Understanding the Steel in Prestressing

by Walter Podolny, Jr.*

SYNOPSIS

On the premise that most of the people who design and fabricate prestressed structures think of the prestressing strand and wire only as a 250 ksi or 270 ksi engineering material, this paper discusses the properties of the material, how it is manufactured, and some of the work that is being done in the steel industry to improve this product.

INTRODUCTION

From the time that reinforced concrete, with its inherent weakness in tension, was first invented, engineers have attempted to tension the steel reinforcement in such a manner that the concrete would be placed in a state of compression, greater than any tensile stress that would be imposed by dead or live load. Under some circumstances a residual tension stress in the concrete may be allowed within code limitations.

Several structures were constructed utilizing this concept; however, only mild reinforcing steel was available at the time. These structures at first behaved according to predictions, but because of the relatively low amount of prestress force that could be induced in the mild steel, they lost their properties due to the creep and shrinkage of the concrete and creep of the reinforcing steel.

In 1928, E. Freyssinet of France, who is generally credited with the modern development of prestressed concrete, began using high-strength steel wires for prestressing.

The first linear structure to be built in this country was a bridge in Madison County, Tennessee, in 1950, which was followed shortly thereafter by the famed 160-ft. span Walnut Lane Bridge in Philadelphia.

MANUFACTURING PROCESSES

High strength wire is made from high carbon steel of the following range of analysis:

Carbon	0.72-0.93%
Manganese	0.40-1.10%
Phosphorus	0.040% max.
Sulfur	0.050% max.
Silicon	0.10-0.35%

The steel is rolled into rods of suitable diameters. The rod then goes through a process called patenting which is a heat treatment applied to the rods to obtain a uniform metallurgical structure which combines high tensile strength with high ductility and thus imparts to the rod the ability to withstand the drafting required to produce the desired wire size and the greatly enhanced tensile and yield strength.

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In drafting or drawing the rod through tapered dies, the shape of the die, Fig. 1, is very critical. There are four distinct zones in the die. The first zone, on the entering side of the die, is somewhat larger in diameter than the rod to be drawn; its purpose is to afford room for the die lubricant that adheres to the rod. This is called the *bell length and entering angle* and gradually tapers into the second zone. The second zone is called the *entrance cone length* and consists of the approach length and the reducing length which is the section where most of the actual reduction takes place. The next zone is called the *bearing length* and it may have a very slight angle of taper. The exit zone or *back relief* is in the form of a countersinking of the back part of the hole. This is done as a strengthening to prevent the circular edge of the hole from breaking away[(1)*].

Fig. 2 shows a 6 Draft Continuous Drawing Machine that is one of the largest made. Its major advantage is that it makes possible more uniform mechanical properties. The machine is equipped with the most efficient cooling to attain strength, toughness and ductility. When the drawing process is completed, the wire has very high tensile strength.

In drawing the wire through the tapered dies to reduce its diameter and increase its tensile and yield strength by the cold work done to it, the outer surface is squeezed and

* Numbers refer to references at end of article.

