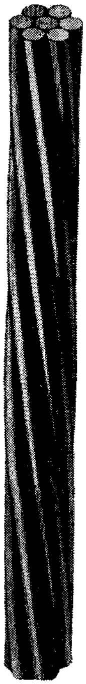

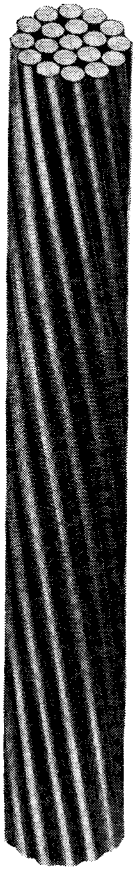

Two types of strand are discussed in this article. At left is 7-wire incoated strand of type used for pretensioned, bonded work. At right is galvanized strand such as is used in post-tensioning, of 1-in. diameter, with 19 wires.

Wire and Strand *for* PRESTRESSED CONCRETE

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Every prestressed concrete tensioning element should have certain properties, namely:

1. High strength, to minimize the percentage of stress loss due to such factors as shrinkage and plastic flow.
2. Low coefficient of creep.
3. Ease of handling. Not only do cranky wire and strand add considerably to the contractor's costs, and therefore to his selling price, but the rough handling necessary to fight them into place often leaves them nicked, kinked, or otherwise permanently damaged.
4. Good surface for bonding to concrete on uncoated tendons.

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5. Sufficient ductility, and uniform modulus of elasticity.
6. Resistance to stress-corrosion.

The wire referred to in this article is high-strength uncoated stress-relieved wire made specifically for use in prestressed concrete. The uncoated strand discussed is the 7-wire stress-relieved strand made specifically for use in pretensioned, bonded prestressed concrete. The galvanized strands for post-tensioning are the type that has been used in suspension bridges for over half a century except that the end connections have been adapted to prestressed concrete.

Wire is made by rolling steel billets into round rods and then drawing the rods through conical dies to produce the required size and strength. The drawing operation reduces the diameter and increases the length. It also changes the internal structure from the crystalline make-up of the rod to the long fibers parallel to the axis which give wire its great strength. As it emerges from the last die, the product is referred to as "cold-drawn" wire.

Wire for use in prestressed concrete is made by subjecting cold-drawn wire to a stress-relieving process. Stress-relieving is not what we usually think of as a heat treatment; the temperature used is not sufficient to change the strength of the wire but it does eliminate the internal stresses which are present in the wire as a result of the drawing process.

The uncoated strand discussed here is composed of seven cold-drawn wires fabricated by laying six wires of one size around a slightly larger center wire. In this case the finished strand is subjected to the stress-relieving operation which eliminates at one time the internal stresses due to both the drawing and the stranding operations.

UNCOATED WIRE AND 7-WIRE STRAND

Creep and relaxation. Numerous studies have been made on the subject of creep and relaxation in wire. Creep is the gradual non-elastic increase in the length of wire under a constant tension. Relaxation is a gradual loss of stress in a wire held at constant length. In a prestressed concrete member, the wire undergoes a modified form of relaxation; that is, the concrete member shortens as a result of its own shrinkage and plastic flow so that the wire is not held at a constant length but shortens with the concrete. Thus, the test values measured for relaxation in wire indicate slightly more stress loss than this factor actually causes.

Creep and relaxation properties of cold-drawn wire, stress-relieved wire, and mechanically straightened wire have been compared in as many different ways as possible. Mechanically straightened wire does not measure up – unless it is stress relieved after straightening – in which case it is in the same class with stress-relieved wire. Although these properties of stress-relieved wire are slightly better than those of cold-drawn wire in the stress ranges in which they are used, the difference is so small that the two materials can be considered as having the same creep and relaxation. In considering this subject, the designer should not lose sight of the fact that a change in the density of the concrete due to more or less vibration, or a slight error in keeping to the specified water-cement ratio, can cause a change in stress loss several times any difference that can be found between the two types of wire.

