What You Should Know About Heat Straightening Repair of Damaged Steel

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INTRODUCTION

The repair of damaged steel through the application of heat has long been considered an art rather than a science. As such both the methodology and results have varied considerably from one practitioner to another. Because steel tends to be a forgiving material, successful repairs outnumber failures. Yet material properties may be compromised resulting in a weakened in-place structure. In addition, it is not unusual for a fracture to occur during the repair process. As a result, the use of heat straightening (or flame straightening) has had limited application. Many engineers are reluctant to allow heat straightening because of the lack of an established method of application as well as the lack of quantification of steel properties after the repair is complete. The purpose of this paper is to provide some engineering guidelines for use of the heat-straightening process.

The ideas presented in this paper are referenced to supporting research and provide the reader with a place to begin when contemplating heat straightening repair. The paper is intended to be a state-of-the-practice report, which should be used to complement sound engineering judgment, not to replace it. In addition, many of the principles discussed here also apply to heat curving to produce camber or sweep.

WHAT IS HEAT SRAIGHTENING?

Heat-straightening is a repair procedure in which a limited amount of heat is applied in specific patterns to the plastically deformed regions of damaged steel in repetitive heating and cooling cycles to produce a gradual straightening of the material. The process relies on internal and external restraints that produce thickening (or upsetting) during the heating phase and in-plane contraction during the cooling phase. Heat straightening is distinguished from other methods in that force is not used as the primary instrument of straightening. Rather, the thermal expansion/contraction is an unsymmetrical process in which each cycle leads to a gradual straightening trend. The process is characterized by the following conditions, which must be maintained:

1. The maximum heating temperature of the steel does not exceed either (a) the lower critical temperature (the lowest temperature at which permanent molecular changes may occur), or (b) the temper limit for quenched and tempered steels.
2. The stresses produced by applied external forces do not exceed the yield stress of the steel in its heated condition.
3. Only the regions in the vicinity of the plastically deformed zones are heated.

When these conditions are met, the material properties undergo relatively small changes and the performance of the steel remains essentially unchanged after heat straightening. Properly conducted, heat straightening is a safe and economical procedure for repairing damaged steel.

HOW DOES HEAT SRAIGHTENING WORK?

The basic concept of heat straightening is relatively simple and relies on two distinct properties of steel:

- If steel is stretched or compressed past yield, it does not assume its original shape when released. Rather, it remains partially elongated or shortened, depending on the direction of the originally applied force.
- If steel is heated to relatively modest temperatures (370-700°C or 700-1300°F), its yield value becomes significantly lower while at the elevated temperature.

To illustrate how steel can be permanently deformed using these two properties, consider the short steel bar in Figure 1a. First, the bar is placed in a fixture, much stronger than the bar itself, and clamped snug-tight (Figure 1b). Then the bar is heated in the shaded portion. As the bar is heated it tries to expand. However, the fixture prevents expansion in the longitudinal direction. Thus, the fixture exerts restraining forces on the bar as shown in Figure 1c. Since the bar is prevented from longitudinal expansion, it is forced to expand a greater amount laterally and transversely through its thickness than in an identical unrestrained bar. Consequently, a bulge will occur in the heated zone. Because the bulge has been heated, its yield value has been lowered, resulting in plastic deformations, which do

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not occur in the unheated portions. When the heating source is removed, the material will cool and contract three-dimensionally. The clamp cannot prevent the bar from contracting longitudinally. As cooling progresses the bar shortens and the bulge shrinks. However, a portion of the bulge is permanent even after the bar has completely cooled and the bar is shorter than its original length, Figure 2.1d. In essence a permanent redistribution of material has occurred in the heated zone leaving the bar slightly shorter with a small bulge. This permanent bulge, or thickening, in the heated zone is called "upsetting". The redistribution of material is referred to as "plastic deformation" or "plastic flow". The clamping force is often referred to as a restraining force. Through cycles of clamping, heating, and cooling, the bar could be shortened to practically any length desired.

This simple example illustrates the fundamental principles of heat straightening. However, most damage in steel members is much more complex than stretching or shortening of a bar. Consequently, different damage conditions require their own unique heating and restraining patterns.

WHY PLACE LIMITS ON HEATING TEMPERATURE AND JACKING STRESSES?

A clear distinction should be made between heat straightening and two other methods often confused with heat straightening: hot mechanical straightening and hot working. Hot mechanical straightening differs from heat straightening in that applied external force is used to straighten the damage. These applied forces produce stresses well above yield, resulting in large movements during a single heat cycle. Often the member is completely straightened by the continued application of a large force during a single cycle. The results of this type of straightening are unpredictable and little research has been conducted on this procedure. Specific concerns about hot mechanical straightening include:

1. Fracture may occur during straightening
2. Material properties may be adversely affected
3. Buckles, wrinkles or crimps may result

The Engineer should recognize that hot mechanical straightening is an unproven method, which may lead to damaged or degraded steel. As such, its use should be considered only in special cases in which other methods are not viable.

Hot working is distinguished from heat straightening in that both large external forces and high heat are used. This method is similar to hot mechanical straightening in that external forces are used. In addition, the steel is heated well above the lower critical temperature and often glows cherry red indicating a temperature above the upper critical temperature. The results of this process are highly unpredictable and may result in:

1. Fracture during straightening
2. Severe changes in molecular structure which may not be reversible
3. Severe changes in mechanical properties including a high degree of brittleness
4. Buckles, wrinkles, crimps, and other distortions

Hot working should not be used to repair damaged steel.

Some practitioners will tend to over-jack and over-heat yet claim to be heat straightening. The reader is cautioned to be aware of these distinctions when specifying heat straightening as opposed to either hot mechanical straightening or hot working.

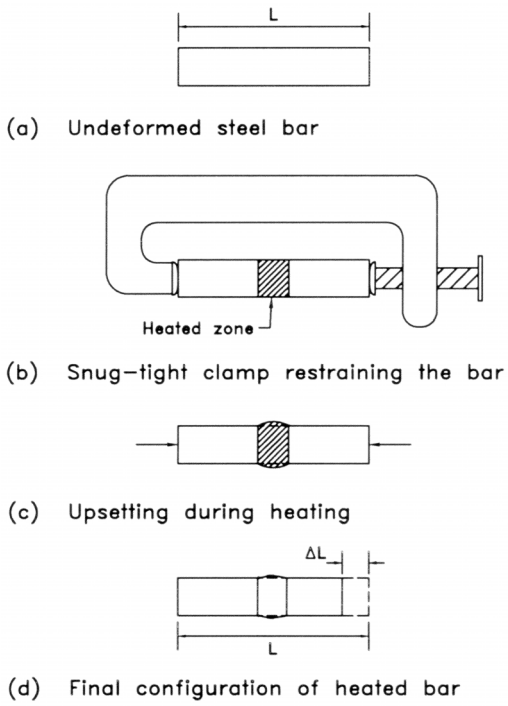


Fig. 1. Conceptual example of shortening a steel bar.

