UNDERSTANDING THE LOSSES IN PRESTRESSING

This paper discusses losses that occur in prestressed concrete and attempts to place them in proper perspective to each other. Loss of prestress due to relaxation of steel, shrinkage, elastic deformation and creep in the concrete, anchorage slip and tendon friction are discussed; methods of evaluating these losses are presented. Temporary overstressing and higher initial stress values are reviewed as means of reducing losses and effecting higher net remaining stresses.

Walter Podolny, Jr.
United States Steel Corporation
Pittsburgh, Pennsylvania

The analysis and understanding of prestress losses is important to both designers and fabricators of prestressed structures. The designer's prime concern is the final prestress force after all losses are accounted for, so that he may predict the behavior of the member or structure under the service loads that will be applied. The fabricator's principal concern is with the initial prestress force to be applied to meet the objectives or use the member or structure will be expected to perform. It is therefore apparent that the calculated loss of initial prestressing force is a very important consideration in the design and fabrication of prestressed concrete.

Because of technological changes that are taking place in both the steel and cement industries, it behooves both the designer and the fabricator to understand the various conditions that effect the loss of prestress and what impact technological change will have upon them.

SOURCES OF PRESTRESS LOSSES

Loss of prestress accrues from a number of sources and conditions that are in some respects dependent upon the materials and in other respects dependent upon fabrication practices and methods.

The initial prestressing force is that force imparted to the steel tendon by the jacking force. From the moment that the force is imparted to the tendon by the jacking mechanism, stress in the tendon diminishes with time and eventually reaches a near-stable condition considered to be permanent which becomes the final or effective prestress force.

The loss of prestress is due to the following causes:

1. Relaxation of prestressing steel
2. Curing of the concrete
3. Shrinkage of the concrete

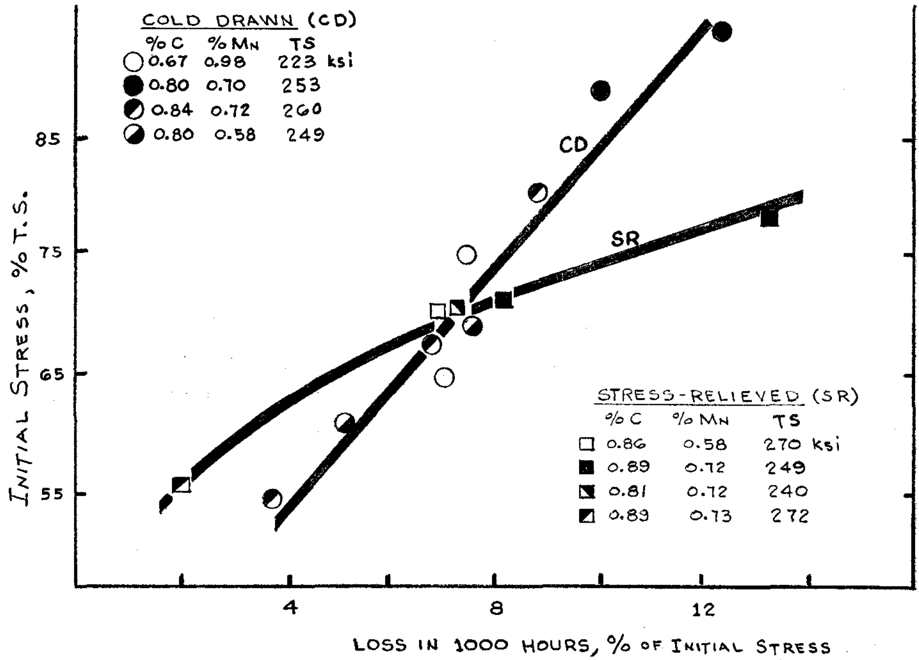

Fig. 1. Relaxation of several types of high-strength, 0.196-in. diameter wire

4. Elastic deformation of the member
5. Creep of the concrete
6. Anchorage slip
7. Tendon friction

All of the above factors may or may not be present. The factors present depend on whether the member is to be pretensioned or post-tensioned.

