UNDERSTANDING THE RELAXATION IN PRESTRESSING

This paper discusses relaxation in prestressing steel wire, defined as stress loss at constant extension and related to creep phenomenon. Both relaxation and creep are correlated to the stress-strain diagram. The effects of time, temperature, rate of loading and re-stressing upon relaxation are presented.

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In the design of prestressed concrete structures, a very important consideration is the loss of initial prestress force that may be expected. Losses are due to various factors which are part of the stressing operation as well as to the immediate and long-term strains in the structural materials. The function of the steel tendon in prestressed concrete is critical to performance and it becomes essential to know the properties of the steel. This knowledge has to be more accurate than heretofore due to increasing concern with the effect of elevated temperatures on prestressed structures. Recently, attention has been focused on the behavior to be expected of the steel tendon in the design of nuclear pressure vessels. Current discussion relating to design of nuclear pressure vessels requires prediction of losses at elevated temperatures for periods of time up to 30 and 40 years.

We must know, or be able to predict, the behavior of the steel subjected to long-term tensile stress and how this behavior is related to time, temperature, magnitude of initial stress, and rate of loading. Therefore, this paper will attempt to describe the effects of the above variables upon relaxation losses in prestressing steel wire.

In the discussion that follows, it must be remembered that the tensile strength referred to is the actual (as opposed to rated) tensile strength of the wire being tested. The specifications by which prestressing steel is purchased call for minimum tensile strength. Actual tensile strength may be as much as 15 percent greater than specified. Further, the data presented are obtained for the steel material acting alone and do not account for any losses that may be superimposed by other causes. The loss of stress in a prestressed concrete member occurs not only from steel relaxation, but also from the greater losses due to concrete creep, shrinkage and elastic shortening, and these in turn reduce the creep and relaxation of the steel.

STRESS-STRAIN CURVE

High strength wire is made from high carbon steel billets that are hot-

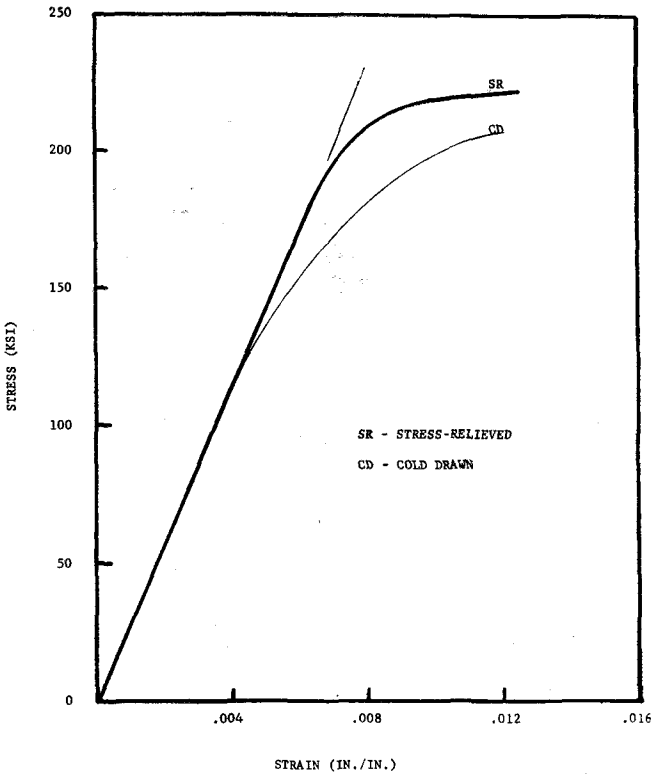


Fig. 1. Stress-strain curve for 0.2-in. dia. prestressing wire

rolled into rods of suitable diameters. The rod then receives a heat treatment process called patenting to obtain the tensile strength and ductility necessary to withstand the subsequent drafting required to produce the desired wire size with enhanced tensile and yield strength. A typical stress-strain diagram of cold drawn wire is indicated by the curve CD in Fig. 1 [1,2,3].

Cold drawing the wire produces residual stresses. To reduce these stresses, the wire is thermally stress relieved producing the stress-strain curve SR in Fig. 1.