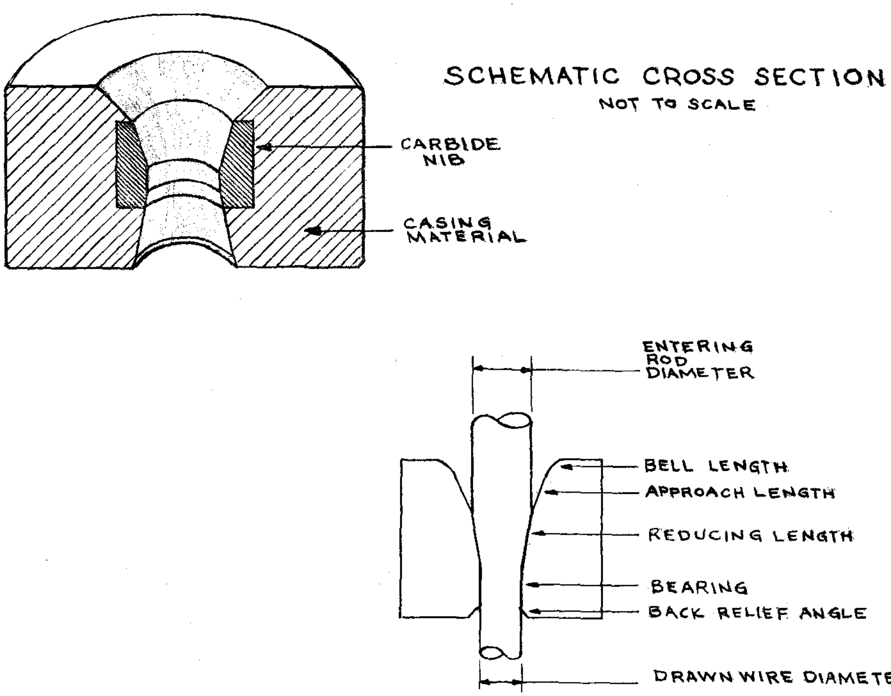


Fig. 1—Wire Drawing Die

Fig. 2—6 Draft Drawing Machine

receives more cold working than the center portion. The resulting wires will have what are known as surface residual stresses. However, these will *not* be uniformly distributed across the wire cross section. The outside surface of the wire will be somewhat different from the interior.

In order to correct this condition, the wire goes through a process known as *stress-relieving*. In this process the wire is subjected to a very carefully controlled time-temperature treatment. The wire passes through a bath of molten lead at about 800 to 825° F, or through heated air in an air-tempering furnace. This produces a wire which is practically straight and more easily handled. The wire is normally taken up on a 5-ft. diameter block; when a piece of wire is taken from a coil, it will spring to a diameter eight times greater. It is, therefore, much more readily held in a straight line. The heat of the stress-relieving bath will burn off much of the residual drawing lubricant and leave a clean surface. Of more importance, stress-relieving causes important changes in the mechanical properties of the wire, which will be discussed later.

Seven-wire strand for prestressing is manufactured by stranding hard-drawn or non-stress-relieved bright wires. The strand is made by stranding six wires to form helices around a straight central seventh wire, Fig. 3. Prestressing strand differs from ordinary seven-wire strand in that the center wire has a larger diameter than the outside wires. This is to ensure that the outer wires, when under stress, will grip the center wire securely. The outside wires are held by the bond of the concrete, but the only thing that maintains stress in the center wire is the pressure and resulting friction of the outside wires. Hence, if slipping is to be prevented, it is very important that the outer wires contact the center wire very tightly. This is accomplished by using a central wire with a diameter about 4 per cent greater than the other 6 wires. When these wires are stretched, they tend to straighten out. Inasmuch as they pass from side to side of the central wire, in attempting to assume a straight line shape they press on the center wire, gripping it very tightly and preventing it from slipping relative to the rest of the strand. This configuration also provides the strand with a high and closely controlled modulus of elasticity. The minimum difference in diameters between central and outside wires is very closely controlled.

Special stranding techniques, including both pre-forming and post-forming operations, ensure strong, tough strand. The strander works in tandem with the straightening and stress-relieving equipment and this assures a high degree of toughness and elasticity in the strand. The straighter the strand, the easier it is to place and tension, and less likely that it will become tangled on the job.

The wire passes through a series of straighteners before and after stranding, then the strand is stress-relieved by the electrical induction stress-relieving process.

Lengths of wire or strand from each production run are cut off at critical check point stages and put through appropriate destructive tests in the laboratory.