CURING LOSSES

In the production of precast prestressed concrete members, economics dictate a daily production cycle with members being taken from the forms 16 to 18 hours after placement of the concrete. Curing at relatively high temperatures is a practical and economical method of obtaining high-strength concrete at an early age and therefore a greater re-use of forms. Heat for curing purposes is generally provided by a steam, hot water or hot oil system.

Steam curing of precast units at atmospheric pressure has long been used for accelerating early strength. Oil or water heated to approximately 150 deg. F (66 deg. C) and forced through piping surrounding the concrete forms may also be used to supply heat for curing.

During this curing period a loss takes place in the prestressing force due to the steel tendon being at an elevated temperature; however, on subsequent cooling, a large percentage of this loss is recoverable.

RELAXATION OF PRESTRESSING STEEL

Creep is defined as the continuing elongation of the steel under constant load; that is, for a constant load the steel will increase its length as time progresses. Because of the conditions prevailing in prestressed concrete, a more valid approach is the measurement of stress relaxation[1], defined as the stress (or load) loss in the steel when the strain (elongation) does not vary[2].

For a given steel, it has been determined that the amount or rate of relaxation is a function of initial stress, temperature and duration of load application. Relaxation is normally expressed in percentage loss of initial stress in 1000 hours at a specified temperature.

Relaxation losses of high-strength, stress-relieved wire at room temperature (20-22 deg. C) may be approximated from Figs. 1 and 2 as follows[1,3,4]:

% of tensile strength	70	65	60	55	50
% relaxation loss/1000 hr.	7	5	3	2	1

Elevated temperatures have the effect of increasing the rate of stress relaxation of steel. Relaxation losses are shown in Fig. 3 for Grade ST 150/170, 0.2 percent proof stress nominal yield point 150 kg/mm² (213,000 psi) and nominal tensile strength 170 kg/mm² (242,000 psi), steel wire of 6.7 mm (0.264 in.) diameter, drawn and tempered (stress-relieved), for initial stresses of 43 to 96 percent of the tensile strength and at temperatures ranging from 22 to 100 deg. C (72 to 212 deg. F) plotted against load duration. Values above 1000 hours were obtained by extrapolation[5].

If the data shown in Fig. 3 are plotted as a three-dimensional diagram, Fig. 4, the influence of temperature and initial stress level on relaxation may be more clearly visualized.

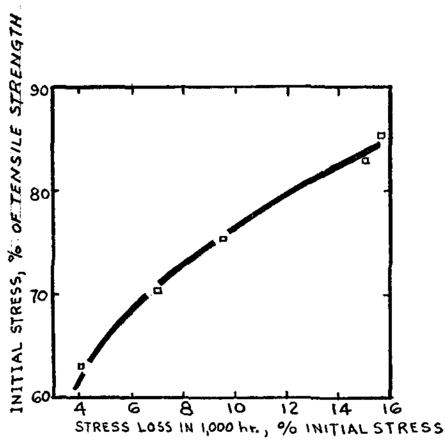

Fig. 2. Relaxation of 0.25-in. diameter, stress-relieved wire

SHRINKAGE OF CONCRETE

Shrinkage of concrete occurs when the moisture content within the mass is reduced. It is affected by the size of the member, the mix composition and the atmospheric conditions of exposure. In general, shrinkage is proportional to water content of the mix. Curing delays shrinkage to an age when the concrete has sufficient strength that it is less susceptible to shrinkage cracking.

British Code of Practice, CP 115[6,7], recommends that for pretensioned members unit shrinkage strain may be taken as 0.0003 in./in. For post-tensioned members in which the prestress transfer occurs two to three weeks after concreting, unit shrinkage strain may be taken as 0.0002 in./in. Shrinkage losses are:

$$\Delta f_s = 0.0003\, E_s \text{ for pretensioned concrete}$$
$$\Delta f_s = 0.0002\, E_s \text{ for post-tensioned concrete} \qquad (1)$$

ACI-ASCE Joint Committee 323[8] stated that the unit shrinkage strain may vary from 0 to 0.0005 in./in. but