CREEP

Prior to a discussion of relaxation loss, an understanding of the creep phenomenon in steel wire is helpful. When wire is required to sustain a relatively high tensile stress, at any temperature, it creeps. Creep is defined as the continuing elongation of the wire under constant stress (load); that is, for a constant stress, the wire will increase its length as time progresses. Fig. 2 is a schematic representation of the creep phenomenon, plotted arithmetically. In this diagram *a* is the immediate strain that occurs on application of load. This strain may be purely elastic or partially elastic and plastic depending upon the magnitude of the initial stress. The creep strain *b* then follows and, upon removal of load, the specimen

shortens by an amount *c*, which is an immediate recovery. Note that a specimen initially stressed only in the elastic range would have a recovery *c* very nearly equal to *a*. There may also be a creep recovery *d*, which is a function of time[4].

Stress-relieved wire will show no appreciable creep when stressed up to 50 percent of its tensile strength. Beyond 50 percent, creep begins to become noticeable, Fig. 3, and gradually increases as the stress approaches tensile strength [5,6,7].

The law governing creep is *not* a linear relationship with the logarithm of time; at stresses as low as 60 percent of the tensile strength, the rate of creep is an increasing value with the logarithm of time. In terms of actual time, however, the rate of creep has decreased. The rule governing the rate of creep of stress-relieved high tensile wire is more complicated than a straight line plot on a semi-logarithmic scale.

In studying the curves represented in Fig. 3, one becomes aware that even when plotted on a semi-logarithmic scale, the curves bend around the time axis. At low stresses, the curves are almost straight, becoming parabolic within the time span investigated. At high stresses the curves are hyperbolic. The S-shaped curve indicates that the rate of creep reaches an inflection point and then tends to level off. Tests over longer periods of time indicate that the S-shaped curve (hyperbolic) also occurs at lower stress levels but over much longer periods of time.

RELAXATION

Because of the relatively constant length of the steel tendon in a prestressed concrete structure, a more reasonable approach to the long-