Fig. 3—7-Wire Strand

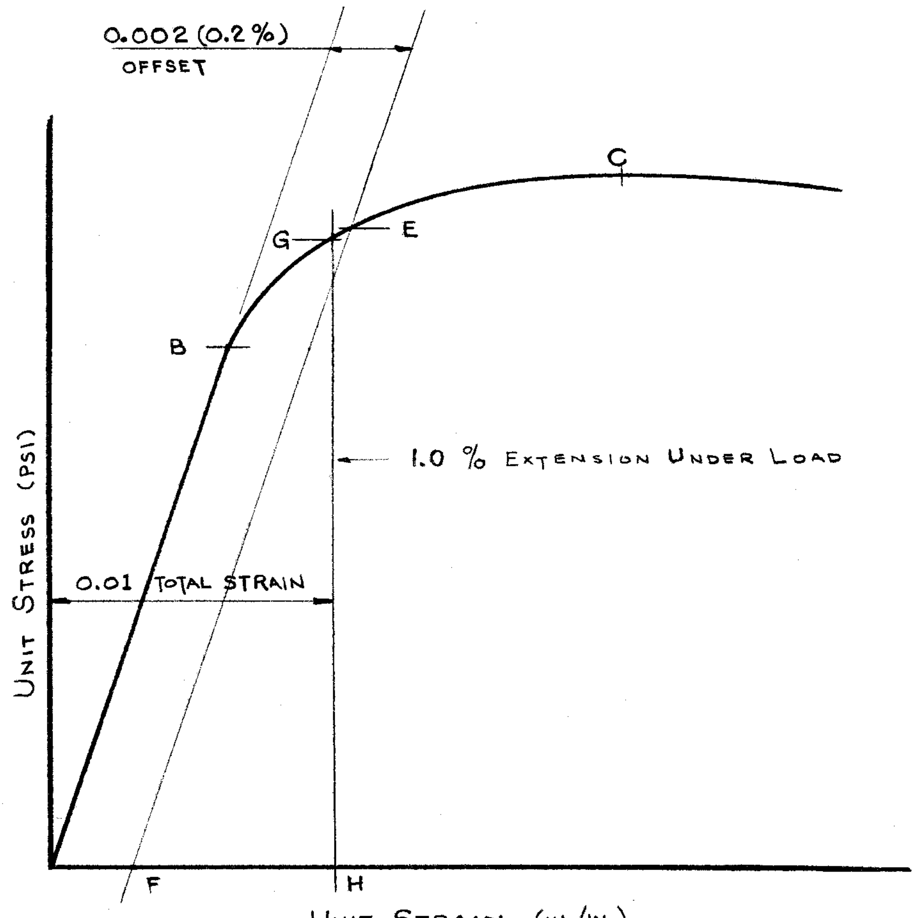
A final check is one in which a tensile-testing machine pulls the strand until it breaks, and then records the breaking load. This confirms that the strand or wire will meet the requirements of the prestressing industry.

STRESS-STRAIN CURVE

Fig. 4 illustrates a typical stress-strain curve which can be applied, in a very general way, to all prestressing steel; there are no units for either stress or strain shown. As stress increases from zero, the strain will also increase proportionally. This is represented by the first portion of the curve which is a straight line up to the proportional limit indicated by point *B*. Beyond the proportional limit, strain begins to increase more rapidly than stress, and the stress-strain relationship becomes a curve with increasing curvature until the ultimate strength, or point *C*, is reached.

An important factor to observe is that there is no yield point as there is in the curve for structural carbon steel; at least, there is no yield point before the ultimate strength is reached. Instead, between the proportional limit, point *B*, and the ultimate strength, point *C*, the elongation of the steel takes place in a regularly increasing manner, without any point where strain increases suddenly without a corresponding increase in stress. However, the idea of yield point strength is so well established in thinking of carbon steel members that an arbitrary means of fixing a "yield strength", for comparing high strength steels of the sort used for prestressing and for use in design equations, has been

Fig. 4—Typical Stress-Strain Curve



established. This is generally called the *0.2 per cent offset yield strength.* ASTM A416 and A421 require that the yield strength be measured by the *1.0 per cent extension under load* method.

If a straight line EF is drawn parallel to the initial straight-line portion of the curve and at a horizontal distance to the right of it equal to a strain 0.002 in./in., which is the same as 0.2 per cent, the point *E,* where that line intersects the stress-strain curve, is called the yield strength.

By the extension under the load method a vertical line is drawn at the point where the total strain *H,* or total extension, is 0.01 in./in.; the point *G* where this line intersects the stress-strain curve is called the yield strength.