WHAT TEMPERATURE LIMITS ARE NECESSARY WHEN HEAT STRAIGHTENING?

One of the most important and yet difficult-to-control parameters of heat straightening is the temperature of the heated metal. Factors affecting the temperature include size and type of the torch orifice, intensity of the flame, speed of torch movement, and thickness and configuration of the member. Assuming that adequate control of the applied temperature is maintained, the question arises as to what temperature produces the best results in heat straightening without altering the material properties.

The large majority of steels used for construction in the United States are either carbon or low alloy steel. At ambient temperature, these steels have two major constituents:

ferrite grains and pearlite grains. Pearlite is itself composed of alternating laths of ferrite iron and cementite (Fe_3C). An iron-carbon equilibrium diagram is shown in Figure 2 illustrating the relationship between the components of steel and temperature. Solid steel is comprised of *grains*. The grains themselves are composed of iron atoms arranged on a crystal lattice. The carbon (and for that matter any other alloyed or *residual* atoms) do not molecularly bond with the iron, but rather; nest within the spaces between the iron atoms (interstitial solid solution), or displaces an iron atom from a lattice node and occupies the position itself (substitutional solid solution). Ferrite is essentially pure iron. However, by examining the iron-carbon Phase diagram (Figure 2), it can be seen that ferrite has a carbon solubility capacity up to .008 percent. Cementite is an orthorhombic crystal structure comprised of iron and carbon. Chemically, cementite contains 6.67 percent carbon dissolved in the crystal matrix (but is not molecularly bonded to the iron). The ratio of ferrite to cementite in pearlite formed under slow cooled and under equilibrium conditions from a eutectoid steel is approximately 6:1. However, under other conditions (slow cool as not to form martensite or bainite) and compositions, pearlite has been observed to contain ferrite in a 3:1 to 2:1 ratio with cementite. A low carbon steel has less than 0.8 percent carbon, too little carbon to develop a 100 percent pearlite structure, resulting in pearlite plus ferrite. This ferrite can exist as both a grain and as a constituent of pearlite. Carbon plus iron alloys with less than 0.8 percent carbon are hypoeutectic steels, commonly known as ferritic steels. These steels have a larger volume fraction of ferrite grains, body-centered crystal structure (BCC), than pearlite. High carbon steels (carbon content between 0.8 and 2.0 percent) are hypereutectic steels, commonly known as pearlite steels. These steels are predominately pearlite (orthorhombic cementite and BCC ferrite). The volume fraction of cementite and ferrite are equal at the eutectic composition

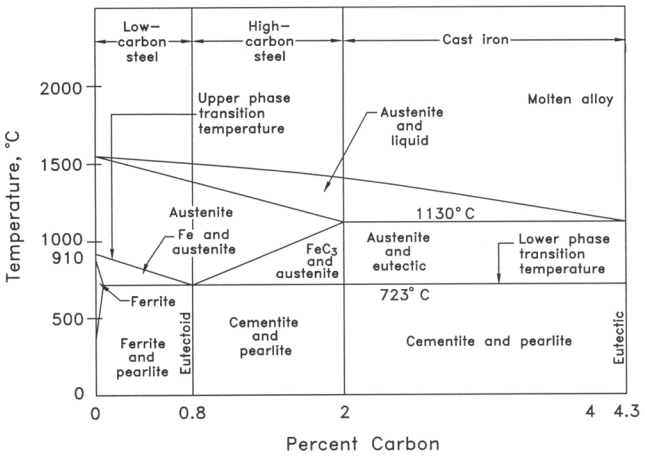


Fig. 2. Iron-carbon equilibrium diagram.

(0.8 percent carbon). The volume fraction of cementite increases with increasing carbon content of steel. Low carbon steels tend to be softer and more ductile because these are characteristics of ferrite. Cementite is hard and brittle thus high carbon steels are harder and less ductile.

Temperatures greater than 727°C (1340°F) begin to produce a phase change in steel. This temperature is often called the lower critical (or lower phase transition) temperature. The ferritic and pearlite crystal structures begin to assume a face centered cubic form (austenite). Thus, as ferrite and pearlite are heated to the austenitic range and their crystal lattices change to face-centered cubic, all contained carbon goes into solution. When steel cools below the lower critical temperature, it attempts to return to its former ferritic or pearlitic structure. Since this change requires a specified time frame, rapid cooling may not permit the complete molecular change to occur. Under these circumstances, a hard, strong and brittle phase called martensite occurs. The steel in this form may have reduced ductility and be more sensitive to brittle fracture under repeated loads.

The upper critical (or upper phase transition) temperature is the level at which the molecular change in structure is complete. At this temperature (around 815 to 925°C or 1500 to 1700°F for most steels, depending on carbon content) the steel assumes the form of a uniform solid solution called austenite. It is at temperatures between the lower and upper critical that a wide range of mill hot rolling and working can occur. As long as the temperature is lowered slowly in a controlled manner from these levels, the steel assumes its original molecular configuration and properties. This temperature control is more difficult to maintain at a fabrication shop or in the field when conducting heat straightening repairs. Consequently, if the temperature during heat straightening is not kept below the lower critical temperature, undesirable properties may be produced during cooling.

It has been shown by Avent, Fadous, and Boudreaux (1991), Avent and Mukai (1998), and Roeder (1986), that the amount of movement during heat straightening of damaged flexural members is directly proportional to heating temperature up to at least 870°C (1800°F). Permanent movement can occur with heating temperatures as low as 370°C (700°F). To avoid the possibility of detrimental changes in material properties, it is recommended that the steel temperature be kept somewhat below the lower phase transition temperature of approximately 700°C (1300°F).

The maximum temperature recommended by most researchers such as Holt (1971), Avent (1995), Roeder (1986) and Shannafelt and Horn (1984), is 650°C (1200°F) for all but quenched and tempered high-strength steels. The limiting temperature of 650°C (1200°F) allows for about 55°C (100°F) of temperature variation, which was found to

be a common range among experienced practitioners. The American Welding Society Bridge Welding Code (1996) specifies maximum heating temperatures of 590°C (1100°F) for quenched and tempered steels and 650°C (1200°F) for all others. For A514 and A709 (grades 100 and 100W), a minimum tempering temperature of 620°C (1150°F) is required. Thus, the 590°C (1100°F) limit provides a 30°C (50°F) safety factor. However, for A709 grade 70W the specified minimum tempering temperature is 590°C (1100°F). A maximum heating temperature of 565°C (1050°F) is recommended for this grade to provide a 30°C (50°F) safety factor and to avoid property changes.