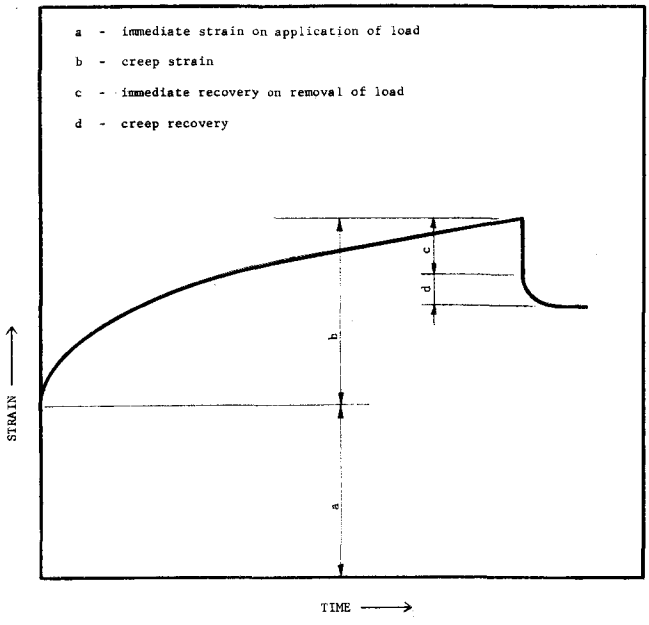


Fig. 2. Schematic representation of creep

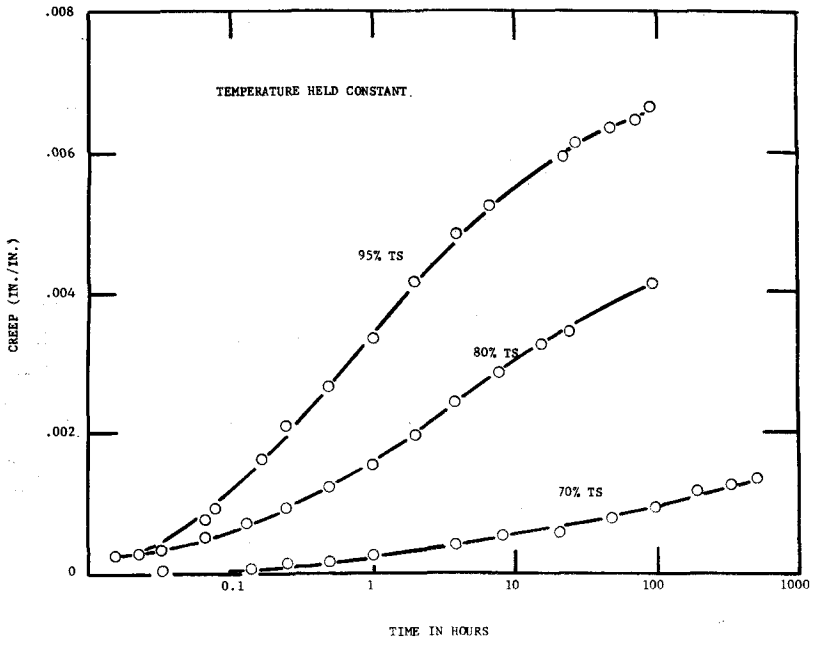


Fig. 3. Creep of stress-relieved wire loaded to different stress levels

term behavior of prestressing steel under load is the measurement of stress relaxation. Relaxation is defined as the stress (or load) loss in the wire when the strain (elongation) does not vary. The loss in initial stress due to relaxation is measured as a function of time. As might be expected, relaxation, like creep, follows a substantially semi-logarithmic law.

Fig. 4 represents a schematic relaxation diagram plotted arithmetically. As in Fig. 2, where *a* represented the immediate strain that occurred on application of load,

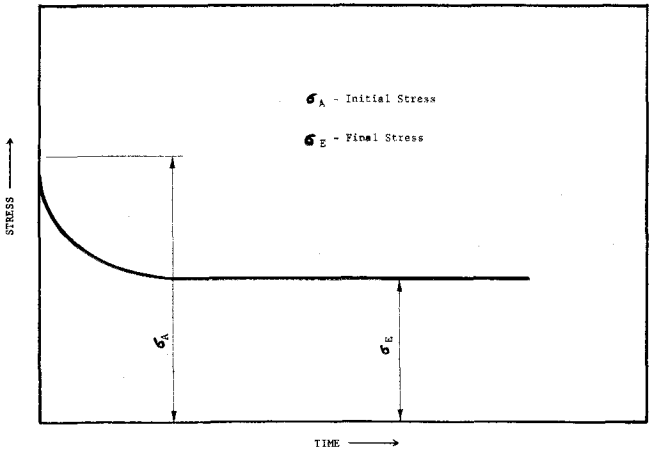


Fig. 4. Schematic representation of relaxation

σ_A in Fig. 4 represents the initial stress. At this point in a test, a strain gage is set at zero. At appropriate small increments, the strain gage is re-set to zero by reducing the load so that the gage length of the specimen is kept constant. In this manner, a progressive loss of stress can be plotted up to the stress σ_E, corresponding to a leveling off of stress loss[4].

Relaxation losses for high strength 0.196-in. diameter wires at various initial stress levels at room temperature are plotted in Fig. 5[1]. In comparing the 1000-hr. values for the cold drawn and the stress-relieved wires, it can be seen that the relaxation losses for cold drawn wire are larger at low initial stresses. Everling has suggested that the stress loss increases almost linearly up to about 12 percent at an initial stress of 90 percent of tensile strength. On the other hand, the relaxation of stress-relieved wire is apparently small

