) \ e^{kt} \tag{2}$$

Duchman's Formula (16),

$$de/dt = ae^{cs} \tag{3}$$

Nadai's Formula (13)

$$S = a(de/dt) \ r \tag{4}$$

Prandtl's Formula (13)

$$de/dt = a \sinh S/b \tag{5}$$

Ross-Lorman Formula (5)

$$E = \frac{mSt}{n + t} \tag{6}$$

An equation of added interest is Prandtl's equation for creep as directly applied to relaxation. The equation: $\tanh (S/c) = \tanh (S_o /c) \ e^{-kt}$. The symbols in the above equations have the following meanings:

L = Length of specimen

L_o = Length immediately after loading

e = The Naperian base

E = Anelastic strain (in./in.

S = Unit stress

S_o = Unit stress at time of loading

t = Time since loading

a, b, c, B, k, m, n, r = Values obtained from tests.

Deduced Equation

However, none of these equations, except the Ross-Lorman formula, can easily be manipulated so that the stress decrease in a relaxation test would be limited, as Figs. 1 through 6 seem to show. Therefore various equations were used, including the Ross-Lorman equation, in an attempt to fit the observed data. After several trials it was found that an equation of the form: $S = S_o \tanh (at^b)$ was satisfactory. The symbols in this equation have the following meanings:

S = Decrease of unit stress (psi)

S_o = Ultimate unit stress decrease (psi)

The following values were found for the constants:

$$a = e^{5.35(S_o - 170,000)10^{-5} - 5.15} + 0.535$$

$$b = e^{4.19(S_o - 170,000)10^{-5} - 6.00} + 0.24$$

Where e is the Naperian base, and S_o is the initial unit stress.

An example of a calculated curve superimposed over the experimentally determined values is shown in Fig. 7.

ANALYSIS OF RELAXATION RESULTS

Effect of Initial Stress on Ultimate Stress

With no prior loading other than that required to obtain the desired initial stress, and in the range of stress investigated, there is an almost linear relationship between the ultimate stress decrease and the initial stress. As seen from Fig. 8, the ultimate stress decrease ranges from 15,000 psi for an initial stress of 170,000 psi to 50,000 psi for an

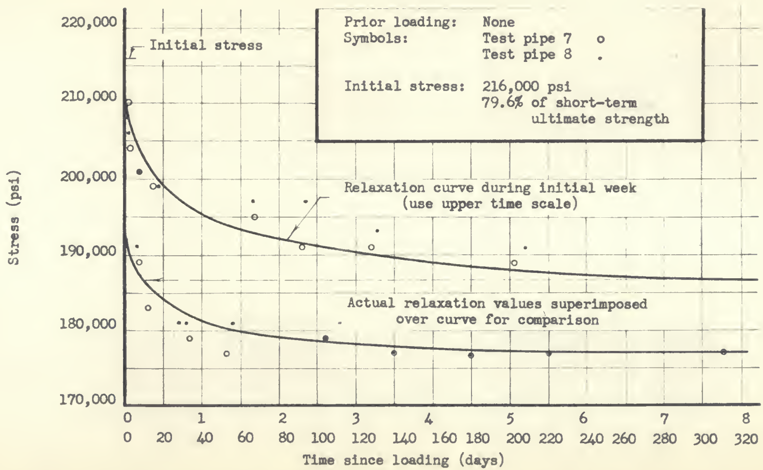


Fig. 7. Calculated relaxation curve for specimens with no prior loading.

