Thermal Prestressing of Structural Steel

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THE THERMAL PRESTRESSING method discussed in this article consists of shop welding heated high strength steel cover plates to the bottom flanges of beams and girders. Heat is produced with a simple device, such as a gas torch; elongation of the plate is measured with a dial indicator. After cooling, the plate creates predetermined favorable stresses in the beam which in effect permit less steel to do more work.

Considering all costs, the savings over conventional construction are shown to amount to about 6 percent. Advantages, limitations and proposed applications of the method are discussed. Underlying theory is limited to end results.

Calculation summaries of actual structures built, as well as of trial designs, are given.

It is shown that this type of prestressing is economical primarily in the following cases:

When cover plates are used for composite beams, the plates can be made much smaller, of low alloy high strength steel, and prestressed; double cover plates can be replaced by a single prestretched plate. Significant savings can be achieved when several hundred similar beams are involved.

In special conditions, including but not limited to strengthening of existing structures, this method is eminently suitable to solve the problem. In particular, when a combination of limitations on headroom, cover plate size, weight and rigidity exists, thermal prestressing may offer the only feasible method.

PRINCIPLES AND SPECIAL FEATURES OF THERMALLY PRESTRESSED STEEL

The purpose of prestressing is to produce beams and girders which will support heavier loads with less material. This is done by partly compensating external load stresses with prestress of opposite direction. To be economical, the method must be simple; prestress should be applied only at critical parts, be exactly predetermined, permanent and independent of live loads.

Girders prestressed by thermally elongated, arc welded high strength steel plates meet all these requirements. Where the magnitudes of applied loads are closely predictable, as in buildings and cranes, use of prestressed steel can be profitable. The required investment consists only of some extra design effort and closer supervision of fabrication.

Structural members which are made up of different strength steels are often called "hybrid." Hybrid girders, when not prestressed, have a major drawback in disproportionate stressing of the different steels. Often a small part of the web is stressed beyond the elastic range. Such effects have not yet been fully evaluated, but it is reasonable to assume that the fatigue strength of such plastically deformed parts suffers. Through prestressing and proper sizing of the component parts of hybrid girders, the cross section becomes balanced, that is, the maximum allowable stresses of the different steels will be reached about the same time.

Utilization of heat to create stresses in steel structures and equipment is not new. Shapes, rods and eyebars have been straightened, tensioned and shortened in this way. Shrink-fitting of shafts and rings is another widely used method. More advanced examples include various types of prestressed multi-cylinder and multi-layer pressure vessels[1] which have been produced from World War II on.

Any method of steel prestressing saves material and may save on costs. Thermal prestressing in conjunction with welding is most economical and practical for the following reasons:

1. A prestressed high strength steel cover plate serves two purposes:
   a. It acts as a prestressing element, transmitting the force to the beam without any loss of prestress. (Creep does not exist in this method. Slippage can occur only if welding is delayed.)
   b. Being rigidly welded to the beam, it becomes an integral part of the assembly and thus materially increases the overall strength and rigidity.

2. A welder's torch and a dial indicator are the only equipment required to create great prestressing forces.

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Contrasted to this, other methods require machined end fittings, adapters, and tensioning jacks.

3. The thermal prestressing method embraces only welded structural steel construction. It is not extrapolated or adapted from prestressed concrete construction. The balanced design feature is the key to ultimate economy.

Limitations of the thermal prestressing method stem primarily from the simple truth that "whatever prestressing can do, a little more steel can also do." Prestressed beams and girders do not look different from ordinary beams and girders; thus, there is nothing to stir the imagination of the architect.

Existing code requirements are not likely to become a restraint on the use of shop-prestressed steel members. Prestressing is but an extension of the generally accepted elastic method of structural analysis. The fact that the beams and girders arrive at the jobsite in a prestressed condition should in all probability not contradict any code provisions. The important point is that no part of the structure will at any time be stressed beyond the prescribed allowable code stress when in service.

Advantages of prestressing are expressed in about 6 percent savings in the total beam or girder costs. The tabulated calculation summaries show that this percentage is fairly consistent. Savings in weight are in the 9 percent range. Cost and weight savings are not equal because the low alloy high strength steel prestressing plate is more expensive and some care must be taken in shop work. A premium of 50 percent over a plate of A36 steel has been used to cover these extra expenses. There is no more welding involved than in conventional coverplated construction.

Savings are not spectacular, but they definitely offer a benefit to whichever party is interested—Owner, Engineer, Architect, General Contractor or Steel Fabricator. This small saving becomes significant when hundreds of similar beams are involved and mass production methods can be applied in the fabrication shop.