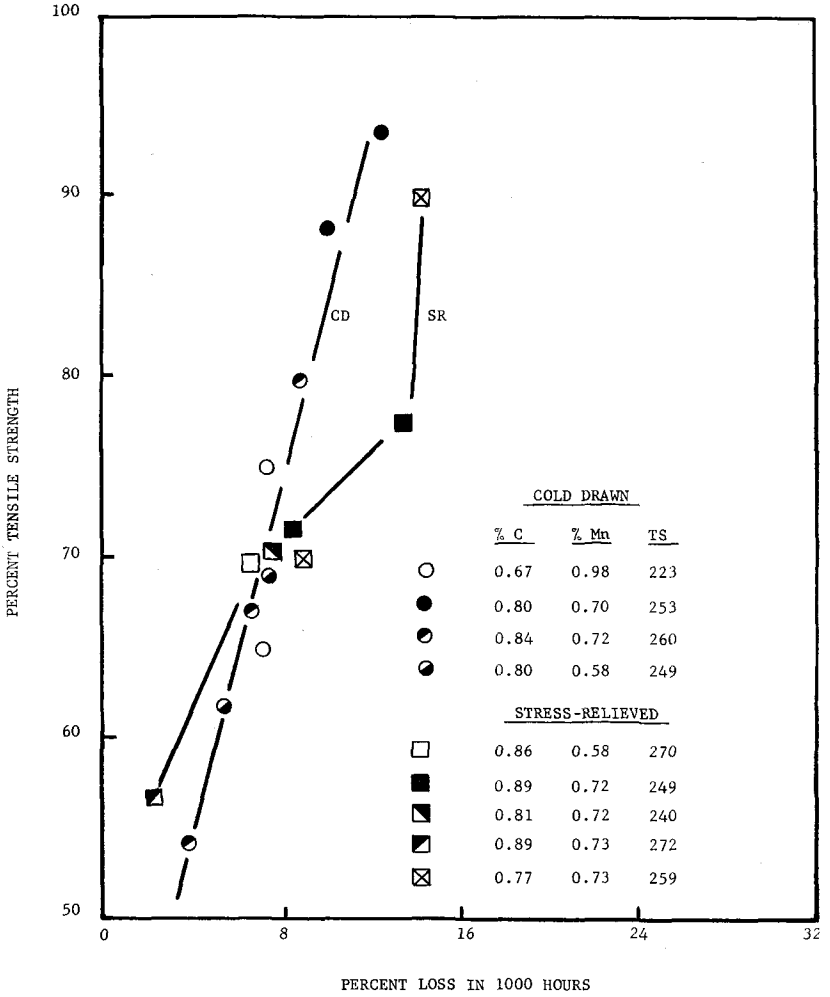


Fig. 5. Relaxation of 0.196-in. dia. prestressing wire

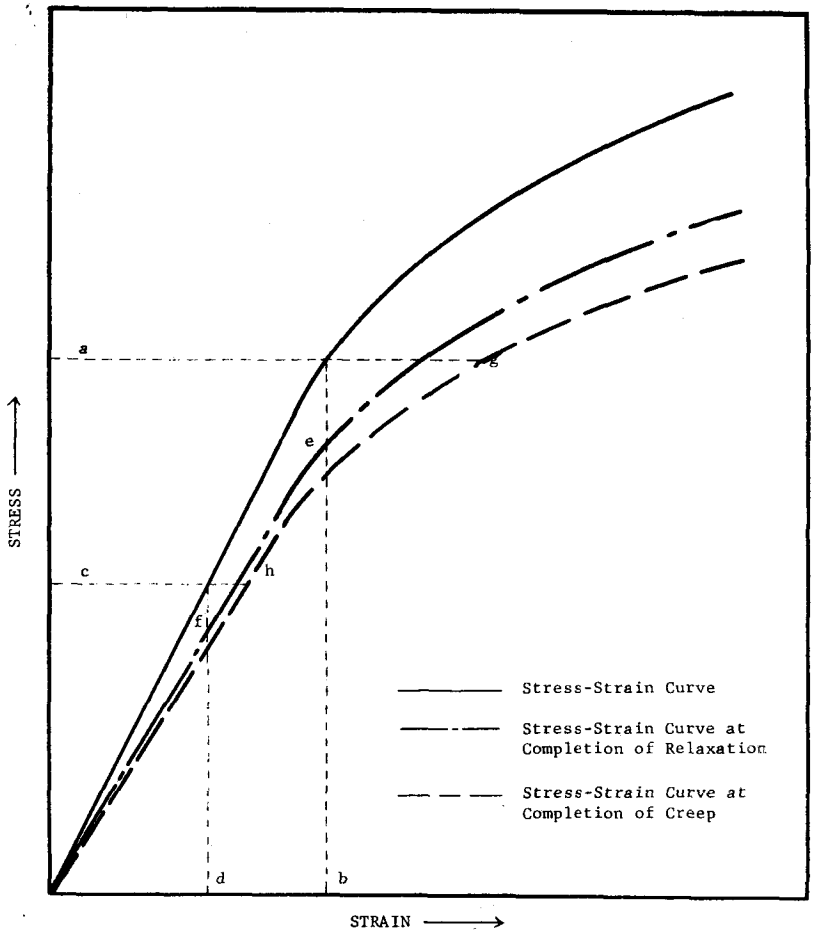


Fig. 6. Schematic representation of creep and relaxation

up to values of about 55 percent of tensile strength. Beyond this point, the rate of relaxation increases gradually, until at about 70 percent of tensile strength, the relaxation of both types of wires is about equal. Beyond 70 percent, the relaxation loss for the stress-relieved wire increases quite rapidly, reaching approximately 15 percent loss at 80 percent of tensile strength. At very high stresses, the curves again tend to converge. Papsdorf and Schwier[4] explain this by indicating that when the elastic range (yield point) is exceeded, every permanent deformation will reduce the elastic limit of the stress-relieved wire where it had previously been raised by the stress-relieving process. Because the creep phenomenon represents a permanent deformation, it will tend to produce approximately the same ultimate conditions as those existing in cold drawn wire. Therefore, the convergence of the curves is a result of appreciably exceeding the

yield point of the stress-relieved wire.

CREEP AND RELAXATION vs. STRESS-STRAIN DIAGRAM

The behavior of steel wires under long-term tensile stress is measured by one of two methods: constant stress (creep) or constant strain (relaxation). The two methods can be more easily understood if they are both plotted and compared to the stress-strain diagram, Fig. 6[4].

If an initial value of stress *a* is applied, an immediate strain value *b* is obtained from the normal stress-strain diagram. If the strain is kept constant, then after a period of time there will be a loss of stress corresponding to a value *e* on the relaxation diagram. At a lower initial value of stress *c* and for the same period of time, the relaxation or loss of stress *f* will be correspondingly smaller.