It should be noted that the yield strength as determined by the 0.2 per cent offset method will be at least 85 per cent of the ultimate tensile strength for stress-relieved wire and strand. ASTM requires that the 1.0 per cent extension under load be a minimum of 80 per cent of the minimum breaking strength of stress-relieved wire and a minimum of 85 per cent of the the minimum breaking strength of stress-relieved strand.

It should be borne in mind that this so-called yield strength has no real significance as far as the ability of the steel to carry stress is concerned. It is purely an arbitrary point, and might have been taken at 0.10 per cent or 0.30 per cent offset or 0.7 per cent extension under load. This arbitrary yield strength has caused the erroneous impression that there is a definite critical stress beyond which one should not go in design. Yielding begins at rather low stresses and the degree of yielding progresses at a faster rate as stress increases. This increased yielding is a very gradual phenomenon and the best that can be said is that there is not any critical point we can define such that there is danger in going beyond or absolute safety below. However, the various yield strength methods have found a place in specifications and are used in establishing working stresses.

MECHANICAL PROPERTIES

The process of stress-relieving had been mentioned previously as causing some important changes in the mechanical properties of the wire. One change is that of ultimate tensile strength. The ultimate tensile strength is slightly reduced, but because the stress-relieving temperature is not high and the wire only reaches a temperature of about 600°F, the reduction in strength is in the order of about 5 per cent. However, the ductility is greatly increased, as there is a 4 per cent minimum elongation for wire and a 3.5 per cent minimum elongation for strand. These are specification minimum values. Average values are approximately 7 to 8 per cent (10-in. gage length for wire and 24-in. gage length for strand). The proportional limit will be much higher than for the non-stress-relieved wire, while the deviation from the initial straight line portion of the stress-strain curve will be more gradual. As a result, the yield strength as determined by the 0.2 per cent offset method will be higher; it will be at least 85 per cent of the ultimate tensile strength.

Typical stress-strain curves are shown in Fig. 5 for both as-drawn and stress-relieved wire. The first part of the curves follow the same straight line; this would mean that the two wires have the same initial modulus of elasticity, approximately 29,000,000 psi.

Because the efficiency of a strand is always less than 100 per cent, the tensile strength of the strand is always less than the tensile strength of the wires composing it. Efficiency of a strand is defined as the percentage ratio of measured breaking strength of a strand to the aggregate strength of all individual wires tested separately. If a tensile test is made on a piece of strand and the stress-strain curves for the non-stress-relieved and the stress-relieved strand are compared, Fig. 6, an interesting observation can be made in that the initial straight line portions of the curves do not coincide; the as-drawn strand is below the stress-relieved and indicates a lower modulus of elasticity. When strand is loaded, a considerable constructional stretch occurs due to the tendency of the helical wires to straighten and the resulting compaction of the strand. For a given stress, a greater elongation is obtained than with a solid wire, and this gives a lower modulus of elasticity. For stress-relieved strand the initial modulus of

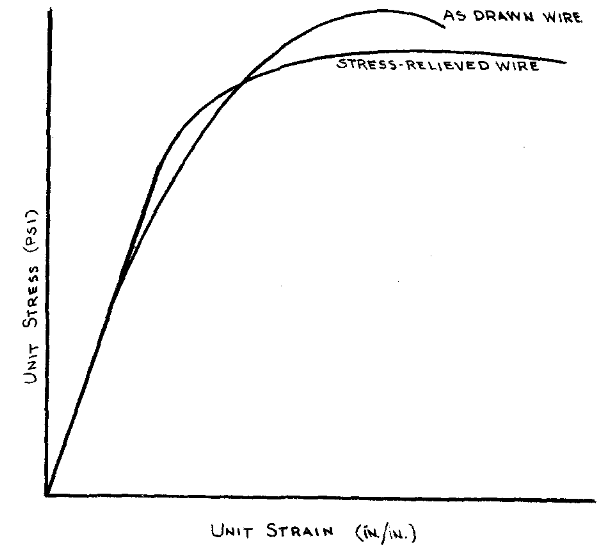


Fig. 5—Stress-Strain Curve—Wire

elasticity has been found to be approximately 28,200,000 psi.

