PRACTICAL THERMAL PRESTRESSING

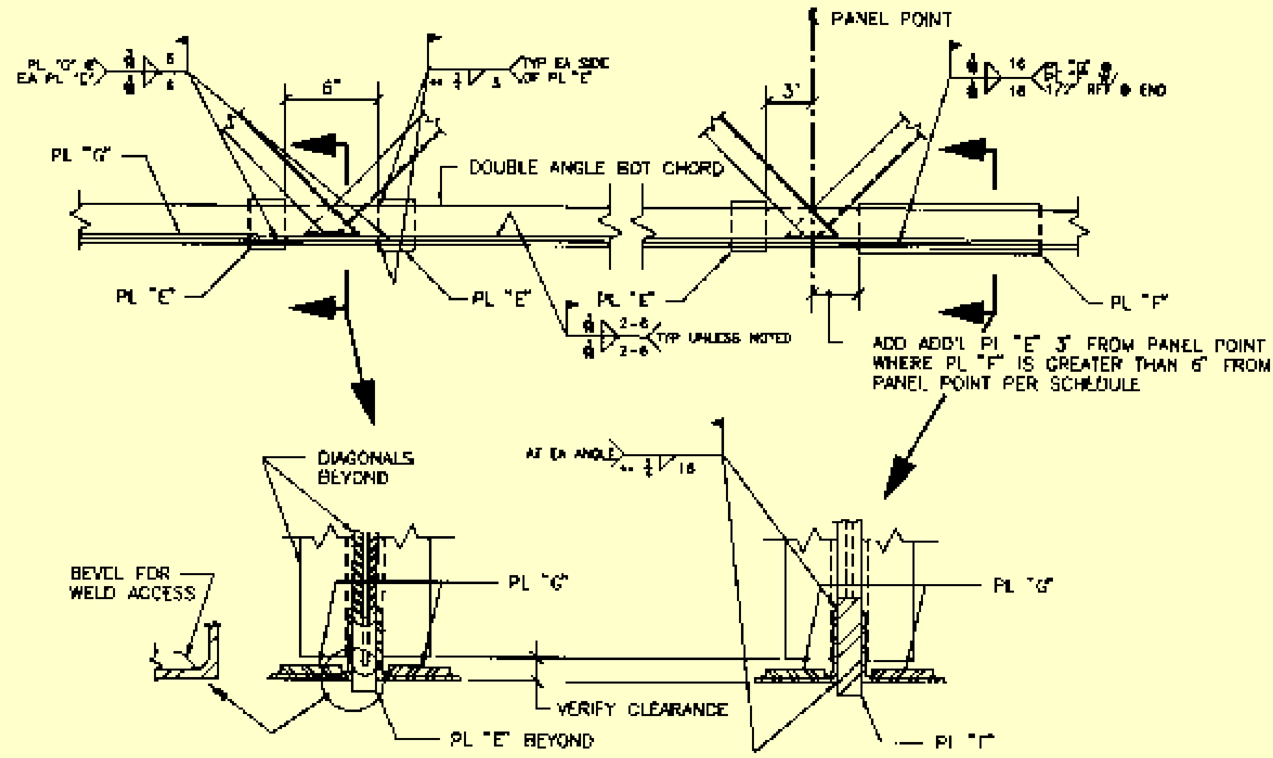
Existing joists in an industrial building were successfully reinforced in part through the use of thermal prestressing while still under load

By John M. Wathne, P.E.

INDUSTRIAL BUILDINGS ARE NEVER QUITE COMPLETE. OWNERS ARE FOREVER MOVING WALLS, expanding and reinforcing the existing structure to accommodate additional machinery or functions. Recently, our firm, Milne Associates, was retained to investigate how to reinforce an already heavily loaded roof system so it could accept an even greater load. Our analysis determined that portions of the existing long span joist system were already overstressing byas much as 20% and would experience up to 20% additional loading when the new catwalks and conveyors required by the client were put in place.

The building, which had a long span joist roof system, originally had been designed for some suspended loads and had a capacity of approximately 30% above roof dead and live snow loads. However, in many locations, this was already overtapped due to the addition of significant quantities of suspended conveyor and walkway loads . Many of the existing suspended items had been connected midway between he joists' panel points and the loadings were in many cases excessive. Because of the existing conditions, we couldn't investigate all the long span joists together as a single system; rather, we had to treat them as a individual trusses.

Adding to the complexity of the situation was the 30-ft. distance to the underside of the



Notes:
1. Preheat PL "G" as shown on joist schedule. Immediately weld ends & then weld length after PL cools. Weld all other work before PL "G"

2. **Preheat PL's "E" and "F" as required for proper welding, complete and cool before adding PL "G".

structure. Since this was one of the company's primary distribution centers, it would be prohibitively disruptive to their operations to jack the joists from the floor during reinforcement. In all but a few cases, it was imperative that the floor remain clear. As a result, we determined that it was necessary to reinforce the overloaded members—in place, while they were under load.