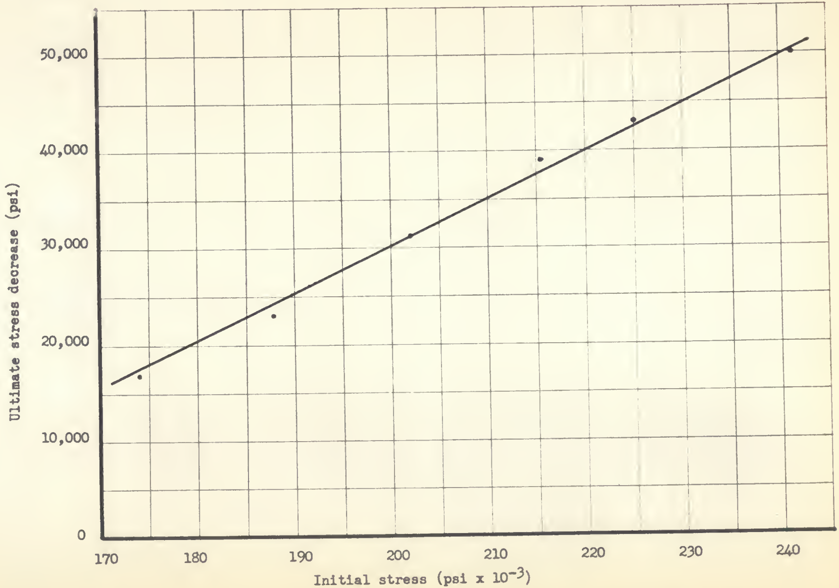


Fig. 8. Ultimate stress decrease for specimens with no prior loading.

initial stress of 240,000 psi. The effect of this is illustrated in Fig. 9 which shows that an increase in the initial stress of 80,000 psi increases the final stress 39,000 psi.

The ultimate stress decrease, as a percentage of the initial stress, is of interest in the actual design of pre-stressed members. Figure 10 shows that this varies from 9.8 percent for an initial stress of 174,000 psi to 20.8 percent for 241,000 psi. The stress decrease occurring after the first day, expressed as a percentage of the initial stress, is also shown in Fig. 10. Because a large portion of the total stress decrease occurred during the first day following loading, these stress decreases are much less than the total stress decrease.

Effect of Initial Stress on Speed of Relaxation

It was found that with no prior loading the specimens with a higher initial stress tended to reach the final stress at a greater rate than those at lower initial stresses. Figure 11 shows that an initial stress of 240,000 psi caused one half of the ultimate stress decrease to occur in the first six hours, while over a day was required for the specimens with an initial stress of 188,000 psi to have a stress decrease equal to one half of the ultimate stress decrease. Similar effects are shown when 95 percent of the ultimate stress decrease is obtained; specimens having an initial stress of 240,000 psi acquire that amount of decrease in 20 days, while specimens having an initial stress of 180,000 psi required 154 days to gain the same figure. Since Fig. 11 was constructed using the empirical equation, the curves are subject to the same inaccuracies as may be inherent in the equation. It is believed that the trends of

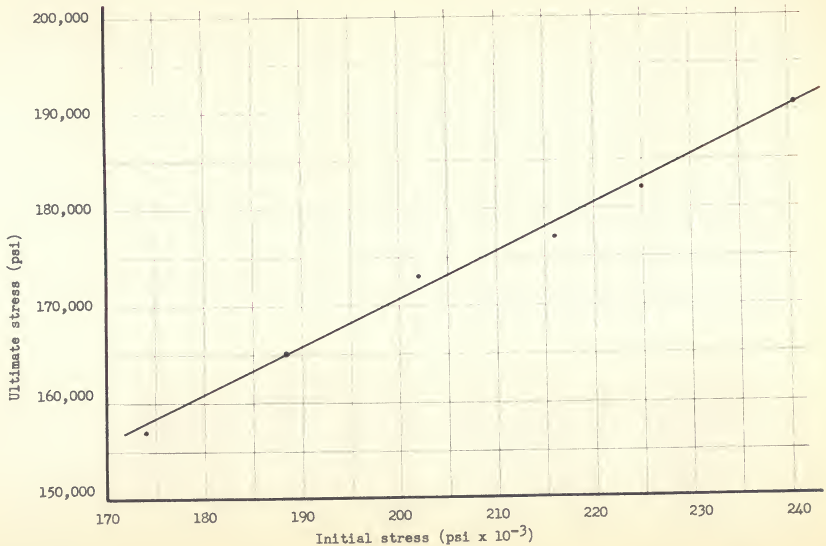


Fig. 9. Ultimate stress vs initial stress for specimens with no prior loading.