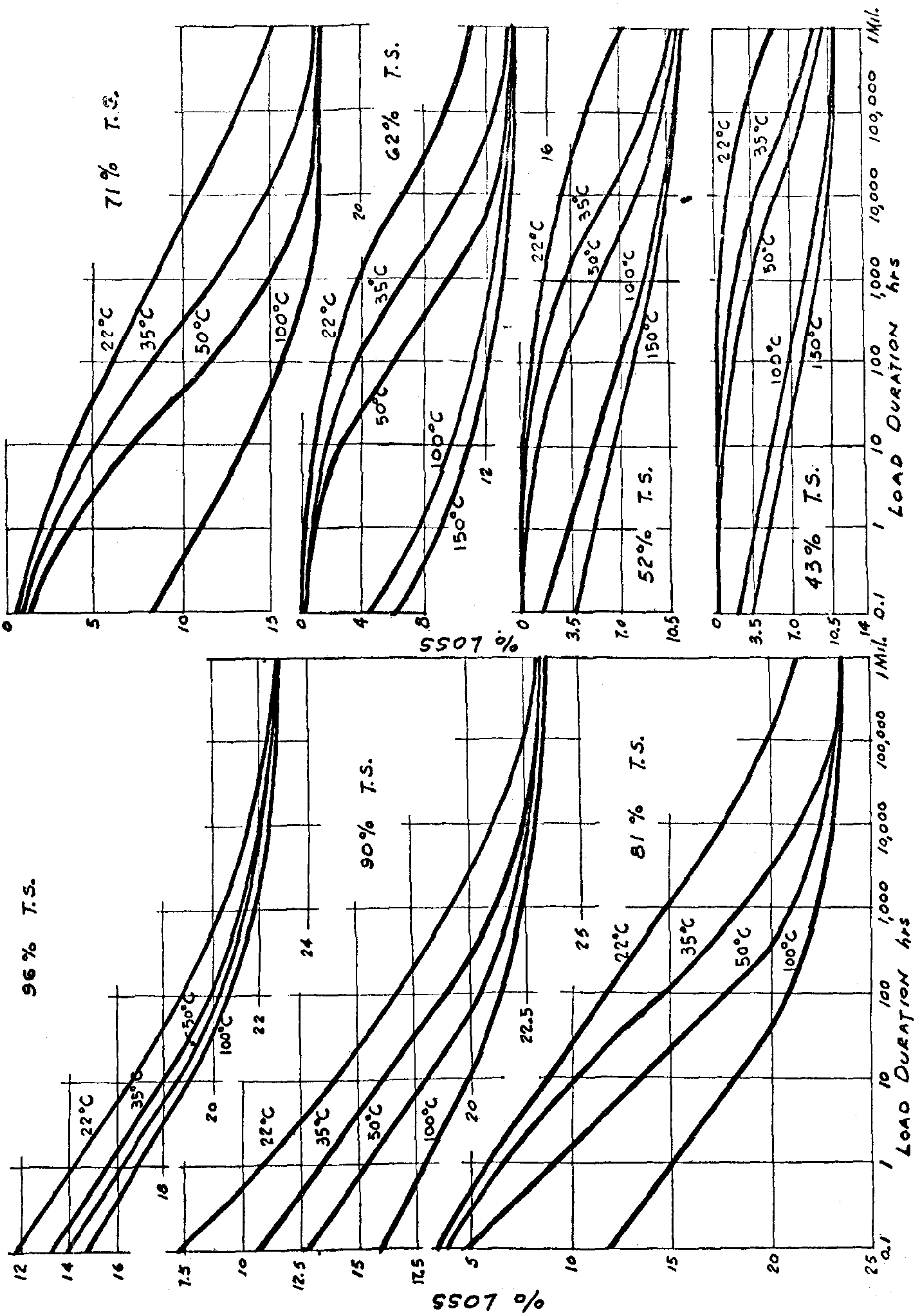

Fig. 3. Relaxation diagrams at varying initial stress and temperature

that a value between 0.0002 and 0.0003 in./in. is commonly used for the calculation of loss.