To control the temperature, the speed of the torch movement and the size of the orifice must be adjusted for different thicknesses of material. However, as long as the temperature is rapidly achieved at the appropriate level, the contraction effect will be similar. Various methods can be used to monitor temperature during heating. Principal among these includes: visual observation of color of the steel; use of special temperature sensing crayons or pyrometers; and infrared electronic temperature sensing devices.

HOW SHOULD THE STEEL BE COOLED AFTER HEATING?

To obtain the maximum effect of heat straightening, the steel should be allowed to cool to approximately ambient temperature. If not, the desired temperature gradient and distribution during the succeeding heating cycle will be changed to produce a less effective pattern. It is recommended that the steel cool to at least 90°C (200°F) prior to applying the next cycle.

The method of cooling most often used is natural cooling without artificial aids. However, this approach slows the repair and increases costs. Theoretically, any artificial cooling procedure could be used as long as the maximum temperature in the steel does not exceed the lower phase transition temperature or the lowest tempering temperature since changes in crystal structure would not occur. From a practical viewpoint, it is difficult to ensure that heating temperature can be perfectly controlled. Therefore, it is recommended that the steel be allowed to cool naturally to 315°C (600°F) prior to using compressed air or water to accelerate cooling.

WHAT LIMITS SHOULD BE PLACED ON THE MAGNITUDE OF JACKING FORCES?

On several occasions, the writers have observed sudden fractures during heat straightening. These types of fractures are not uncommon. The usual explanation is that small microcracks must have occurred as a result of initial damage. Thus, during heat straightening, one of these cracks propagates. However, no experimental evidence validating this assumption has been published. The senior writer has investigated this phenomenon (Avent and Fadous, 1989). Successively higher jacking forces were used in heat straightening minor axis damage in a W24×76 beam. This beam suddenly fractured during the eighth heating cycle with the highest jacking force applied. Based on the movement per heat as well as jacking force measurements, the jacking stresses exceeded the reduced yield (but not reduced tensile strength) in the heated zones. It was concluded that over-jacking, which produced stresses that were additive to residual stresses, produced this failure. Typically, heat straightening practitioners do not use calibrated jacks but rather control the force by "feel". The number of variables makes this approach likely to produce over-stress. For example, consider a composite bridge girder. The following variables are associated with inducing stress by jacking the bottom flange: diaphragm spacing, number of diaphragms, beam length, section modulus of beam, depth-to-web thickness ratio, and section modulus of lower flange. For a given stress level, the interaction of so many variables means that the jacking force could vary over a wide range. By using the "feel" method, it is erroneously assumed that the jacking force varies little from one structure to the next. Thus, it would not be unusual to over-stress such a beam with the likely result of a fracture during heat straightening.

It is therefore recommended that stresses in the heated zone due to jacking not exceed 50 percent of the nominal yield stress at ambient temperature. Since the yield stress at 1200°F is reduced by approximately 50 percent, this criterion prevents the heated steel stress from becoming significantly larger than yield. In addition, because the entire cross-section does not reach the maximum heating temperature simultaneously, the 50 percent value includes an additional margin of safety. Thus, it is also recommended that jacks always be calibrated and the structure be analyzed to prevent over-stress.

HOW SHOULD HEAT BE APPLIED TO THE STEEL?

The primary equipment utilized for heat straightening is a heating torch. The heat source is typically an oxygen-fuel mixture. Typical fuels include acetylene, propane, and natural gas. The appropriate fuel is mixed with oxygen under pressure at the nozzle to produce a proper heating flame. Either a single or a multiple orifice tip may be used. The size and type is dictated by the fuel selected and thickness of material to be heated. A No. 8 single orifice tip is generally satisfactory for thicknesses up to 20 to 25 mm (¾ or 1 in.) with acetylene. For thinner material a smaller tip is recommended. If heavy sections are being heated, a single orifice tip may not be adequate. For such cases, either heat

from both sides or use a rosebud or multiple orifice tip. The size may vary depending on the material thickness. The determining factor is the ability to raise the through-thickness steel temperature to the specified level. Note that whether a single or multiple orifice is used, the torch should be a heating torch and not a cutting torch.

WHAT ARE THE BASIC TYPES OF HEATS?

There are several basic types of heats that are frequently used as illustrated by Avent et al. (1991), Avent and Mukai (1998), Ciesicki and Bulter (1968), and Holt (1955, 1965, 1971, 1977). For some applications only one type is required. However, in many cases a combination of these basic types is necessary. The three basic types most often used in heat straightening are described as follows.

Vee Heat

The vee heat is used to straighten strong axis bends in steel plate elements. As seen in Figure 3, a typical vee heat starts at the apex of the vee-shaped area using an oxy-fuel torch. When the desired temperature is reached (usually around 650°C or 1200°F for mild carbon steel), the torch is advanced progressively in a serpentine motion toward the base of the vee. This motion is efficient for progressively heating the vee from top to bottom. The plate will initially move upward (Figure 3a) as a result of longitudinal expansion of material above the neutral axis producing negative bending. The cool material adjacent to the heated area resists the normal thermal expansion of the steel in the longitudinal direction. As a result, the heated material will tend to expand, or upset, to a greater extent through the thickness of the plate than longitudinally, resulting in plastic flow. At the completion of the heat, the entire heated area is at a high and relatively uniform temperature. At this point the plate has moved downward (Figure 3b) due to longitudinal expansion of material below the neutral axis, producing positive bending. As the steel cools, the material contracts longitudinally to a greater degree than the expansion during heating. Thus, a net contraction occurs. Because the net upsetting is proportional to the width across the vee, the amount of upsetting increases from top to bottom of the vee. This variation produces a closure of the vee. Bending is produced in an initially straight member, or straightening occurs (if the plate is bent in the opposite direction to that of the straightening movement, Figure 3c). For many applications, it is most efficient to utilize a vee that extends over the full depth of the plate element, but partial depth vees may be applicable in certain situations. When using partial depth vees, the open end should extend to the edge of the element. The vee depth is varied by placing the apex at a partial depth location. For example, in deep plate elements the depth of the vee may result in too much cooling near the apex prior to completing the heat at the open end. A ¾ depth vee may be applicable in reducing this problem. Other examples of partial depth vees will be shown in later sections.