CREEP

When cold drawn wire sustains a high tensile stress, it creeps. Creep is defined as the continuing elongation of the wire under constant load, that is, for a constant load the wire will increase its length as time progresses.

The amount of creep increases linearly as the logarithm of time as indicated in Fig. 7 for as-drawn wire loaded to different stress levels. This means that the extension of the wire, or creep, progressively decreases. Stating it in a different manner, one could say that it would take one hundred years to double the creep which is observed in the first month[2].

Stress-relieving makes a pronounced change in the creep characteristics of a wire. If properly made, stress-relieved wire will show no appreciable creep when stressed to about 50 per cent of its ultimate tensile strength. Beyond 50 per cent creep begins to become noticeable, Fig. 8, and gradually increases as the stress approaches ultimate strength[2].

The rate of creep is no longer a logarithmic one; at a stress as low as 60 per cent of ultimate the rate of creep is increasing against the logarithm of time. In reality, the rate of the creep has decreased very much, compared to as-drawn wire when measured in terms of actual

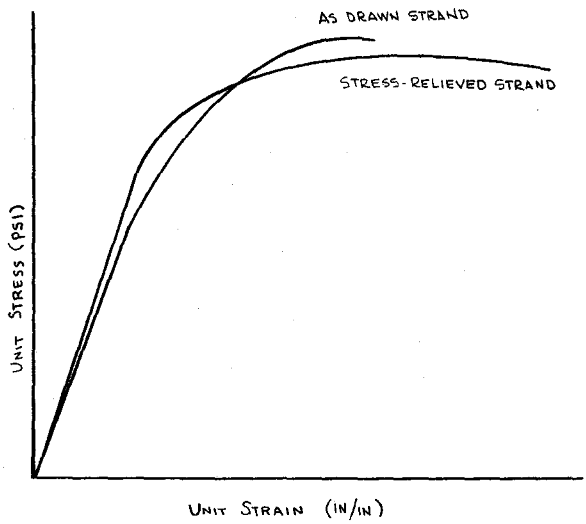