Unfortunately, this presented a number of problems:

- An existing overloaded member cannot be brought into an acceptable level of stress through reinforcement alone unless it is somehow relieved of at least a portion of its stress.
- Extreme care must be exercised in making connections to members under load, especially if they are overloaded. Holes cannot be drilled into these members and they cannot be indiscriminately welded as the heat of the welding operations results in local yielding of the surrounding steel.
- Attention must be given to maintaining dimensional and geometric properties of axially loaded members so as not to induce or encourage buckling modes or bending stresses. Forces need to be transferred between reinforcement and the main members along a path whose centroids follow original load paths as closely as possible, avoiding eccentricities, which result in bending stresses.

Unique Solution

To solve the problem, we developed a system of applying thermally pre-elongated and pre-shortened steel reinforcement to the loaded tension and compression chords and struts, allowing their stresses to equalize with their temperatures. We basically thermally prestressed the members and their reinforcement. The basic principle is to thermally elongate or shorten the reinforcement members to a strain equivalent to—or greater than—that which would correspond to the stress level in the existing loaded material.

This can be achieved with surprisingly low amounts of changes in heat: A temperature change of 80 degrees F corresponds to approximately 15 ksi of stress. In other words, if the existing steel has an ambient service temperature of 70 degrees F and an existing tensile stress of 15 ksi, a new member could be fastened to unyielding supports

adjacent to it at a temperature of 150 degrees F and it would develop a tensile stress of 15 ksi upon cooling to 70 degrees F. If the new member is attached to the existing member rather than to unyielding supports, the new member would shorten as much as it causes the existing member to shorten. This would reduce the stress level in both members by the same amount, leaving both at the same reduced stress level.

The amount of axial shortening increases with the ratio of reinforcement to base steel areas and results in a direct reduction in overall stress.

Theoretical Examples

Case One: A 1-sq.-in. bar is stressed to 20 ksi tension at room temperature and another 1-sq.-in. bar is thermally elongated to 20 ksi equivalent strain. These two bars are then attached at their ends and the heated bar is allowed to cool to room temperature. As the added bar reaches room temperature, the 20 ksi equivalent strain becomes 20 ksi of stress. As the resulting 20 kip load is applied to the adjacent bar (restraining it), the bar shortens, as does the attached bar. By basic mechanics, this equalizes to a 10 ksi compression stress in the original bar and a reduction of 10 ksi stress in the added bar. As a result, the original bar reduces from 20 ksi to 10 ksi tension stress and the added bar reduces from 20 ksi equivalent stress to 10 ksi real stress.

Case Two: Next, consider that a 1-sq.-in. bar that is loaded to 20 kips tension has a stress of 20 ksi. Two 1-sq.-in. bars are loaded equally with a 20 kip total load on them and both have a tensile stress of 10 ksi.

The similarity between the two cases is the basis for a simplified, rational approach to thermal prestressing.

Step 1: Determine the stress level in the existing member by dividing the axial load by the cross-sectional area.

Step 2: Select the desired stress level and determine the required total cross-sectional area by dividing the applied load by the desired stress. Subtract the existing steel area from the required steel area to get the required reinforcement steel area.

Step 3: Determine the required differential temperature by dividing the existing stress level by the modulus of elasticity and the coefficient of thermal expansion. Add this to the ambient temperature to get the thermal prestressing temperature.

Step 4: Heat or cool the reinforcement steel to the thermal prestressing temperature and instantaneously rigidly attach this to the loaded member. Stand back and let the temperatures equalize. The stresses will equalize, too.

Be sure to preheat reinforcement for tension and pre-cool for compression. The wrong application of these techniques could be disastrous, as they would conversely increase existing stress, rather than reducing them.

The Real World

The real world presents some

complications, but these can be fairly easily handled.

Temperature Loss During Attachment:

During the time that it takes to actually make the rigid attachments between the reinforcing and the base members, the temperature differential diminishes. If you preheat for 15 ksi, for example, you might have a reduced equivalent stress of 10 ksi by the time the attachments actually are made. To compensate:

1. Minimize the amount of time it takes to make attachments by having both ends attached simultaneously. Also, preheat or pre-cool within a few feet of the installation to minimize transit and adjustment times. However, do not let the pre-cooling or preheating operations affect the base member temperature.

2. Make the primary attachments first. Attach the ends and then make the stitch welds along the reinforcement length. Stress can then begin to equalize between members while the final attachments are underway.

3. Overheat or overcool for the application. This makes up for inaccuracies in the pyrometer readings and compensates for losses during handling and attachment. We went 20 degrees beyond our calculated temperatures and then watched them reduce during attachment—usually to within 5 degrees of the design at the time of transfer. Use a steel with at least 30 percent higher yield then the existing steel. While overcompensation reduces the equalized stress in the main members, it increases it in the reinforcement. We overheated or overcooled and continuously checked temperatures with a pyrometer and paced the end connection welding for completion before the design temperature differentials were reached.

4. Leave some reserve strength in the overall design to account for inaccuracies in the thermal prestressing. In this type of work, even as much as 10 to 20% additional capacity amounts to a small amount of additional material cost. Labor costs on this type of project are much higher than material costs.