CREEP OF CONCRETE

Creep varies with time and load, i.e., duration of load, and is detectable at all magnitudes of stress. A number of factors have an effect on creep. For example, members with a small cross-section and weak concrete mixes having high water/cement ratios creep more than rich mixes. The environment surrounding the structure with respect to dampness or humidity is important. Very damp conditions will produce less creep than dry air. The German Code of Practice makes an allowance for this by introducing the following "exposure" coefficients[7,9]:

	Creep coefficient, C_c
Under water	1.5 - 2.0
In very moist air	2.5 - 3.0
In ordinary atmosphere	3.0 - 4.0
In dry air	4.0 - 5.0

Prestress loss due to concrete creep is equal to [7]:

$$\Delta f_s = (C_c - 1)\, f_c\, E_s/E_c$$
$$\Delta f_s = (C_c - 1)\, n\, f_c \qquad (2)$$

where C_c is a creep coefficient usually taken in this country as 2.5 for good concrete of dense aggregate. Here, f_c is taken as the concrete stress at the centroid of the prestressing steel.

The age of the concrete at transfer of prestressing force affects the prestress loss due to creep. Since pretensioned elements are stressed at an early age with a lower E_c than post-tensioned members, they will have larger losses.

British Code of Practice CP 115 recommends that creep, measured in inches per lineal foot, be taken as[6]:

$$4 \times 10^{-6} \times \frac{6000}{\sigma_{cu}} \text{ for pretensioned members}$$

$$3 \times 10^{-6} \times \frac{6000}{\sigma_{cu}} \text{ for post-tensioned members} \qquad (3)$$

where σ_{cu} is the cube strength of the concrete at transfer in psi.

From the above it can be seen that the determination of the effects of creep differs in various countries and is dependent upon concrete modulus which in itself may be difficult to determine other than empirically.

In using CP 115 recommendations it must be remembered that cube strength and cylinder strength are not the same. A ratio of cylinder

Table 1. Strength of cubes and cylinders

Compressive strength psi		Ratio of strengths cylinder/cube	Difference of strengths psi
Cube	Cylinder		
4000	3160	0.790	840
4200	3330	0.794	870
4300	3420	0.796	880
5200	4220	0.812	980
5300	4310	0.814	990
6100	5040	0.826	1060
6400	5310	0.830	1090
7000	5870	0.838	1130
7600	6430	0.846	1170

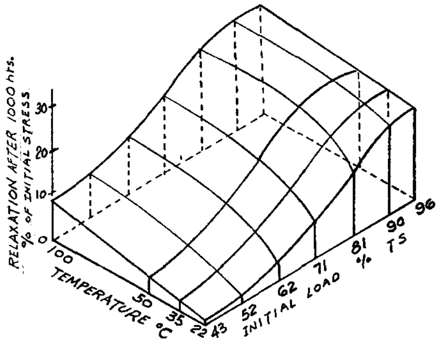

Fig. 4. Three-dimensional relaxation diagram

strength to cube strength may be taken as follows*:

$$\text{Cylinder/cube} = 0.76 + 0.2 \log_{10} \frac{\sigma_{cu}}{2840} \qquad (4)$$

A tabulation of cube and cylinder strength is given in Table 1.

ELASTIC DEFORMATION

Loss of prestress force due to elastic shortening of the member at transfer of prestress force is a function of the stress in the concrete and its modulus of elasticity.

Using the transformed section method, the loss of prestress may be determined by the following[7]:

$$\Delta f_s = \frac{n\,F_t}{A_t} \qquad (5)$$

where n = modular ratio at time of transfer

F_t = transferred prestressing force

A_t = transformed area, $A_c + n\,A_s$

A_s = steel area

A_c = actual concrete area (gross area can be used with little error)

In post-tensioned work, where tendons are not stressed simultaneously, the losses due to elastic deformation may be taken as one-half that calculated by Equation 5, due to the progressive loss of prestressing force in the tendons which are stressed in the initial stages of the tensioning operation.