Fig. 6—Stress-Strain Curve—Strand

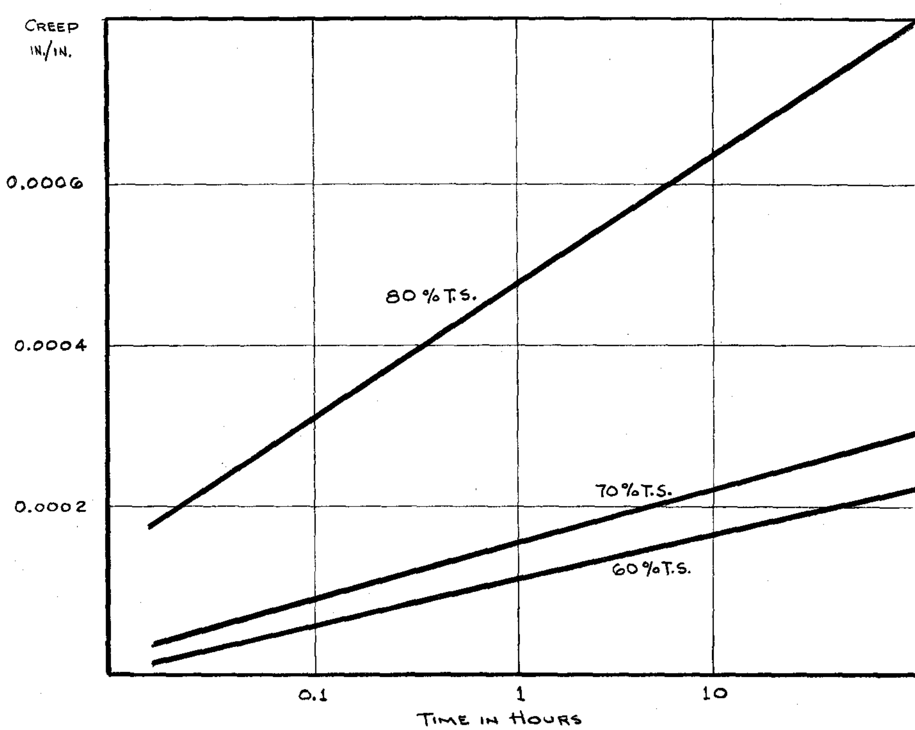


Fig. 7—Creep—As-Drawn Wire

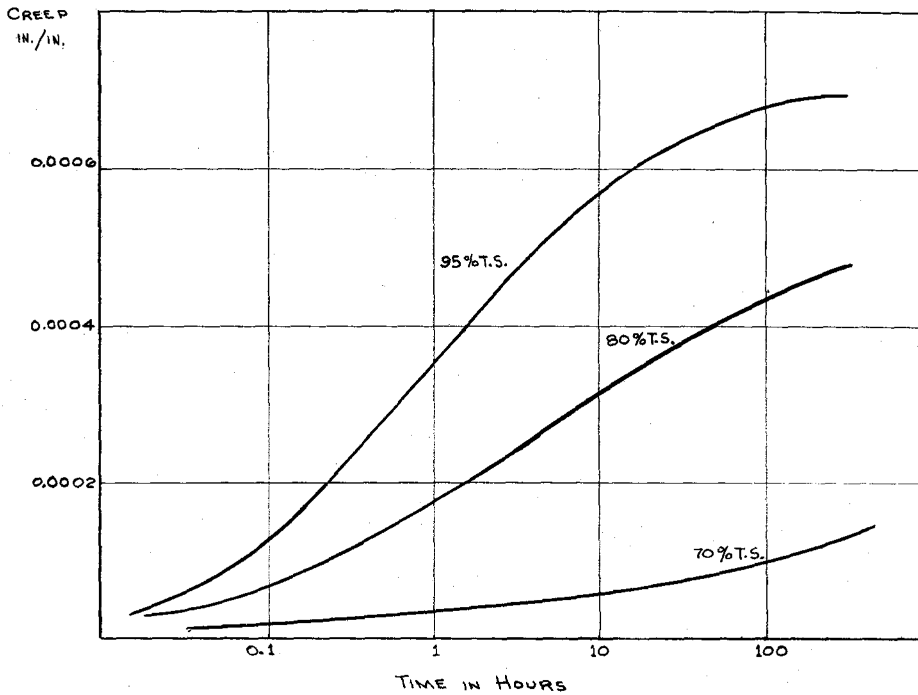


Fig. 8—Creep—Stress-Relieved Wire

time. The actual rule governing the rate of creep of stress-relieved high tensile wire is more complicated than a straight logarithmic relationship.

RELAXATION

Because of the logarithmic time nature of creep phenomenon in wire and a doubt as to its validity when applied to conditions prevailing in prestressed concrete, a more valid approach to the creep behavior of prestressing steels for the designer is the measurement of stress relaxation when the wire is held at constant length or strain. As might be expected, relaxation, like creep, follows a substantially straight logarithmic law at normal stress and temperature.

A logarithmic progression has two limits, zero and infinity. For all practical purposes, in prestressed concrete, 1000 hours seems to be a practical measure of an end point. If one considers that the shrinkage, creep and elastic shortening of the concrete itself will reduce rather quickly the initial tension in the steel, and the approximate logarithmic nature of the steel relaxation, nothing very important can be expected to happen after 1000 hours.