If the initial stress *a* is kept constant, then there occurs, after a period of time, a creep strain indicated by *g*, and correspondingly by *h* at constant stress *c* for the same period of time.

Creep and relaxation modified stress-strain curves are governed by load duration (time) and temperature and usually do not coincide with each other. Papsdorf and Schwier[4] explain this by the fact that most tests are conducted to 100 or 1000 hours and, depending upon the magnitude of the initial load and temperature, the final values of creep and relaxation have not been reached. Therefore, Fig. 6 actually illustrates the inseparableness of the creep and relaxation phenomenon, i.e., relaxation is another form of creep measurement.

TIME AND TEMPERATURE vs. RELAXATION

As has been shown in Fig. 3, constant stress (creep) curves have a point of inflection and take an S-shape if the values are plotted on a logarithmic time scale. As might be expected, constant strain (relaxation) curves also show this point of inflection when plotted on a logarithmic time scale.

Fig. 7 is a schematic description

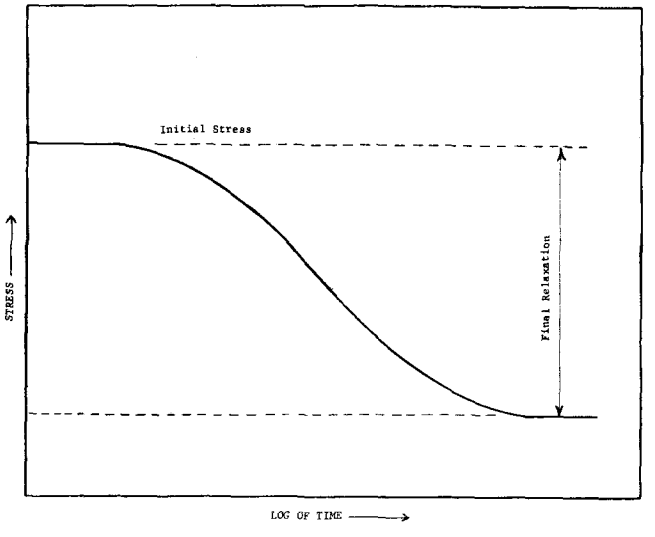


Fig. 7. Schematic representation of relaxation

of the relaxation phenomenon[4] plotted on a semi-logarithmic scale. For low values of initial stress and a 1000-hr. load duration, only the first straight portion of the curve is traveled. At medium values of initial stress, a substantial loss will occur and the point of inflection may be reached. For high initial values of stress, the losses occur so rapidly in the first few minutes that the point of inflection is passed and the lower portion of the curve is approached indicating a final value of relaxation.