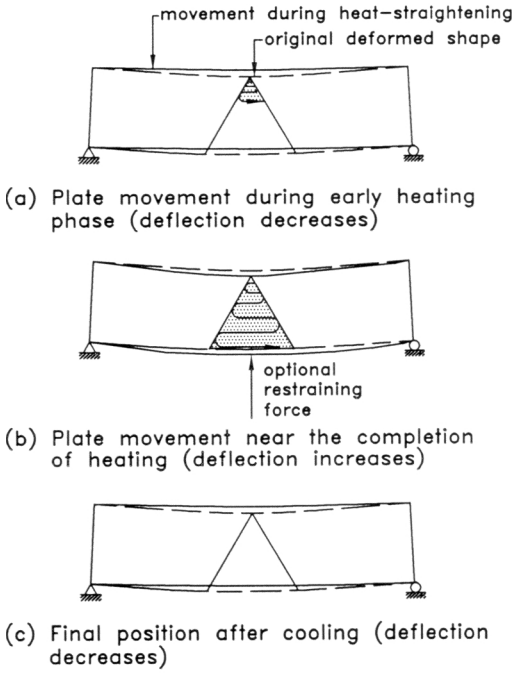


Fig. 3. Stages of movement during vee heat.

Line Heats

Line heats are employed to repair a bend in a plate about its weak axis. Such bends, severe enough to produce yielding of the material, often result in yield lines. A line heat consists of a single pass of the torch. The restraint in this case is often provided by an external force although movement will occur without external constraints. This behavior is illustrated in Figure 4. A line heat is applied to the underside of a plate element subjected to bending moments produced by external forces (Figure 4a). As the torch is applied and moved across the plate, the temperature distribution decreases through the thickness (Figure 4b). The cool material ahead of the torch constrains thermal expansion, even if bending moment constraints are not present. Because of the thermal gradient, more upsetting occurs on the torch (or hotter) side of the plate. During cooling this side consequently contracts more, creating a concave bend on the torch side of the plate similar to that shown in Figure 4d. Thus, to straighten a plate bent about its weak axis, the heat should be applied to the convex side of the damaged plate. The movement can be magnified by the use of applied forces, which produce bending moments about the yield line (Figure 4c). Referring to a section through the

plate transverse to the line heat (Figure 4c), the restraining moments tend to prevent transverse expansion below the plate centerline. In a manner similar to the vee heat mechanism, the material thus tends to expand through the thickness, or "upset". Upon cooling, the restraining moments tend to magnify transverse contraction (Figure 4d). The speed of the travel of the torch is critical as it determines the temperature attained. With proper restraints and a uniform speed of the torch, a rotation will occur about the heated line.

Strip Heats

Strip heats, also called rectangular heats, are used to complement a vee heat. Strip heats are similar to vee heats and are accomplished in a like manner. Beginning at the initiation point, the torch is moved back and forth in a serpentine fashion across a strip for a desired length, Figure 5a. This pattern sequentially brings the entire strip to the desired temperature. The orientation can be an important consideration. The strip heat may be initiated at the midpoint and moved toward both edges simultaneously using two torches. A second alternative with similar effect is shown in Figure 5b using a single torch and starting from one side. Depending on the structural configuration, the strip may also be started at a free edge as shown in Figure 5c. However, without restraints, this orientation may produce some weak axis bending. By alternating the initiation point to opposite edges in successive heating cycles, the weak axis bending can be minimized.

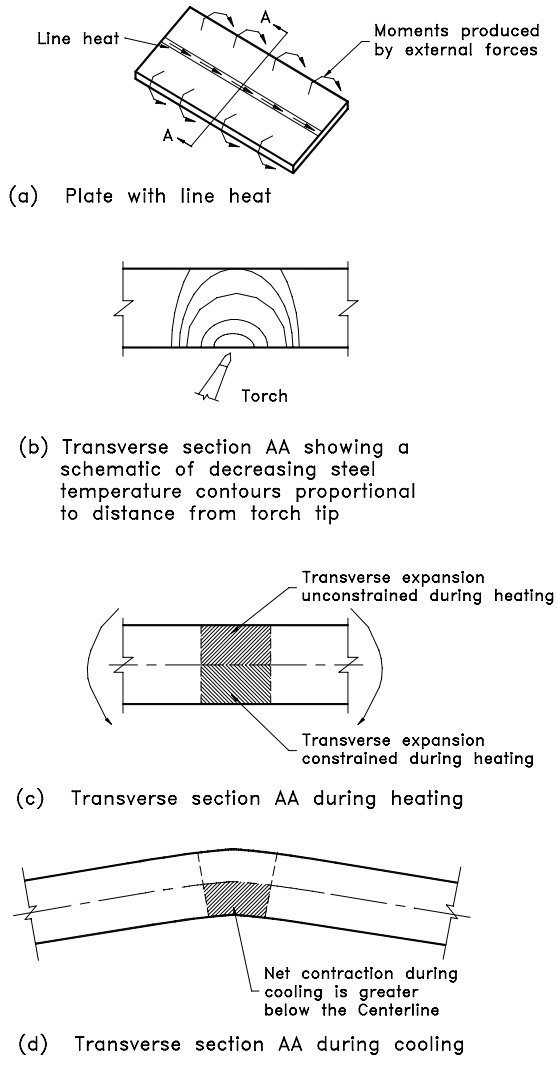


Fig. 4. Schematic of line heat mechanism.

IS THERE A RELATIONSHIP BETWEEN FUNDAMENTAL DAMAGE PATTERNS AND BASIC TYPES OF HEATS?