Where existing beams or girders need strengthening, welding of ordinary cover plates to the bottom flange and the addition of web stiffeners, if required, will solve the problem easily. However, if a support of an existing structure has to be removed, coverplating does not eliminate the dead load settlement at the point of former support. A solution to this problem could be achieved by application of a heated cover plate. Cooling of the plate would create a closely predictable upward deflection in the strengthened beam.

EXISTING THERMALLY PRESTRESSED STRUCTURES

Thermally shop-prestressed structural steel is no longer in the "proposed" stage. The method has been proven in fair competition with conventional steel fabrication.

Three single panel rigid steel frames were built in the summer of 1962 at the Brookhaven National Laboratory, Upton, N. Y., to serve as 10-ton monorail bents. The rigid frame girders were prestressed in the shop by welding heated high strength low alloy steel plates to the bottom flanges.

The 35 ft-6 in. span girder of one typical bent, as shown in Figs. 1 and 2, is an 18WF50 with a 15[33.9 welded cap channel, both ASTM A36 steel. The combined bottom cover plate and prestressing element is a $\frac{3}{4}$ x 6 in. plate, ASTM A441 steel. Columns are tubular, 10 in. square by $\frac{1}{2}$-in. wall, ASTM A36 steel. Moment connections between columns and girder were high strength bolted in the field. Live load deflections were limited to $\frac{1}{800}$ of the span.

The steel fabricator had a free choice of using prestressed girders or conventional girders consisting of 24WF76 with 15[33.9 cap channel and 14WF87 columns, all A36 steel. He chose the prestressed design, which resulted in about a 13 percent saving in girder weight and an 8 percent saving in girder steel cost. This relatively large saving was due to a special condition, namely the restriction placed on the cover plate size by the trolley hoist clearances.

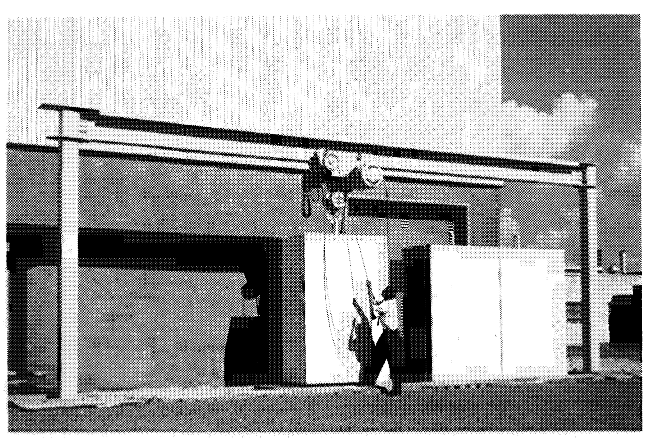


Fig. 1. Finished structure

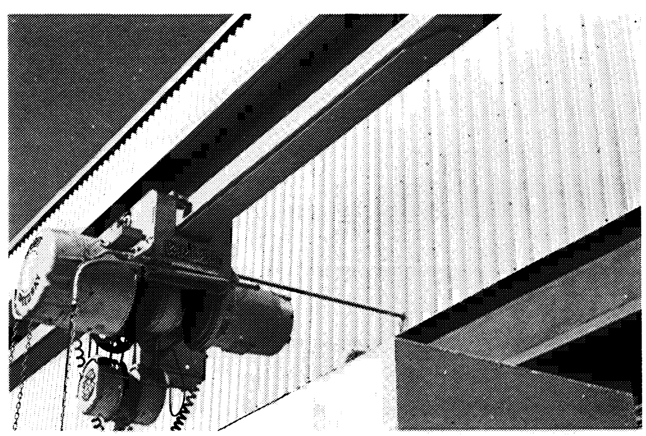


Fig. 2. Finished structure

Prestressing by the thermal method was extremely simple. The ironworkers needed no special instructions; they prestressed and welded three girders in less than two hours, so smoothly that extra labor costs were not significant.

First one end of the high strength steel cover plate was welded to the bottom flange of the girder, with the girder positioned upside down. Then the central portion of the plate was heated with an oxyacetylene torch. After the predetermined elongation of 0.045 in. was recorded on a dial indicator (Fig. 3), the other end of the plate was welded to the beam. Contraction, as the plate cooled to air temperature, prestressed the girder.

To insulate the beam flange from the heat applied to the plate, a cement-asbestos sheet was placed between the girder flange and the prestressing plate, with additional air space provided by spacers. By clamping the plate to the girder, the workmen prevented the two elements from separating as they deflected. During the heating operation the clamps were loosened to allow free movement of the expanding plate. The clamps were tightened when the welding had begun at the free end.

The operation required only one special tool—the dial indicator, which is a standard piece of equipment in any machine shop. Except for the favorable effect caused by weight reduction, prestressing in no way influenced handling and erection.