With regard to the S-shape of the curves, the raising of temperature has the same effect as raising the initial value of stress, i.e., at low values of stress and medium values of temperature the inflection point is discernible.

Relaxation losses are shown in Fig. 8 for steel wire Grade St. 150/170, 0.2 percent proof stress, nominal yield point 150 kg/mm^2 (213,000 psi), nominal tensile strength 170 kg/mm^2 (242,000 psi), 6.7 mm (0.264 in.) diameter, drawn and tempered (stress-relieved). Initial stresses vary from 43 to 96 percent of the tensile strength and temperatures range from 22°C to 100°C. Relaxation stress loss is plotted against load duration with values above 1000 hr. obtained by extrapolation[4].

At an initial stress of 43 percent of tensile strength, the loss of stress in the wire is hardly noticeable at 1000 hr. for room temperature (22°C). A deviation from the horizon tal occurs at 100 hr. for a temperature of 35°C and at 20 hr. for 50°C. The curve for 100°C indicates that the deviation from the horizontal has already occurred during the first six minutes and reaches a tangent point at approximately 50 hr. At 150°C, the point of transition is at about 5 hr.

The curves at higher initial values of stress show the same behavior pattern, displaying an earlier deviation from the horizontal and with correspondingly larger losses at 1000 hr.

Fig. 8 also shows that although temperature effect on relaxation is considerable at 1000 hr., there is hardly any difference in effect at 100 years (about 900,000 hr.) for temperatures between 35 and 150°C. These curves also indicate that relaxation curves are S-shaped and tend toward a final value depending upon initial stress, temperature and time.

Table 1. 1000-hr. stress relaxation tests*

Tensile strength** (psi)	Initial stress (psi)	Initial stress % TS	1000-hr. stress loss % init. stress
254,300	216,000	84.9	15.7
254,300	210,375	82.7	15.0
254,300	192,000	75.5	9.6
254,300	178,500	70.2	7.0
254,300	160,000	62.9	4.2

* *On SUPER-TENS stress-relieved wire at room temperature*
** *Rated tensile strength=240,000 psi*