In comparing the 1000-hour values of stress relaxation for the as-drawn and the stress-relieved wires, Fig. 9, it can be seen that the line for the relaxation values of the as-drawn wire progresses to large values at low initial stresses. In looking at the curve for the stress-relieved wire, it is evident that relaxation, by comparison, is very small up to values of about 55 per cent of ultimate

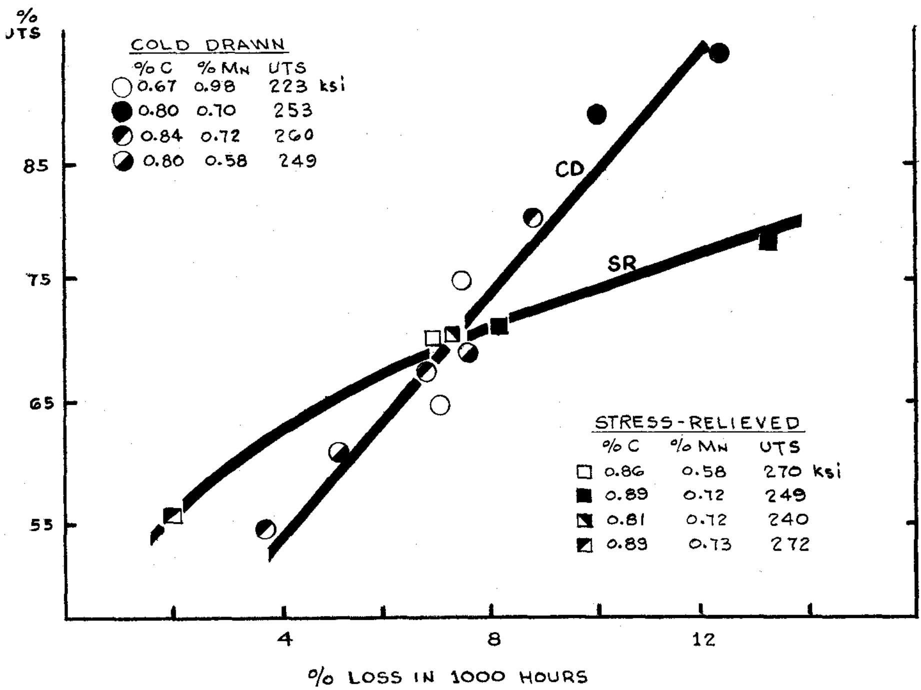


Fig. 9—Relaxation of Several High-Strength 0.196-in. Diameter Wires at Various Stress Levels

strength. Beyond this point the rate of relaxation increases gradually, until at about 70 per cent the relaxation of both wires is about equal. Beyond 70 per cent the relaxation of the as-drawn wire is actually less than that of the stress-relieved wire[2].

DESIGN STRESSES

At this point, one might ask what working or initial stress should be used for design. A conclusion could be made that there is no point of stress where the behavior of the steel changes radically or even markedly. Stress-relieved wire could be used, at least for linear structures, at a level of design stress less than 55 per cent of the ultimate. However, there are thousands of structures in which initial values larger than 55 per cent have been employed. Unlike other materials of construction, prestressing is a system, and all factors have to be considered in determining a level of safety, including design, shape, materials and workmanship. Safe working stresses cannot be determined for any one element by itself.

The design working stresses in the steel are fixed at 0.6 of the ultimate tensile strength or at 0.8 of the yield strength, whichever is lower.

Initial prestress loads of 60 to 70 per cent of ultimate strength are commonly used in practice. Here, stress-relieved wire with its lower relaxation and its larger coil diameter are important advantages. One code had issued design criteria which permitted temporary initial stresses as high as 80 per cent of ultimate tensile strength. Some European practices allow initial stressing as high as 90 to 95 per cent of ultimate tensile strength. No exception can be taken to this, provided the designer is aware of the increased stress relaxation, as indicated in Fig. 9. *It is not intended to suggest that stresses higher than are now considered safe should be recommended. The data presented here is only for informative purposes.* One must remember that the ultimate tensile strength referred to in these illustrations is the actual ultimate strength of the specimen being tested. The specifications by which prestressing steel is purchased call for minimum guaranteed ultimate tensile strength. Actual tensile strength may be as much as 15 per cent greater than specified. Therefore, anyone who assumes to be working at a 90 per cent level may actually be at an 80 to 85 per cent level which might cause some confusion if not thoroughly understood.