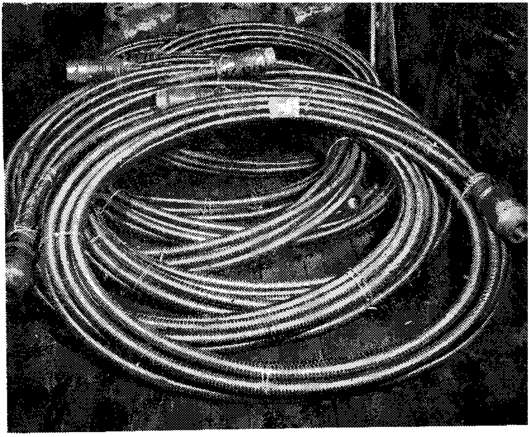
Preloading. Some designers feel that preloading wires — holding them at a tension above the specified initial tension for a few minutes before anchoring them at the specified tension — is advantageous.

It is probable that this impression stems from European practice which is explained by the report in the late Gustav Magnel's book, *Prestressed Concrete,* in which he discusses the wire used in Belgium. This wire, of 5-mm (0.196-in.) diameter has an ultimate strength of 216,000 psi. It is used at an initial tension of 123,000 psi, but its stress-strain curve begins to bend quite sharply away from a straight line at two-thirds of this stress. His tests showed a stress loss of 12 percent in the wire alone when used at an initial tension of 123,000 psi. When preloaded to 137,000 psi for two minutes, and then anchored at 123,000 psi, this loss was reduced to 4 percent. Obviously it pays to preload such a wire, especially when the preload required is only 63.5 percent of the ultimate strength of the wire.

The stress-relieved wire of 0.196-in. diameter used for prestressed concrete in the United States has an ultimate strength of 250,000 psi. Most designers use it at an initial tension of 67 percent of its ultimate. At this stress, the stress-strain curve of the stress-relieved wire is still a straight line. Tests on this wire show a maximum stress-loss of less than 4 percent from the initial 67 percent. The Bureau of Public Roads' "Criteria for Prestressed Concrete Bridges" assumes a 4 percent loss due to creep in the steel, and considers that "overstretching" is not necessary.

Tests made at Roebling's Trenton plant show less stress-loss in a wire which has been preloaded than in one which has not, but these tests cover only a relatively short period of time. DeStrycker has studied creep of wire over a period of years (*Revue de Metallurgie,* Oct. 1948, p. 411). In his tests he preloaded the wire by 10 percent for two minutes. His results indicate less loss in the preloaded wire at first, but the difference between the two procedures after several years is negligible. The results obtained by preloading stress-relieved strands are identical with those obtained by preloading stress-relieved wire.

In the final analysis, the increase in final tension obtained by preloading the high-quality wire used in the United States is so small that it cannot be applied to reduce the amount of wire in a member. On the other hand, the contractor will definitely increase his price when this operation is required in the specifications.



Galvanized strands of 1-9/16 in. diameter encased in flexible metal hose of 1-13/16 in. inside diameter, are coiled and loaded in truck for shipment. Sockets for end anchorages are tapped for permanent stud, which will be applied in the field.

Fatigue. As with any material, the stress range through which a wire can stand repeated loadings decreases as the stress increases. Using the initial stresses recommended later on, the minimum final stress in both wire and strand will be 58 to 60 percent of the ultimate. Data already available demonstrate that fatigue is not a problem on these wires and strands in this stress range. If higher stresses are contemplated, a thorough investigation of fatigue under such stresses should be conducted before they are permitted.

A review of European specifications for post-tensioned members compiled in 1952 shows initial tensions of 50 to 60 percent of the ultimate. Taking advantage of the superior elastic properties of the stress-relieved wire available in the United States, designers using this wire are specifying an initial tension of 67 percent of the ultimate. Ultimate strength varies with wire size but is in the neighborhood of 250,000 psi.

Although an initial tension of 67 percent is desirable, there are several reasons why we should not design to initial tensions in excess of 70 percent:

1. Common sense says we should not approach the ultimate too closely as there are other factors which may create stresses higher than anticipated. For instance, many cables must be over-tensioned to overcome friction between wire and concrete.

2. As the initial tension increases beyond this point, the percentage of stress loss increases much more rapidly. This means a greater differential between the initial and final tension conditions. Engineers familiar with prestressed concrete design realize that the larger this differential becomes the less efficient may be the design of the prestressed member.

3. All members must meet both a design load and an ultimate-strength specification. Excessively high stresses in the prestressing steel reduce its quantity and lower the ulti-

mate strength of the member. This often necessitates extra steel to meet the ultimate strength requirement.