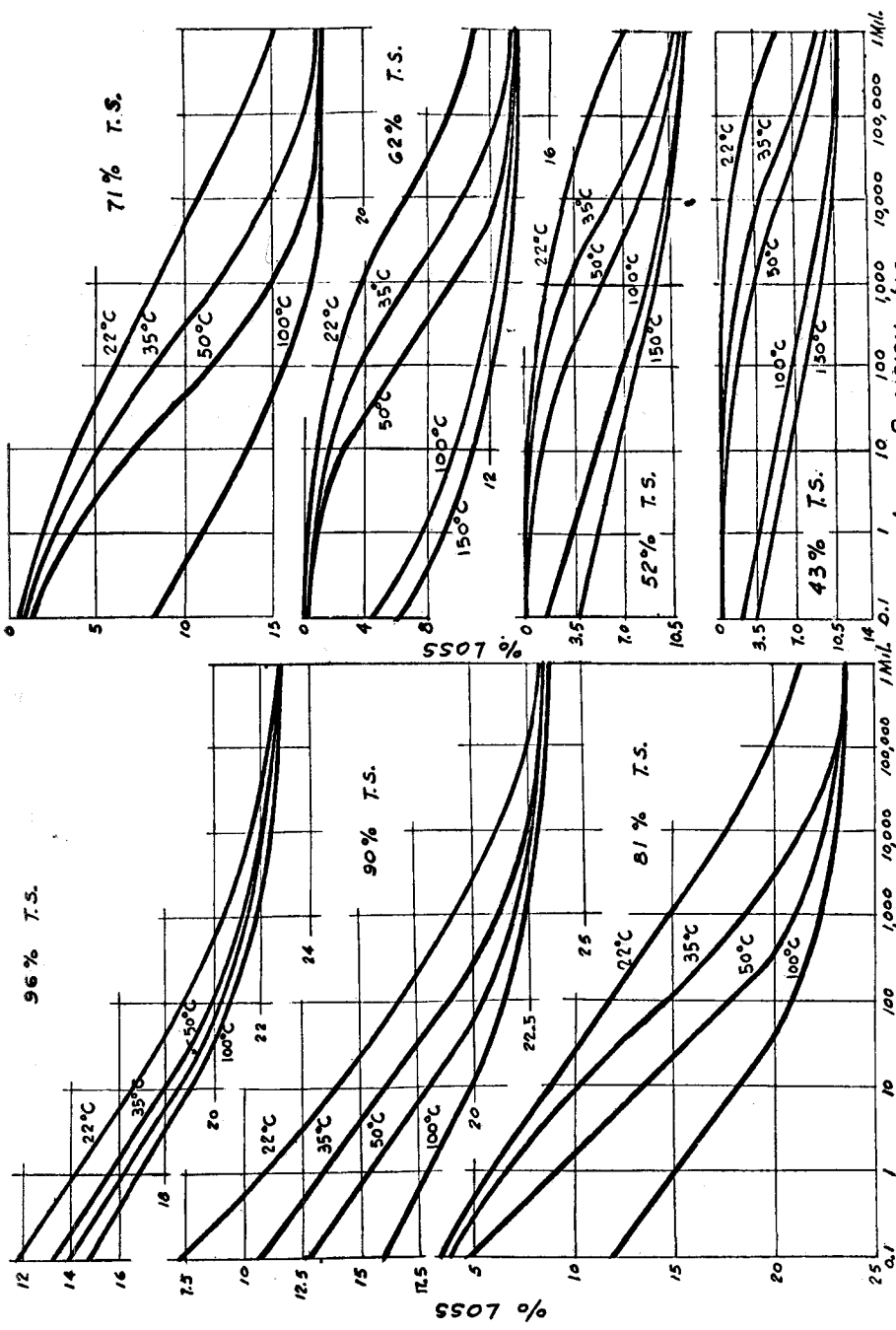


Fig. 8. Relaxation diagrams at varying initial stress and temperature

Data shown in Fig. 5 agree well with that shown by Papsdorf and Schwier in Fig. 8. In addition, recent new data obtained by U.S. Steel Applied Research Laboratory for 1000-hr. relaxation of SUPER-TENS stress-relieved wire at room temperature, Table 1, show a remarkable correlation to that in Fig. 8, within the measured time.

Therefore, for a given steel, it has been determined that the rate of relaxation is a function of initial stress, temperature and duration of load application.

RATE OF LOADING

Fig. 5 indicates that the rate of relaxation of stress-relieved wire does not keep increasing with increasing levels of initial stress, but reaches a peak at about 80 percent of tensile strength and then becomes less beyond that point.

If the rate of loading up to the initial stress is varied from 2 min. to 4 min., some differences take place, Fig. 9[2]. The point, at 90 percent, which lies on the heavy line represents the relaxation when the initial stress was reached in 4 min. whereas the corresponding point reached in 2 min. is on the light line, indicating a substantial difference. However, this difference was not observed at the 94 and 96 percent levels, and recent data obtained by U.S. Steel Applied Re-