All the foregoing steps were outlined in detail on an addendum to the standard specification, but in this particular case the mechanics were sufficiently skilled that only a few words were necessary to explain the nature of the prestressing method to them.

THE MECHANISM OF PRESTRESSING

Transfer of the prestressing forces from the plate to the beam is the most involved phenomenon in this method, but basically it does not differ much from the problems encountered in coverplated beams and girders.

Various effects of the prestressing force P have been investigated elsewhere.[2] The effects of the following forces and deformations were found to be negligible:

a. Vertical component of the force P in a deflected beam
b. Change in the eccentricity e of the horizontal component of the force P, as caused by the flexure of the loaded beam

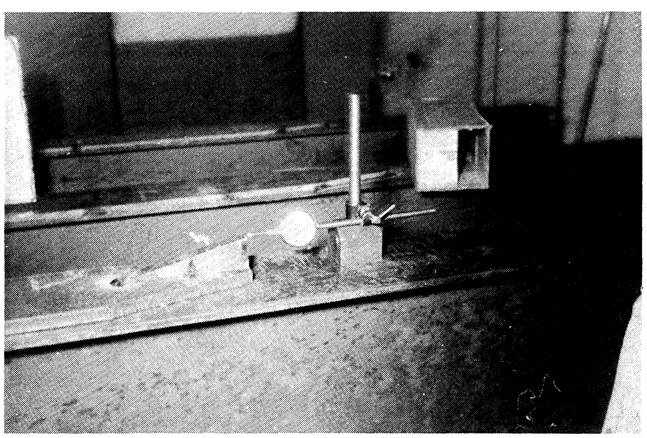


Fig. 3. Dial indicator for measuring the elongation of heated plate

It was also found that the elementary beam theory is entirely sufficient for analyzing rolled beams. Further, it was shown that the moment created by the prestressing force P can be assumed to decrease linearly from Pe (e being constant eccentricity) at the center of the span to zero at the end of the prestressing element. Such a triangular prestressing moment diagram is the smallest of all the possible diagrams and thus eliminates any chance of overestimating the effect of the prestressing force.

The stress P/A_{PL} in the prestressing plate actually is never attained. Once both ends of the plate have been welded to the beam flange and welding between the ends has begun, the cooling plate starts to flex the beam. The slow changes in the stresses of both the plate and the beam are interesting and they should be understood by the man in charge of the prestressing operation for the sake of safety of all those involved, but from the practical design standpoint, they are of no consequence. What does count is only the final stress in beam, after all welding is completed and the plate has cooled. Then the plate and beam form one integral member with greatly increased cross-sectional area and moment of inertia.

Final stress in the prestressing plate becomes:

$$f_{PL} = P\left(\frac{1}{A_{PL}} - \frac{1}{A} - \frac{ey}{I}\right)$$

With high strength, low alloy plates, f_{PL} often reaches 6 ksi.

At extreme fibers of bottom flange, the prestress is:

$$f_{bot} = P\left(-\frac{1}{A} - \frac{ey_b}{I}\right)$$

For a design to be economical, f_{bot} should be in the 3 to 5 ksi range.

At the very top of beam, the prestress is:

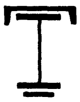
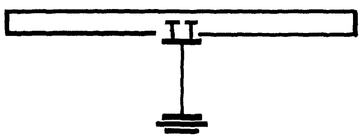
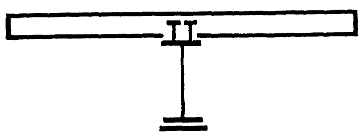
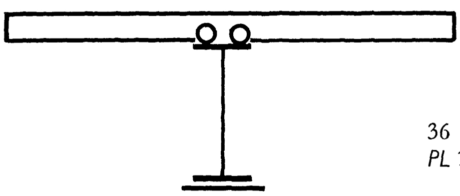
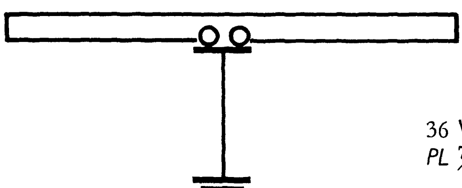
$$f_{top} = P\left(-\frac{1}{A} + \frac{ey_t}{I}\right)$$

In most cases, f_{top} is less than 1 ksi.