4. Fatigue stresses may become a factor.

Intial tension in strand. A review of European specifications for pretensioned members compiled in 1952 shows initial tensions of 60 to 70 percent of ultimate. It should be noted that all the tensioning elements were single wires, which cannot be used in the United States for economic reasons—because of the high labor cost of handling so many small units and the need to use small aggregate so that the concrete will flow around the many tensioning elements.

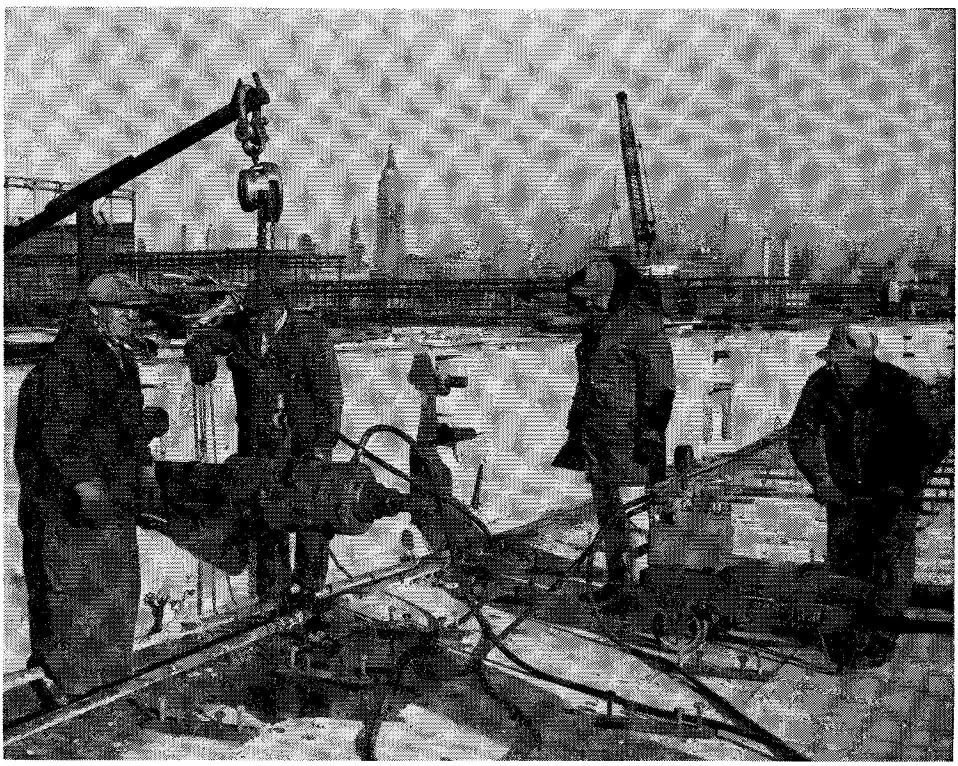
An initial tension of 70 percent of the ultimate is recommended for 7-wire stress-relieved prestressed concrete strands used in pretensioned bonded members. Ultimate strength varies with strand size but is in the neighborhood of 250,000 psi. In addition to the four reasons mentioned above, there are several other reasons for using the 70 percent value:

1. The stress loss in a pretensioned member is greater than in a post-tensioned member because all the elastic compression and some of the shrinkage are eliminated by post-tensioning but not by pretensioning. The final stresses resulting from initial tensions of 67 percent for post-tensioned members and 70 percent for pretensioned members are about the same.

2. Initial tension can be specified as high as it is safe to tension the strand since it will never be necessary to over-stress the strand to overcome friction or for any other reason.

Stress-relieved materials. From the designer's point of view, stress-relieved wire and strand have several advantages over the cold-drawn materials. For instance, they have several times as much resistance to stress-corrosion; the stress-relieving process removes the wire-drawing lubricant, providing a better bonding surface; and the stress-relieved materials have a much more uniform modulus of elasticity. When a group of such wires or strands is tensioned at one time, the stress in each will be the same and the elongation can be used to check the load. Finally, the cold-drawn materials are cranky and hard to handle. This results in rough handling by the erectors and the material is sometimes damaged by the time it is in place.

All prestressed concrete fabricators in the United States insist on stress-relieved wire



Long-stroke center-hole ram tensions strand of 1-9/16 in. diameter in post-tensioned pile cap of Pier A, Hoboken, N. J. Note New York skyline in background.

because of the difficulty of handling cold-drawn wire. If cold-drawn wire were specified, the fabricators' cost would increase considerably (if they felt they could do the job at all) because of the extreme difficulty of handling this material.