Loss of prestress due to elastic shortening may aso be calculated by the following expression[10]:

$$\Delta f_s = n \times f_b\,(\Sigma_1)\frac{f_{ce}}{f_b} \qquad (6)$$

where $f_b\,(\Sigma_1)\frac{f_{ce}}{f_b}$ is the concrete stress at the centroid of the prestressing steel for pretensioned members, and in post-tensioned members it is the average concrete stress along one prestressing tendon from end to end of the beam caused by subsequent post-tensioning of adjacent elements. Based on the assumption that, in post-tensioning, the tendons are stressed individually and in turn, and that all tendons are extended by the same amount with respect to the end of the member being stressed, this loss is equal to the average of the loss in the first and last tendons stressed and the above equation then becomes[10]:

$$\Delta f_s = \tfrac{1}{2}\,n\,f_b\,(\Sigma_1)\frac{f_{ce}}{f_b} \qquad (7)$$

The term $\frac{f_{ce}}{f_b}$ may be taken as 0.8 and $f_b(\Sigma_1)$ as $0.60f'_{ci}$ for both pretensioning and post-tensioning.

ANCHORAGE SLIP

Friction wedges will slip a small

This relationship suggested by R. L'Hermit, "Idées Actuelles sur la Technolgie du Béton," Documentation Technique du Bâtiment et des Travaux Publics, Paris, 1955.

amount before the tendon can be gripped. The amount of slippage is a function of load in the tendon and type of anchorage. An average value is about 0.1 in. Since the amount of slippage is a definite amount, the percentage loss of prestressing force is a function of length and will be higher for short lengths than for long lengths. In direct bearing anchorages the heads or nuts may deform approximately 0.03 in. Where shims are used, the deformation may be of the order of 0.001 in. per inch of thickness[7].

Loss of prestress may be calculated as follows:

$$\Delta f_s = \frac{\Delta_a E_s}{L} \tag{8}$$

where Δ_a is the total anchorage deformation.

TENDON FRICTION

Friction losses occur in post-tensioning systems due to curvature of the tendon, wobble, friction in the jack and friction at the anchorages. Friction between the prestressing steel and duct is a function of the angle, α, through which the tendon is turned, and the coefficient of friction, μ, between the duct and the tendon.

Because of physical construction problems, it is impossible to maintain a straight alignment of the duct and a number of undulations or "wobbles" occur along the length of the duct. The "wobbles" produce additional friction which is expressed as a coefficient, K. The value of K is a function of the type of tendon and type of duct or sheath. Suggested values of K and μ are tabulated in Table 2[11].

The ACI Building Code[11], Sect. 2607 (b), states that friction losses shall be calculated by the following equation:

$$T_o = T_x e^{(KL + \mu\alpha)} \tag{9}$$

when $(KL + \mu\alpha)$ is not greater than 0.3, the following equation may be used:

$$T_o = T_x (1 + KL + \mu\alpha) \tag{10}$$

where T_o is the force in the steel at the jacking end, T_x is the steel force at any point x, L is the length of

Table 2. Friction coefficients for post-tensioning tendons

Type of tendon	Wobble coefficient K	Curvature coefficient μ
Grouted tendons in metal sheathing		
Wire tendons	0.0010 - 0.0015	0.15 - 0.25
7-wire strand	0.0005 - 0.0020	0.15 - 0.25
High-strength bars	0.0001 - 0.0006	0.08 - 0.30
Unbonded tendons (pre-greased) Wire tendons and 7-wire strand	0.0003 - 0.0020	0.05 - 0.15
Unbonded tendons (mastic-coated) Wire tendons and 7-wire strand	0.0010 - 0.0020	0.05 - 0.15

prestressing steel from jacking end to any point x, and e is equal to the base of Naperian logarithms.

The loss of prestress for the entire length of a tendon may be considered from section to section. The reduced stress at the end of a segment may be used to compute the frictional loss for the next segment, etc.[7]. Cooley has shown[12] that the tension, T_x, in the tendon at a distance x from the jack can be determined by the following expression:

$$T_x = T_o\left[1 - \left(KL_t + \frac{\mu\, L}{R}\right)\right] \quad (11)$$

where R and L_t are the radius of curvature and length of the section of tendon being considered.