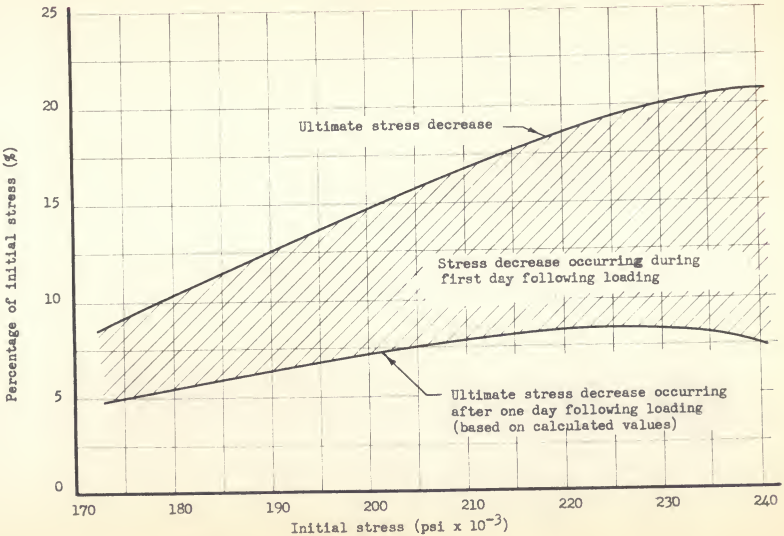


Fig. 10. Ultimate stress decrease expressed as a percentage of initial stress for specimens with no prior loading.

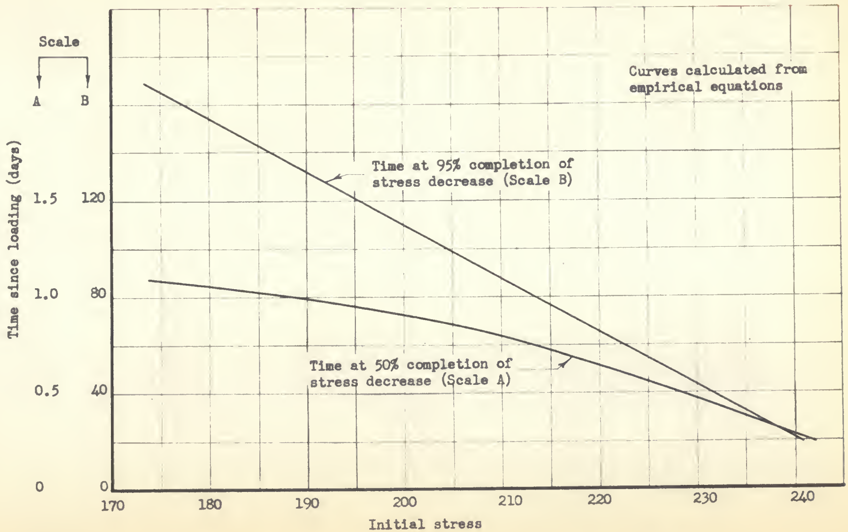


Fig. 11. Speed of relaxation for specimens with no prior loading.

the curves are accurate, even if specific values are not.

The Effect of Prior Loading on Subsequent Relaxation

It can be seen from Plates III and IV that pre-loading the cables to a larger stress than the desired initial stress reduces the subsequent decrease. Curves "a" of the two Plates show the relaxation with no prior loading. The amount that the pre-loading stress is greater than the desired initial stress is termed the pre-load. Curves "b" show the effect of pre-loading for five minutes to one half the ultimate stress decrease that would occur with no prior loading. Curves "d" show the effect of pre-loading for one day to a stress equal to one half of the ultimate stress decrease with no prior loading. Similarly, Curves "c" and "e" show the effect of pre-loading for five minutes, and one day to a stress equal to the ultimate stress decrease that would occur with no prior loading.

Although it is obvious that there is benefit from pre-stressing the cable, actual values of ultimate stress decrease are not now available. It would seem, though, that the amount of relaxation can be greatly reduced by pre-stressing, especially if a pre-loading time of one day is available.

CLOSURE

In the actual field use of steel cable, the constant length conditions assumed throughout this experiment are not rigidly satisfied. Rather, the actions mentioned previously (elastic reduction immediately after pouring of the concrete, concrete creep, concrete shrinkage, etc.)

would tend to reduce the cable length. This reduction would of course result in an elastic reduction of the cable stress, but this elastic reduction would reduce any further anelastic deformation. Therefore, the results of this research give an indication of the anelastic deformation which is larger than would be expected in a field test. It is believed that pre-loading of the cable, plus a more accurate simulation of actual field conditions, would result in less anelastic deformation of the cable. Perhaps this would be a satisfactory subject for further investigation.

CONCLUSIONS

Based on this research work, the following conclusions may be drawn, for the range of stress investigated, regarding the relaxation of prestressing cables. Because the lengths of the test periods were limited, the conclusions regarding ultimate stress decrease are tentative.

1. The stress in the cables decreased rapidly at first, and then more slowly, approaching a limit asymptotically.

2. With no loading other than that required to obtain the desired initial stress, the ultimate stress decrease ranged from 50,000 psi for an initial stress of 240,000 psi to 17,000 psi for an initial stress of 174,000 psi.