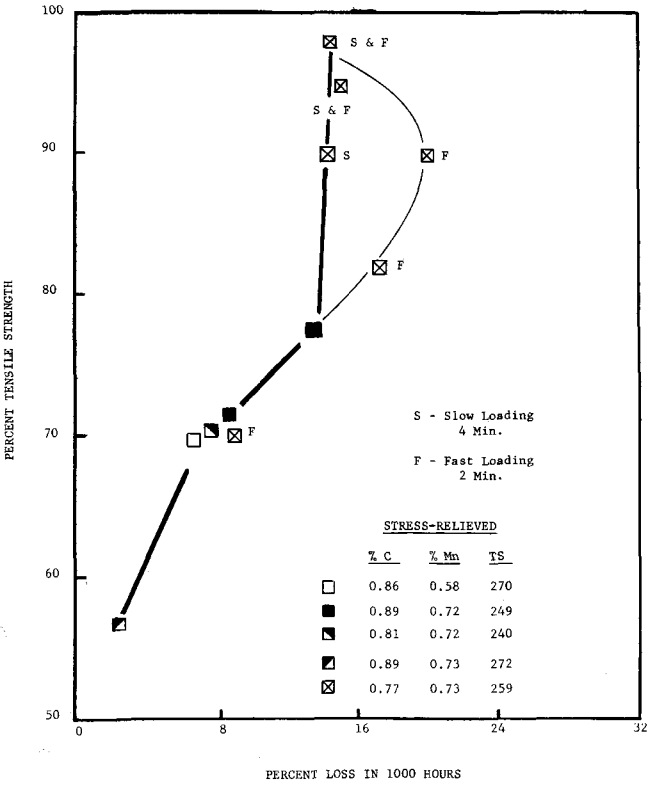


Fig. 9. Effect of load rate on relaxation of 0.196-in. dia. prestressing wires

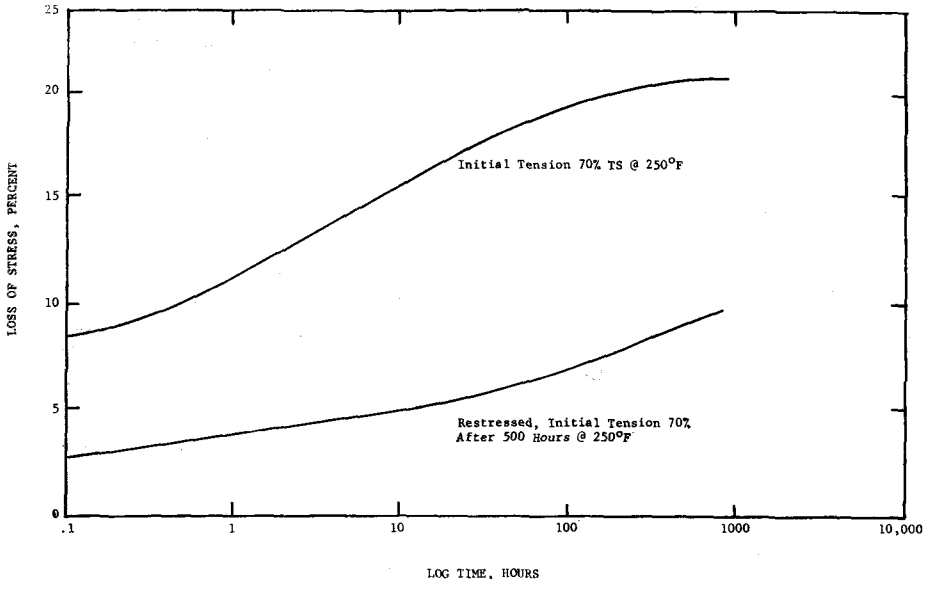


Fig. 10. Effect of re-stressing on relaxation

search Laboratory with rate of loading varying from 2 min. to 60 min. at 70 percent of tensile strength showed little or no difference in relaxation loss. This behavior due to rate of loading only appears to manifest itself in the approximate range of 80 to 94 percent of tensile strength of stress-relieved wire.

RE-STRESSING

In certain types of structures, where there may be considerable prestress losses due to causes other than relaxation, it may become economically feasible to re-stress tendons after some period of time. Tests have indicated that relaxation losses may be considerably less after re-tensioning.

Fig. 10 shows that at 250°F (121°C) and at an initial tension of 70 percent of tensile strength, the 1000-hr. relaxation of stress-relieved wire approached 20 percent. When the same material was re-tensioned after 500 hr., a further 1000-hr. relaxation value was approximately 9 percent. Of course, the total length of tendon after re-stressing is longer than for a non-re-stressed tendon.

Re-stressing may be economically questionable unless losses due to creep, shrinkage and elastic shortening of the concrete are simultaneously being compensated for as well.

CONCLUSION

When the designer of prestressed concrete structures attempts to apply relaxation data, he must understand how the data was obtained and what significance it has to actual design considerations for the structure.

Relaxation data is obtained in the laboratory for the steel material acting alone and does *not* account for any losses that may be superimposed by elastic shortening, creep

and shrinkage of the concrete. When one is designing to a 30- or 40-year criteria, the validity of applying relaxation data based on a 70 percent stress value may be questionable when the short-term (one month) superimposed losses due to other causes may reduce the initial stress in the prestressing tendon considerably.

At normal initial stress levels and temperatures, relaxation is predictable and is of relatively minor significance in terms of other losses imposed upon the structure or member. At elevated temperatures, the losses due to relaxation of the prestressing steel is of greater significance and is being investigated further to provide more meaningful design information.

The engineer must apply relaxation data to the actual conditions applying to the structure he is designing with rational reasoning and judgment.

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