When applying the above equations, the designer must bear in mind whether the jacking is being done from one end or both ends. If the jacking is done from both ends, in the case of symmetrical tendons, the friction loss will be equal from each jack to the center. When jacked from one end the friction loss may be twice, or more, than that by jacking from both ends.

LOSSES FOR A TYPICAL PRETENSIONED MEMBER

Assume that a ½ in. diameter, 270 K, stress-relieved strand is to be initially stressed to 70 percent of its specified minimum tensile strength in a 250-ft. long pretensioning bed. Area of steel is 0.1535 sq. in., minimum tensile strength is 269,100 psi and E_s is 28.2 x 10^6 psi.

Initial stress = 0.70 x 269,100
= 188,370 psi

Assume a slippage of the anchorage in the transfer of force from the jacks to the pretensioning bed abutments of 0.1 in., then the loss due to anchorage slip is:

$$\Delta f_s = \frac{\Delta_a E_s}{L}$$

$$= \frac{0.1 \times 28.2 \times 10^6}{250 \times 12} = 940 \text{ psi}$$

percentage loss of initial stress = 0.5%

net remaining stress = 187,430 psi

percentage of initial stress remaining = 99.5%

percentage of ultimate tensile stress = 69.4%

If it is assumed that during the next 24 hours in the curing life of the member an average temperature of 35 deg. C will be reached in the prestressing steel due to curing operations, then a thermal loss of 5 percent can be approximated. However, upon subsequent cooling, perhaps as much as 95 percent of this loss is recoverable, leaving a loss of 0.25 percent.

net remaining stress = 186,961 psi

percentage initial stress remaining = 99.25%

percentage ultimate tensile stress = 69.3%

Section 2605(a) of the ACI Building Code allows a temporary compression stress in the concrete at time of transfer of 0.60 f'_{ci}, where f'_{ci} is the concrete strength at time of transfer.

Section 1102(a) of the ACI Building Code gives E_c for concrete as $w^{1.5}\,33\sqrt{f'_c}$. The term w for normal weight concrete is taken as 145 lb. per cu. ft.

Values for elastic shortening, creep of concrete and shrinkage for various values of concrete strength at transfer are tabulated in Table 3.

At this point the designer must "recalibrate" his thinking in regard to steel relaxation losses. Due to the superimposed losses of elastic shortening, creep and shrinkage (anchorage and curing losses may be neglected when compared to the magnitude of other losses), the steel tendon can no longer be considered

Table 3. Losses at various concrete strengths

f'_{ci}, concrete strength at release (psi)	3500	4000	4500
$f_{ci} = 0.60 f'_{ci}$ (psi)	2100	2400	2700
E_c, at transfer (psi $\times 10^6$)	3.41	3.64	3.87
n, E_s/E_c	8.3	7.7	7.3
Compressive stress in concrete along axis of tendon (psi)	1680	1920	2160
Elastic deformation, Eq. 6 (psi)	13,940	14,780	15,770
Concrete creep, Eq. 2 (psi)	20,920	22,180	23,650
Shrinkage, Eq. 1 (psi)	8460	8460	8460
Total loss—elastic shortening, creep and shrinkage (psi)	43,320	45,420	47,880
Loss, percent initial stress, %	23.0	24.1	25.4
Net remaining stress* (psi)	143,640	141,540	139,080
Percent initial stress remaining, %	76.2	75.1	73.8
Percent tensile strength remaining, %	53.4	52.6	51.7

*Includes anchorage slip and curing

to be acting at an initial stress level of 70 percent of tensile strength, but rather at a range 50 to 55 percent of tensile strength, Table 3. At this level the relaxation losses may be estimated from Fig. 3 at approximately 5.0 percent, at 20 years at room temperature (269,100 x 0.55 x 0.05 = 7400 psi) or 3.92 percent of initial prestressing force.