CORROSION

Corrosion is the term used to designate the deterioration of a metal by the surrounding environment. Moisture is a necessary requirement for the corrosion process to proceed at ordinary temperature. The severity of corrosion is influenced by the presence of dissolved salts such as chlorides and sulfates that may be present with the moisture. Carbon steel can be attacked and destroyed by corrosion from a number of sources. As an illustration, when carbon steel is exposed to an industrial atmosphere, the presence of nitric, hydrochloric or sulfuric acids, or phosphates and ammonium salts, such as occur around fertilizer plants, can cause severe corrosion. It is thus evident that corrosion is a function of the environment. What effect a particular environment will have on a specific metal can only be determined by exposing that metal to the environment.

Calcium chloride has the ability to stimulate pitting of high-strength steel wires. The use of calcium chloride in concrete can seriously affect the performance of prestressing wires or strand. In a Russian investigation it was demonstrated that the inclusion of two per cent calcium chloride, by weight of cement, in specimens of prestressed concrete girders, resulted in failure before full design static load was reached at the end of one year. In the absence of calcium chloride, the members withstood the design load as well as the expected failure load.

When prestressing wire is held in outdoor storage for short intervals of time, little loss in mechanical properties will occur if the environment is one in which only general corrosion occurs. For example, tests conducted in Great Britain on 0.200-in. diameter degreased wire exposed during seasonally bad weather showed that the reductions in tensile strength recorded after periods of one, two and three months were 1.01, 1.52 and 2.10 per cent respectively[4].

If the wire is to be stored for any length of time, some means should be taken to protect it. For example, recent developments in the field of vapor phase corrosion inhibitors have resulted in their being incorporated into specialized wrapping papers. Protection of this type is effective in preventing damaging localized pitting. Currently, a pack is available such that the strand coil is spirally wrapped with corrosion inhibiting paper and then locked into a shipping stand after which the entire pack is covered with waterproof reinforced paper.

Concrete of appropriate composition and thickness is completely protective of prestressing steel by virtue of the environment it creates. However, if a non-dense composition is selected, if an open-structured, porous aggregate is employed, if calcium chloride is used to accelerate setting time, or if the external environment is likely to be wet for extensive periods, corrosion may occur.

When it is known that a prestressed concrete structure will be subject to frequent contact with moisture, then steps should be taken to prevent water seepage through pressure or capillary forces by selecting a formulation that results in a dense, impervious concrete. If necessary, consider the incorporation of a damp-proofing agent, such as butyl stearate or mineral oil, and employ a low water-to-cement ratio and avoid the use of calcium chloride[10]. If it is desirable to obtain other properties through the use of additives, information should be sought from the additive supplier concerning the effect to be expected on the prestressing wire.

ELEVATED TEMPERATURE

Elevated temperatures reduce the tensile strength of wire and strand. There is a loss in strength of strand of about 10 per cent at 400° F, a 50 per cent loss at 800° F. Part of the loss at elevated temperatures is recoverable after cooling as shown by the following table of the behavior of the steel strand[5]:

Temperature Deg. F.	Loss of Prestress %	Recovery of Loss %
400	10	70
600	15	50
700	23	30

Very little has been published on the effect of low temperatures on steel wire. In the tensile strength range of 200-220 ksi, steel wire shows a slight increase in strength and elastic properties as the temperature falls. Sub-zero temperatures on the Fahrenheit scale would be required to produce a 5 per cent increase in tensile strength. As a rule of thumb, it may be useful to remember that a change in temperature of 1°C will produce a change in stress of a fixed wire in the order of 240 to 280 psi[4].

CONCLUSION

The best quality of steel available is used in the manufacture of prestressing wire and strand, and the utmost control is used during its manufacture. It cannot be emphasized strongly enough that the care and handling of this material is critically important. Damage to wire can have serious consequences.

When flame cutting wires at the end of a member, it is important to prevent molten metal from coming into contact with any other wire. The globule of metal can produce an alteration in the strength and ductility of the wire or strand by changing the structure of the steel.

Some properties of this material require further investigation. There have been many definitions of an ideal wire; however, the ideal is seldom possible for economic or other practical reasons.

Hopefully, the material in this paper has conveyed to the reader a better understanding and respect for the steel material that is the backbone of the prestressed concrete industry.

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