GALVANIZED STRAND

Galvanized strands prove most economical where the tensioning elements are long, where the prestressing force is large, or where rust or corrosion is a consideration.

Wire for these strands is made by passing high-strength cold-drawn wire through a bath of molten zinc. The result is a thoroughly stress-relieved wire protected by an outer coating of pure zinc, plus a hard zinc-steel alloy between the zinc and the wire. Although the zinc is a protective coating which carries no load, it is standard practice in the wire industry to refer to the overall diameter of the wire including the zinc and to use the gross cross-sectional area including the zinc. On this basis the minimum ultimate strength of the wires is 220,000 to 225,000 psi, although the strength of the steel, which is carrying all the load, is appreciably higher.

Galvanized strands for prestressed concrete are made by laying one or more layers of wire around a center wire. Most of the wires are of 0.196-in. diameter, supplemented by a few wires of other sizes to get the required overall diameter and strength. Standard sizes range from 0.600 to 1-11/16 in. diameter, with minimum ultimate strengths varying from 46,000 lb. to 352,000 lb. per strand.

Although the individual wires have been stress-relieved by their passage through the molten zinc, the finished strand as it comes from the stranding machine does not necessarily have a constant modulus of elasticity. It is given a constant modulus by a prestretching operation in which it is held at a high stress for a period of time during which the individual wires adjust themselves to each other.

End anchors, referred to as fittings, are attached at the manufacturer's plant so that the strands arrive on the job ready to be placed in the structure. Several styles of fittings are available. One has a permanent stud the length of which can be varied to suit the details of the particular job. A jacking unit is attached to the end of the stud for the tensioning operation, and a permanent nut on the stud holds the load after jacking is completed. If it is in the way, that part of the stud outside the nut can be burned off after tensioning has been completed.

Another type of fitting is threaded on the outside and has a large nut to hold the load. It is also tapped to receive a jacking rod which is removed after the tensioning operation. The thread on both types is long enough to allow for reasonable errors in the length of the concrete member. A third type of fitting is a steel casting with a wide flange on the end which serves as a bearing plate. For most strands this fitting is cheaper than one with threads, and it eliminates the need for a bearing plate. The concrete is cast directly around this fitting and the tensioning is done from the opposite end, which is provided with a threaded fitting for the purpose.

Galvanized strands are used in several ways for post-tensioned members — in the open space in a concrete hollow-box, on the outside of a concrete member, or encased in a paper or plastic tube to prevent bond and covered by the concrete as it is poured. When grouting is required, strands are supplied encased in flexible metal hose, which is filled with grout after the jacking operation.

Creep and relaxation. The percentage of stress loss due to relaxation in a galvanized strand is approximately the same as that in a parallel wire cable. The initial stress is lower—140,000 psi compared to 167,500 psi —but the modulus of elasticity is also lower in almost the same ratio—25 million psi to 29 million psi—so that the two factors cancel each other.

Fatigue. Galvanized strand assemblies with fittings attached have been subjected to fatigue loadings as separate assemblies, in prestressed concrete test members, and in service in forging hammer foundations. There has never been any evidence of damage to the assembly due to such loadings. These strands are generally designed for an initial tension of 140,000 psi.

Desirable properties. Galvanized strands have several desirable properties which should be considered when the tensioning elements for a project are being selected:

1. A minimum amount of field labor is required for placing and tensioning. Regular job personnel can handle both placing and tensioning without special supervision. Long lengths are as easy to handle as short lengths because they can be supplied on reels.
2. The corrosion problem is virtually eliminated. A galvanized suspender recently removed from the Brooklyn Bridge for test after sixty years of service was found to be in satisfactory working condition.
3. Galvanized strands can be left exposed to the weather where uncoated tendons have to be protected. If grouting after tensioning is required, and the tendons will first be exposed to the weather, a galvanized flexible metal hose can be used and the entire assembly will be rustproof.
4. Galvanized strands can be tensioned more accurately to specification requirements than uncoated tendons. The coefficient of friction for the galvanized strand is much lower and quite uniform, whereas this value for uncoated tendons becomes increasingly higher as surface rust develops during the curing period of the concrete. This is of extreme importance in long or continuous structures, since high and non-uniform friction values result in varying tension throughout the length of the tendon. Galvanized strands assure much greater uniformity in this respect.