LOW RELAXATION STEEL

Recently there has appeared on the scene material referred to as "stabilized" or "thermalized" wire or strand that has lower relaxation values than the stress-relieved wire or strand that is now commonly used in the United States. This material shows a considerable difference in relaxation loss values, when compared with stress-relieved wire, at high percentages of tensile strength and high temperatures. For normal structures at normal temperatures, however, the difference in losses between the two wire types is slight. For example, at a range of 50 percent of tensile strength, a temperature of 20 to 22 deg. C (68 to 72 deg. F) and at 1000 hr. the percentage loss of initial stress differs by approximately 0.5 percent. Assuming that "stabilized" material lowered the relaxation value by 60 percent, it would change the percentage loss of initial prestress in the example above from 3.92 percent to 1.71 percent. Because of the high percentage losses due to creep, shrinkage and elastic deformation, and the inaccuracies in determining these values, relaxation is of relatively minor significance. However, at elevated temperatures, losses due to relaxation may be of more significance and should be investigated.

STRESSING LOADS

Recommendations for initial stressing loads vary from country to country. However, the usual condition is the requirement that the initial stress be not more than 70 percent of the specified minimum tensile strength with a temporary allowable overstress of 80 percent of the specified tensile strength.

Relaxation losses can be reduced by temporary overstressing. A recent British publication[13] states the following: "If a 0.276-in. pre-straightened and stress-relieved wire is stressed to 80 percent of the tensile strength and the load immediately reduced to 70 percent, the relaxation loss after 1000 hours is reduced by 25 to 30 percent in comparison with the relaxation loss for the same wire stressed initially to 70 percent without overstressing."

In some instances it may be practical to apply an *initial* prestress force higher than 70 percent of minimum tensile strength. Initial stresses up to 75 and 80 percent have been used. Some European practices allow an initial stress as high as 90 to 95 percent. However, the designer must be aware of the higher relaxation values at these ranges of percentage of tensile strength, Fig. 1.

Table 4. Typical changes in steel stress

Initial stress tons*/in.^{2}	Temporary overstress tons*/in.^{2}	Residual stress tons*/in.^{2}
70	—	67.4
70	80	68.2
75	—	71.0

* Long tons

Greater relaxation losses at high initial stress may not be a sufficient disadvantage to the use of a higher initial stress. This procedure may be a more efficient way of achieving a higher net remaining stress than by temporary overstress.

Table 4 shows a comparison of initial stress and temporary overstress values based on 1000 hr. relaxation losses[13].

In certain structures it may be more practical to restress after a period of time for reasons other than relaxation. Tests have shown that the relaxation loss is considerably less after restressing than the loss that occurs after the first stressing. British tests show that for an initial stress of 70 percent with a relaxation loss of 3.9 percent after 1000 hours (temperature level not disclosed), the loss after another 1000 hours was reduced to 1.2 percent after restressing[13]. Other tests indicate that at 250 deg. F (121 deg. C) and an initial tension of 70 percent of tensile strength, the relaxation loss approached 20 percent. When the same material was restressed after 500 hr., a further 1000 hr. relaxation value was reduced to approximately 9 percent.

The restressing approach may be questionable, unless other losses are simultaneously compensated as well.

CONCLUSION

Loss in prestressed concrete results from a variety of reasons and the amount of loss from these causes varies considerably in magnitude. As technology develops, it becomes necessary for the designer to evaluate and attach a proper perspective to these changes.

It becomes mandatory for the designer to have a knowledge of the reasons and causes for the losses that occur and to be able to apply material data from all sources in a logical manner. For example, when attempting to apply relaxation data to a structure under consideration, he must understand how the data were obtained and then apply them to the actual conditions in the structure under consideration with some rational reasoning. Steel relaxation data do not account for any losses that may be superimposed by other causes. It should also be noted that these data are obtained for the steel material acting alone. In an actual structure several losses are occurring simultaneously and are affecting each other, becoming variables that are dependent on each other, rather than acting independently. Therefore, the percentages given in the last two lines of Table 3 are somewhat erroneous in that they represent a summation of losses and do not account for an interaction of losses. However, the designer should be aware of the source and relative magnitude of all losses so as to preclude unsatisfactory deflections and premature cracking, especially in specialized structures.

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Discussion of this paper is invited. Please forward your decision to PCI Headquarters by April 1 to permit publication in the June 1970 issue of the PCI JOURNAL.