A convenient way to classify damage is to define four fundamental damage patterns (Avent, 1995). For each damage pattern, there is a sequence of specific heating types that will produce straightening. In most cases, actual damage to steel structures is a combination of two or more of these fundamental damage patterns. However, more complex damage can be repaired by sequentially using the heating patterns for these four fundamental damage patterns. For purposes of defining heating patterns, it is convenient to refer to the elements of a cross section as either primary or stiffening elements. The primary elements are plate elements damaged by bending about their major axes. The stiffening elements are those bent about their minor axes. Typically, vee heats are applied to primary elements while strip, line or no heat at all may be applied to stiffening elements. The combination of these heats, applied either simultaneously or consecutively, represent a single cycle of the heating pattern. Because the net change in curvature after one heating cycle is small, a number of cycles are required to straighten a damaged member. For each cycle

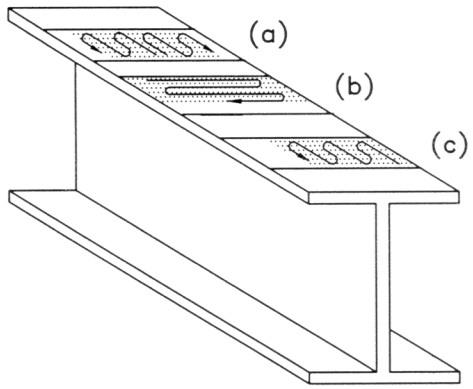


Fig. 5. Schematic of strip heat on the top flange of a wide flange beam.

the heating pattern should be shifted to a different location within the yield zone region, although the same location can be returned to after every third cycle. More heats should be placed in the region of largest curvature and fewer near extremities to reflect the difference in damage curvature. The fundamental damage categories and their heating patterns are described in the following sections.

Category S

This type refers to bending about the "strong" or major axis. The heating pattern consists of a vee and strip heat as shown in Figure 6. This pattern is superimposed on a typical yield zone for a wide flange beam bent about the strong axis. The strip heat and open end of the vee are placed on the flange damaged in tension. The vee heat is first applied to the web. Upon completion, a strip heat is applied to the flange at the open end of the vee. The width of the strip heat always equals the vee width at the point of intersection. This procedure allows the vee to close during cooling without restraint from the stiffening element. No heat is applied to the flange at the apex of the vee. This vee/strip combination is repeated by shifting over the vicinity of the yield zone until the member is straight. The pattern is shown for a wide flange and channel in Figure 6.

Category W

This category refers to damage as a result of bending about the "weak" or minor axis. For rolled or built-up shapes the web is usually at, or near, the neutral axis. Consequently, it may not deform into the inelastic range. The heating pattern for this case is similar to the previous case but note the primary and stiffening elements are reversed. The vee heat is first applied to both flanges (either simultaneously or one at a time) as shown in Figure 7. After heating these primary elements, a strip heat is applied to the web. The only exception is that no strip heat is applied to stiffening elements located adjacent to the apex of a vee heated element since this element offers little restraint to the closing of the vee during cooling. Note that the width of the strip heat is equal to the width of the vee heat at the point of intersection. For all cases the pattern is repeated by shifting over the vicinity of the yield zone until the member is straight.

Category T

This type refers to damage as a result of torsion or twisting about the longitudinal axis of a member. For rolled or built-up shapes, the flange elements tend to exhibit flexural plastic deformation in opposite directions. The web is often stressed at levels below yield. If one flange is constrained (such as the case of a composite beam), then only the unconstrained flange element is subjected to plastic deformation and yielding may also occur in the web. The heating pattern for this damage case is shown in Figure 8. The vees on the top and bottom flange are reversed to reflect the different directions of curvature of the opposite flanges. The vee heats are applied first and then the strip heat is applied. Note that for the channel, the strip heat need only be applied to half depth. This half depth strip allows the lower flange vee to close with minimal restraint from the web. If one flange is a composite connection, then that flange is not heated.

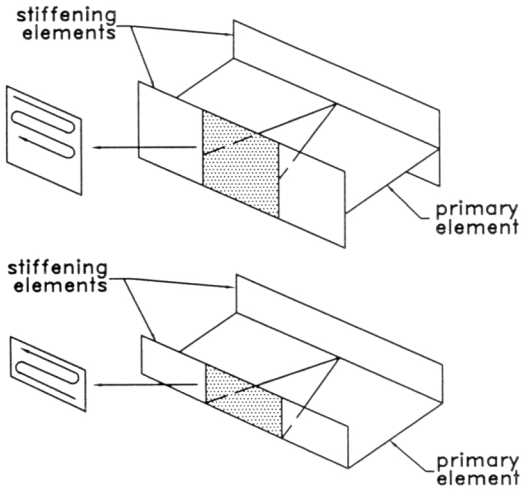


Fig. 6. Heating patterns for wide flanges and channels bent about their major axes (Category S).

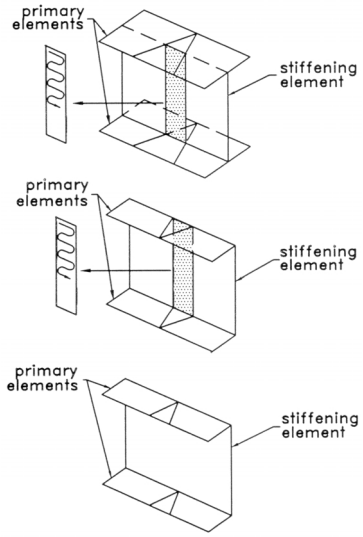


Fig. 7. Heating patterns for wide flanges and channels bent about their minor axes (Category W).

Category L

This category includes damage that is localized in nature. Local flange or web buckles, web crippling and small bends or crimps in plate elements of a cross section typify this behavior. A local buckle or bulge reflects an elongation of material. Restoration requires the bulging area to be shortened. A series of vee or line heats can be used for this purpose as shown in Figure 9. These vees are heated sequentially across the buckle or around the bulge. For web bulges either lines or vees may be used. If vees are used, they are spaced so that the open end of the vees touch. There is a tendency for practitioners to over-heat web bulges. For most cases, too much heat is counter-productive. The preferred pattern is the line heats in the spoke/wagon wheel pattern. For the flange buckle pattern (Figure 9b), either lines or a combination of lines and vees may be used. For most cases, the line pattern with few or no vees tends to be most effective. Since the flange damage tends to be unsymmetrical, more heating cycles are required on the side with the most damage. When possible, the heating should be done on the convex side.

IS THE SEQUENCING OF HEATING IMPORTANT?

When a combination of vee, strip or line heats is used, the order of heating is referred to as the sequence. The sequencing of heats may be important in some straightening operations. However, little research has been conducted to verify its effects. Some practitioners feel that proper sequencing will accelerate the straightening and help keep residual stresses to a minimum. Consider the case of an I-beam with Category S damage requiring a vee heat in the web and a strip heat in the flange as shown in Figure 6.

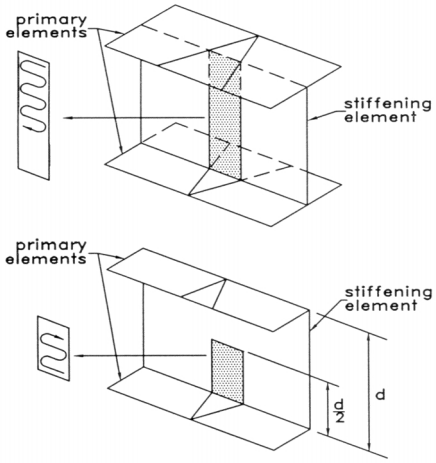


Fig. 8. Wide flanges and channels with twisting damage (Category T).