End Connection Design:

Design the end connections of the reinforcement within allowable stress for at least 30% greater than the anticipated transfer loads. Consider the effects of all eccentricities on both the main members and the reinforcement. Locate the end connections where the eccentric stresses, when combined with the reinforced stress in the main member, are within acceptable limits.

Design weldments to reduce the amount of warping due to weld cooling and out-of-plane bending, and to provide as much rigidity as possible.

Consider the temporary section losses of all sequential weld lines and weld parallel to stress paths. Because of the potential magnitude of the forces being transferred, improper end connection design could cause sudden failure on the connection and the main member.

Non-Uniform Stress Levels Along Member:

Non-uniform stresses along the length of a member, such as a truss chord, actually facilitates attachment since they can be located at points of low or opposing stress. The reinforcement would be designed for the worst panel and run through the lighter loaded ones until termination. We know of no problems in over-reinforcing a less loaded panel (as long as a tension member remains a tension member, etc.).

It is important to design shear connections between reinforcing and main truss panel points so that the reinforced truss acts as a reinforced truss, rather than an overloaded truss with an axial load on it. Again, we recommend at least a 30% over design on the connections.

Bending Stresses In Member:

For members with bending stresses, two considerations can be made. First, for reinforcements without eccentricity, the total axial and bending loads can be applied to the composite section and the stresses calculated directly. Second, for reinforcements with eccentricity, the eccentric prestressing force moments must be added to the bending stresses and axial stresses to determine the final stresses.

Do not simply assume that eccentricities do not exist. Improper utilization of these principles could result in a system that self destructs.

Truss Applications

The reinforcement of truss systems by thermal prestressing uses this technique in its most basic form. The bottom chord members can be reinforced by simply pre-elongating cover plates or angles and anchoring these at their ends. End anchorages should be located within a panel where stresses from the anchorages will not cripple the chords' performance. Staggered stitch welds between anchorages are sufficient to hold the cover plates in place. Heavier welding should be added at panel points to ensure proper load transference.

Top chord members can be reinforced in a similar fashion, but reinforced members must be precompressed. We found that the most economical way of doing this was to use dry ice.

Tension diagonals can be reinforced by thermal pretensioned plates or angles, with properly adapted anchorages. Compression diagonals can be reinformced by heating the base metal and adding reinforcement cold. To avoid bucling, consider llossening diagonal bridging, which would restrain elongation of the diagonal.

Field Experience

Our first—and largest—application of thermal prestressing involved eight bottom chord reinforcements, one top chord reinforcement, 25 tension or compression diagonal reinforcements, and the addition of numerous vertical tension struts to reduce bottom chord bending between panel points.

The most stressed members were the bottom chords, where suspended loads added high bending moments for which they were never designed. Our first plan of attack was to add threaded rod tension struts from the upper panel points to reduce the bottom chord spans and moments. These were pre-tightened by turning end nuts and satisfactorily reinforced 31 joists without additional chord reinforcement.

Diagonal tension struts were reinforced by pre-heated welded angles added to each side. Compression struts were preheated and the reinforcement steel was added while cold. Midspan diagonals were conventionally reinforced as needed, since they would see a reversing level of stress and were very small in cross-sectional area and easily reinforced with smaller attachments. Bottom chords were reinforced with pre-heated plates added to the top surfaces of the chord angles flat legs. The contractor suspended a movable working platform from the truss reinforcement each day and had a welder at each end of the reinforcement. Welded stitch plates were added between chord angles at panel locations to avoid distortion by opposing prestressing forces. Pre-heating was done on the platform with a flame thrower (and a fire watch). Several laborers were on hand to lay the 20-ft.-long plates in place. I was equipped with a pyrometer and directed the preheating and welding sequence.

The plates were preheated, installed and end connections were made. Intermediate panel points were then welded. Staggered stitch welds were added along each edge of the plates after cooling.

Due to extremely high loads on particular joist, it was necessary to do compression chord reinforcement. This followed the same general procedure, but required a 25-ft. tub of dry ice to precool the plates down to less than -30 degrees F. Because of the potential danger of buckling the top chord if we encountered problems, we added one snug-fit jack beneath a strategically located middle panel point. After they were fully cooled, the plates were set in position and clamped down intermittently to avoid buckling at they returned to ambient temperature. Welding was started at the ends. We vibrated the plates during welding with hammers as they warmed to help them slide through the clamps and stress themselves uniformly. Occasionally, the plates would buckle between clamps, shaking the entire joist and the working platform. The 10 of us nervously scrambled to complete the installation before the frost disappeared.

After we finished our work on this joist and stresses had equalized, we climbed down, and—to our amazement—noticed that the joist had lifted itself more than $^{3}/_{8}$-in. off its jack. We had hoped to verify our work with strain gage measurements during the project, but both the schedule and the budget precluded this. We therefore had to take the brute force approach, with the built-in safety features we described. Ultimately, seeing the joist lift from its jacks was all the verification we needed.

John M. Wathne is chief structural engineer with Milne Associates, Inc., a multi-disciplinary engineeirng consulting firm located in Salem, MA. He also is president of Historic Salem, Inc., a 50-year old preservation society.