3. There was an almost linear relationship between ultimate stress decrease and initial stress.

4. The rate of stress decrease was more rapid for the specimens having higher initial stress.

5. One half of the ultimate stress decrease was obtained in 30 hours or less.

6. Loading to a stress greater than the desired initial stress, and then lowering the stress to the desired level reduced subsequent relaxation.

7. With no loading other than that required to obtain the desired initial stress, the ultimate relaxation of the cable, computed as a percentage of the initial stress, ranged from 9.8 percent for an initial stress of 174,000 psi to 20.8 percent for an initial stress of 241,000 psi. These values are higher than would be expected for an initial stress of 140,000 psi, which is a typical value of current design stress. However, the results of this preliminary study also show that this cable relaxation could be substantially reduced by more strict adherence to actual field conditions, and by pre-loading the cables above the desired initial stress; this study indicates that these actions could reduce relaxation to an acceptable value.

8. The design values of initial stress (that are currently typical) are approximately 100,000 psi less than the short-term ultimate strength. Therefore, this study suggests that more efficient use of the pre-stressing materials can be achieved by using higher initial stresses, and subsequently fewer cables. There must exist an awareness, however, that these higher stresses will tend to produce greater relaxations that must be controlled if the desired pre-stress will remain in the concrete. Further study of the control of these relaxations is necessary before design criteria can be established.

ACKNOWLEDGMENTS

The author wishes to express his gratitude to Dr. M. E. Raville, Head of the Department of Applied Mechanics, for his help and advice in preparing this thesis; to Professor C. H. Scholer for his advice and encouragement during this study, and to Mr. E. R. Chubbuck for his help and guidance in performing the tests.

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RELAXATION OF STEEL CABLES EMPLOYED
IN PRE-STRESSED CONCRETE

by

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B. S., Kansas State College of Agriculture
and Applied Science, 1956

AN ABSTRACT OF A THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Applied Mechanics

KANSAS STATE COLLEGE
OF AGRICULTURE AND APPLIED SCIENCE

1957

The primary purpose of this investigation was to determine the relaxation characteristics of steel cable employed in pre-stressing concrete. The range of initial stresses to be investigated was 65 to 90 percent of the short-term ultimate stress. A secondary objective was to determine qualitatively the effect of different loading prior to the relaxation tests. The term relaxation is defined as the anelastic deformation in a structure when the sum of the anelastic and elastic deformations remains constant. Numerous short-term tests and sixteen long-term tests were performed. Six pairs of the long-term tests were performed to evaluate the relaxation characteristics of cables having no prior loading.

The results of these twelve tests were correlated by an equation of the form: $S = S_m \tanh (at^b)$ where S = stress decrease (psi), S_m = ultimate stress decrease psi, t = time, a and b are two constants to be determined.

It was found that, with no prior loading, the following conclusions may be drawn: Ultimate stress decrease ranged from 50,000 psi for an initial stress of 241,000 psi to 17,000 psi for an initial stress of 174,000 psi; there was an almost linear relationship between ultimate stress decrease and initial stress; the rate of stress decrease was more rapid for the specimens having higher initial stresses; one half of the ultimate stress decrease was obtained in thirty hours or less. It was also found by loading to a stress greater than the desired initial stress and then lowering the stress to the desired level, reduced subsequent relaxation.

With no loading other than that required to obtain the desired initial stress, the ultimate relaxation of the cable, computed as a percentage of the initial stress, ranged from 9.8 percent for an initial stress of 174,000 psi to 20.8 percent for an initial stress of 241,000 psi. These values are higher than would be expected for an initial stress of 140,000 psi, which is a typical value of current design stress. However, the results of this preliminary study also show that this cable relaxation could be substantially reduced by more strict adherence to actual field conditions, and by pre-loading the cables above the desired initial stress; this study indicates that these actions could reduce relaxation to an acceptable value.

The design values of initial stress (that are currently typical) are approximately 100,000 psi less than the short-term ultimate strength. Therefore, this study suggests that more efficient use of the pre-stressing materials can be achieved by using higher initial stresses, and subsequently fewer cables. There must exist an awareness, however, that these higher stresses will tend to produce greater relaxations that must be controlled if the desired pre-stress will remain in the concrete. Further study of the control of these relaxations is necessary before design criteria can be established.