A common sequence is to heat the vee first, followed immediately by the strip. An alternative used by some practitioners is to heat the web vee first and allow it to cool for a few minutes before heating the flange strip. It is felt by some that this approach will reduce the residual stresses significantly. The available research data and different sequences used in practice indicate that more than one sequence can be successful for many cases. Since different sequences are successfully used in practice, it appears that heat straightening is not overly sensitive to the sequence used. At this time there is not adequate documentation to support one sequence over another for a particular heating pattern. The experience of the practitioner is the most reliable guide to proper sequencing. The sequencing patterns shown here are based on those often successfully used in practice.

HOW CAN THE HEATING PATTERNS FOR THE FOUR FUNDAMENTAL DAMAGE TYPES BE MODIFIED FOR MORE GENERAL DAMAGE CONDITIONS?

Since typical damage is often a combination of these fundamental damage categories, a combination of heating patterns is often required. The key is to select the combination of patterns to fit the damage. When in doubt, a good policy is to address one of the fundamental damage patterns at a time. For example, remove the Category W damage prior

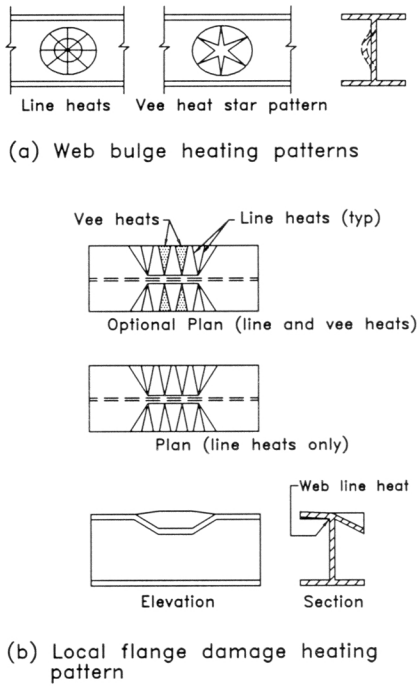


Fig. 9. Typical heating patterns for local damage.

to addressing the Category L damage. It should be noted that with proper combinations, several types of damage could be removed expeditiously. For example, suppose that a wide flange section is impacted such that the bending occurs about an axis at an arbitrary angle to the principal axes, i.e., bending occurs about both the strong and weak axis. The heating pattern, Figure 10, requires a vee heat on the web to restore the strong axis damage and vee heats on the flanges to restore the weak axis damage. The heats should be executed sequentially as numbered in Figure 10. Note that no strip heat is required on the web since a vee is used there. Restraining forces should be used to produce bending moments about both the strong and weak axis as indicated in Figure 10, tending to straighten the damage. Once the damage is corrected about one of the principal axes, the heating pattern should revert to one of the fundamental patterns until straightening is complete about the other principal axis.

As a second example, consider a wide flange beam with weak axis bending damage combined with a local bulge in one flange. The heating pattern is shown in Figure 11. Vee heats are used on the top and bottom flanges along with a web strip heat similar to the standard weak axis pattern. However, partial depth vees are used on the flange with the bulge along with a series of line heats along bulge yield lines. Since a yield line is likely to occur at the lower web fillet, a line heat is also needed on the web. Restraining forces are used to create bending moments about the weak axis as shown in Figure 11. In addition, a jacking force should be applied on the local bulge as shown on the cross section in Figure 11. The sequence of heats is also indicated in the figure.

A final example is the case of multiple plastic hinges formed about the weak axis such as might occur for a beam continuous over interior supports. The heating pattern is shown in Figure 12. Note the reversed direction of the vees to reflect the multiple curvature damage. The restraining moments must also reflect the reverse curvature nature of the damage as shown in the figure.

WHEN EVALUATING DAMAGE, HOW SHOULD IT BE QUANTIFIED?

It is important to quantify the level of damage prior to deciding if heat straightening is the best repair approach. Of particular interest is the degree to which the material has been strained past yield. A useful measure is the strain ratio, μ, which is the ratio of the maximum actual strain to the strain at initial yield. The maximum actual strain, ε_{max}, can be expressed in terms of radius of curvature, R, as

$$\varepsilon_{max} = \frac{1}{R} y_{max} \tag{1}$$

where y_{max} is the distance from the extreme fiber to the neutral axis. The yield strain, ε_y, is

$$\varepsilon_y = \frac{F_y}{E} \tag{2}$$

where F_y is the yield stress and E is the modulus of elasticity. Combining these equations, the strain ratio is

$$\mu = \frac{\varepsilon y_{max}}{R F_y} \tag{3}$$

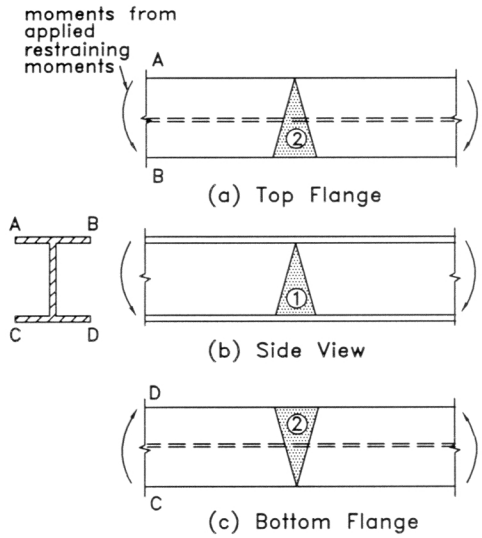


Fig. 10. Heating pattern and sequence for bending combination about both the strong and weak axis.

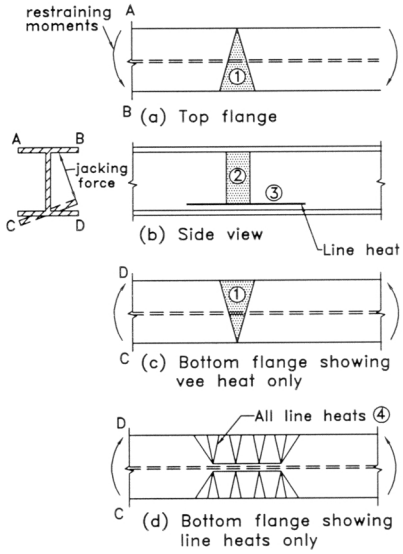


Fig. 11. Heating pattern and sequence for combination weak axis bending and local flange bulge.