During and after the prestressing operation, the beam behaves somewhat like a compressed strut. The compressive force P is applied with the eccentricity e about the strong axis and with zero eccentricity with respect to the weak axis. It is possible that a small inherent eccentricity could cause lateral collapse of the beam during prestressing operation or handling. Ob-

Calculation Summary

Three pairs of equal strength beams

Section	Type of Steel	Prestress Force and *P* Elongation	Stiffness Index	Weight Index	Cost Index
 Conventional 15⊓33.9 x 35 ft 24 WF 76 x 35 ft	A36 A36	. . .	100%	100%	100%
 Prestressed, as built at Brookhaven Nat'l. Lab. 15⊓33.9 x 35 ft 18 WF 50 x 35 ft *PL* ¾ in. x 6 in. x 26 ft	A36 A36 A441	30 kips 0.045 in.	62%	87%	92%
5 in. × 7 ft-4  Conventional 21 WF 55 x 60 ft *PL* ½ in. x 10 in. x 30 ft *PL* ½ in. x 9 in. x 20 ft (or one *PL* 1 in. x 10 in. x 30 ft)	A36 A36 A36 (A36)	. . .	100%	100%	100%
5 in. × 7 ft-4  Prestressed 21 WF 55 x 60 ft *PL* ½ in. x 10 in. x 30 ft	A36 A242	50 kips 0.104 in.	78%	92%	94% (±)
6 in. × 9 ft-4  Conventional 36 WF 300 x 60 ft *PL* 1½ in. x 18 in. x 40 ft	A36 A36	. . .	100%	100%	100%
6 in. × 9 ft-4  Prestressed 36 WF 300 x 60 ft *PL* ⅞ in. x 14 in. x 40 ft	A36 A441	100 kips 0.101 in.	83%	91%	94%

viously the remedy is to avoid beams with high lateral slenderness ratios and to check the handling stresses in all suspected cases.

Various semi-empirical formulas can be derived to quickly estimate the most economical prestressing force and the size of prestressing plate. However, it is wise to first investigate the availability of plates of the particular higher strength steel decided upon.

Once the size of the plate and the required prestressing force are determined, the necessary elongation is computed from the Hooke's Law:

$$\Delta = \frac{PL_2}{A_{PL}E}$$

where L_2 is about three-fourths of the length L_1 of the prestressing plate, often one-half of the span L.

The amount of heat does not enter the picture at all, since this elongation can be read directly from a dial indicator. If this instrument is not available, it is necessary to specify the length of plate to be heated to a specific temperature. Temperatures of the heated plate can be checked within accuracies of a few degrees by temperature indicating crayons. However, this method cannot be termed as precise, and a variation of ± 20 percent should be allowed for in the created force.

The increase in temperature above room temperature required for the portion of the plate to be heated is

$$T = \frac{\Delta}{L_3\epsilon}$$

where T is the increase in temperature in degrees Fahrenheit, ϵ is the dimensionless coefficient of linear expansion (about 0.00063 per 100° F temperature rise for A441 steel), and L_3 is the length of plate to be heated. The heated length of plate L_3 preferably should be such that the needed temperature differential does not exceed 200° F; otherwise the variation in thermal expansion coefficient has to be considered. Above 400° F, the problems related to the decrease of the modulus of elasticity and strength begin to appear. Creep will be no problem at temperatures below 600° F.

Prestressing creates a camber in the beam. Within the prestressed area, its value is somewhere between:

$$\delta_2 = \frac{PeL_2^2}{12EI} \quad \text{and} \quad \delta_2 = \frac{PeL_2^2}{8EI}$$

For the full length L of the prestressed beam, the camber becomes approximately

$$\delta = \frac{2\delta_2(L - L_2)}{L_2}$$

All other steps in the beam analysis parallel ordinary design practice. These items include choice of proper welding electrodes and sizing of the welds; shear and principal stress, web crippling and lateral support investigations.

The subjects of the failure mechanism and ultimate strength of prestressed beams need more studies and experimentation. Investigations to date indicate that the quality of welds is the most important factor in affecting flexural fatigue strength of prestressed beams[3,4] As is good practice with any welded structure, and particularly with those in cyclic load service, uniformity of welds is most important. Undercutting, discontinuities and overwelding must be avoided. Likewise, the edges of the beam flange and of the prestressing plate must be smooth and free of any discontinuities.

FUTURE POTENTIALS OF THE THERMAL PRESTRESSING METHOD

Prestressed steel is, and very likely will remain, a specialty item, since a particular reason must exist for its application. Reduction of costs by a few percent should be a sufficient reason for its use if a structure is large and has hundreds of similar beams which could be redesigned for heat-prestressing in the shop.

For exceptionally large structures of composite design, it might even be feasible to use specially rolled unsymmetrical beams. The top flange could be limited to a size necessary to fasten the shear connectors and most of the steel would be concentrated at the bottom flange. With the addition of a high strength steel cover plate and prestressing force, perfectly balanced designs could be produced. Stresses in such standardized building components can be determined with the help of computers.

Beams in existing structures which need both strengthening and camber are most appropriately reworked by the thermal prestressing method.

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