If the material properties are known, the strain ratio can be computed once the radius of curvature has been determined. One convenient approach is to determine the radius of curvature by measuring the degree of damage. The degree of damage, φ_d is defined as the change in slope of an element over the yield zone as shown in Figure 13. φ_d can be computed as:

$$\varphi_d = \tan^{-1}\left(\frac{y_2 - y_1}{L_1}\right) + \tan^{-1}\left(\frac{y_3 - y_4}{L_2}\right) \quad (4)$$

where φ_d is the degree of damage or angle of permanent deformation at the plastic hinge and y_i is a measured offset as shown in Figure 13b. If C is defined as the chord length between tangents at the edges of the yield zone, then

$$\frac{1}{R} = \left(\frac{2}{C}\right)\sin\frac{\varphi_d}{2} \quad (5)$$

A more accurate approach is to take offsets within the damaged zone where curvature is the sharpest. From Figure 13a the radius of curvature, R, can be directly approximated as

$$\frac{1}{R} = \frac{y_{r-1} - 2y_r + y_{r+1}}{L^2} \quad (6)$$

Using either approach the strain ratio can be calculated from Equation 3 once R has been determined.

ARE THERE LIMITS ON THE LEVEL OF DAMAGE THAT CAN BE HEAT STRAIGHTENED?

Surprisingly little information is available on the effect of damage level (strain history). It is known that cold bending into the yield range reduces the ductility of steel in general (Brockenbrough and Johnston, 1968). However, the application of heat tends to restore the original material characteristics. Shanafelt and Horn (1984) recommended that the maximum allowable strain be limited to 15 times the yield strain and/or 5 percent nominal strain for repair of tension members. The limit approximately defines the delineation between the plastic region and the strain-hardening region. However, these recommendations were not backed by specific research data. No limits were suggested for compression members. A 5 percent nominal strain corresponds to a $\mu = 15$ for $F_y = 100$ ksi. The writers have conducted a number of tests on plates and beams in which the maximum strain ratio, μ, was 100. Each of these members was successfully heat straightened. Stress-strain curves taken from tensile coupons after heat straightening indicated that there was no significant degradation of the material. These tests indicate that the limiting strain for heat straightening repair should be equal to or greater than 100 times the yield stain. Based on anecdotal evidence even larger strains can probably be repaired. However, research has not been conducted past 100 times the yield strain.

WHAT IS THE IMPACT OF HEAT STRAIGHTENING REPAIR ON YIELD STRESS AND TENSILE STRENGTH?

Most testing for the basic mechanical properties of heat-straightened plates and beams has been conducted on undamaged material after 3 or 4 vee heats (Welding Engineer, 1959; Nicholls and Weerth, 1972; Pattee, Evans, and Monroe, 1969, 1970; Roeder, 1986; Rothman, 1973; and Rothman and Monroe, 1973). Researchers concluded from these tests that: (1) little change occurred in modulus of

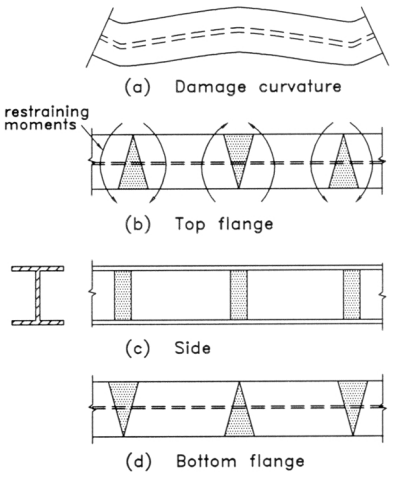


Fig. 12. Heating pattern for reverse curvature bending.

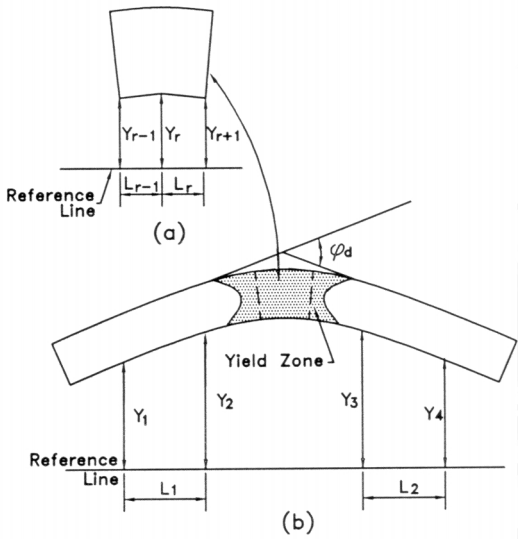


Fig. 13. Offset measurements to calculate degree of damage and radius of curvature.

elasticity, (2) slight increases were found in yield and ultimate tensile stress, and (3) 10 to 25 percent reduction in ductility was observed. Of more significance are the properties of damaged plates (or rolled shapes) after experiencing the large number of heats required to fully straighten the member. Avent, Robinson, Madan, and Shenoy (1993a), Avent and Mukai (1998) conducted tests on seven plates and four beams which were damaged to strain ratios ranging from 30 to 100 and then heat straightened. In general, it was found that the yield stress in the heated regions increased approximately 10 percent over that of the unheated member. The largest increases were found at the apex of the vee heats where yield increased by 15 to 20 percent. The maximum tensile stress values showed a smaller increase of around 4 to 6 percent. This test data indicates that heat straightening has a small but significant heat-treating effect on steel.

WHAT IS THE IMPACT OF HEAT STRAIGHTENING ON MODULUS OF ELASTICITY AND DUCTILTY?

Tests on undamaged plate specimens have suggested that heat straightening had little effect on modulus of elasticity. However, the writers' tests, Avent et al. (1993a), on actual damaged and repaired plates and beams indicated reductions on the order of 8 to 23 percent. The most significant changes occurred in ductility, which was typically reduced by one-third. While this loss of ductility is significant, all members tested still met ASTM specifications.

WHAT IS THE IMPACT OF HEAT STRAIGHTENING ON TOUGHNESS?

Various types of notch toughness and hardness tests have been conducted on heat-straightened steel by Rothman (1973), Rothman and Monroe (1973), Pattee et al. (1970) and summarized by Avent (1989). In general, little significant change was found using Charpy V-notch or Rockwell Hardness tests. Only the quenched and tempered steels showed evidence of small reductions in toughness.

ARE THERE TESTS OR ACCEPTANCE CRITERIA FOR HEAT STRAIGHTENING?

Since hardness tests may be inconclusive, there are currently no nondestructive testing procedures to determine the condition of the steel after heat straightening. Visual inspection during and after repair remains the most viable option. It is particularly important to monitor the heating temperature, as over-heating is the most likely cause of damage to the steel. Other visual signs of possible problems include pitting and blackened spots on the surface. Properly heated steel will have a silvery color after cooling.

DOES MEMBER SHORTENING OCCUR DURING HEAT STRAIGHTENING?

The subject of member shortening due to heat straightening has been mentioned in the literature but little research has been conducted. One researcher stated that using smaller vee depth ratios should result in less member shortening, given any particular damage situation, (Moberg, 1979). However, it could be argued that less shortening would occur when using full-depth vee heats, since the top fibers have been heated and are subjected to a tensile stress. In fact, the amount of shortening in a member can be quite significant, regardless of the vee depth used. If a plate is damaged about its strong axis with a midpoint loading, the top edge of the plate experiences compressive yielding (shortening) and the bottom edge of the plate experiences tensile yielding (stretching). As the plate is subjected to the heat straightening process, the top edge experiences some "restretching" in the longitudinal direction. However, these positive strains are small in comparison to the simultaneous shortening of the bottom edge of the plate. Tests indicate that shortening at around 0.10 inches occurs during the straightening of W6×9's with a degree of damage, $\varphi_d = 6°$. Tests on plates have indicated that up to one-half inch of shortening can occur for $\varphi_d = 25°$. Since member shortening may be significant it should be anticipated when conducting repairs.

HOW DOES HEAT STRAIGHTENING AFFECT FATIGUE LIFE?

Only one series of fatigue tests on flame straightened members was found in the literature (AREA, 1946). In this case three eye bars of A7 steel were heat shortened and then fatigue cycled. When compared to similar specimens, which had not been heated, the fatigue strength at both 500,000 and 1,000,000 cycles was similar. Although data is sparse, there is no indication that carbon steels will have a shortened fatigue life after heat straightening.

WHAT TYPE OF RESIDUAL STRESES OCCUR AFTER HEAT STRAIGHTENING?

Although residual stresses are often mentioned in literature on heat straightening, there has been little documented research in this area. Past research was conducted in the context of heat curving (not heat straightening), and thus is somewhat limited in its applicability to heat straightening. Some of the most notable research was conducted at the University of Washington (Roeder, 1986), where a finite element model was developed to predict the local behavior of a plate element subjected to a vee heat. Residual stresses were estimated using the model and experimental strains were also measured. An example of Roeder's results are

shown in Figure 14 where tension stresses are positive in this and other figures of residual stress distribution.

Experimental research was conducted by Brockenbrough (1970b) to back up earlier theoretical residual stress studies, (Brockenbrough, 1970a) on heat-curved plate girders subjected to line heats. These stresses, determined by the "sectioning method," were reasonably consistent with the theoretical values. Similar theoretical methods were used on vee-heated plate elements by Nicholls and Weerth (1972) and on wide flange beams by Horton (1973). However, the results were not supported by any experimental data. Avent et al. (1993a) and Avent and Mukai (1998) conducted a study on residual stresses that included both plates and rolled shapes; variations in vee angle, vee depth, and level of restraining forces; and degree of initial damage. Residual stress patterns were determined by using the sectioning method (Avent and Wells, 1982). The change in strain before and after heating was measured on small strips cut from the heated zone. The strains were converted to stresses using an E = 29,000 ksi.

Shown in Figure 15 are residual stress patterns for initially undamaged plates, which were vee heated four times. A four-inch (100mm)-gauge length centered in the heated zone was used. For the eight plates tested, relatively little difference in residual stresses were found for: vee angles between 20 to 82°, moments due to jacking forces between zero and 50 percent of member capacity, and vee depths between ¾ and full depth of the plate. The average values are shown in Figure 15 and were similar to those obtained by Roeder (1985) as shown in Figure 14.

A second series of tests were conducted on plates which had been damaged over the range of 6 to 24° corresponding to a strain ratio, μ, ranging between 30 and 100. The number of heating cycles required to straighten the plates ranged from 25 to 100. The distribution of residual stresses at the center of the heated zone was similar to Figure 15. The large number of repetitive heats tended to slightly reduce the residual stresses in comparison to those of the undamaged plates having only four heats. Overall, maximum compression residual stresses were approximately 45 percent of yield at the flange tips for either case and maximum tensile stresses varied from 20 to 30 percent of yield at the center of the plate.

The maximum residual stresses tend to be higher in rolled shapes. Typical residual stress distributions are shown in Figures 16 through 19 for typical rolled shapes with a negative sign indicating compression. For angles, high compression residual stresses (approaching yield in some cases) were found at the toes and heel as shown in Figure 16. Similarly high values were found at the heels and toes of channels (Figure 17). Note that strips were not measured at the web-flange junctures resulting in discontinuities in the graphs. For the Category W heating pattern, wide flange beams tended to have tensile stresses across most of both flanges and compression stresses in the web, as shown in Figure 18. When the beam was re-damaged and heat straightened multiple times, the residual stresses were mitigated. For Category S damaged wide flange beams, the pattern reversed with compression stresses in both flanges and tension in the web, as shown in Figure 19. Residual stresses were measured for a single W6×9 beam with Category S damage which was repaired using the standard pattern. The maximum compressive stresses in the flanges approached yield while those in the web were somewhat less. A comparison of the residual stresses for the undamaged and damaged beams showed a reasonably good correlation for Category S.

The large residual stresses created during heat straightening have several implications. First, if the member is a compression element, the high residual stresses are similar

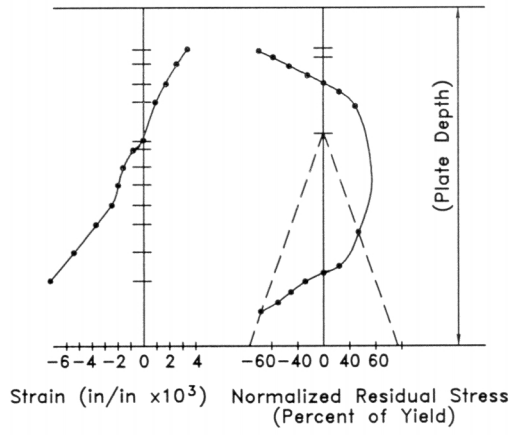


Fig. 14. Experimental strain and theoretical residual stress distribution for ⅔ depth, 45° vee heated plate subjected to 1000°F temperature (Roeder, 1985).

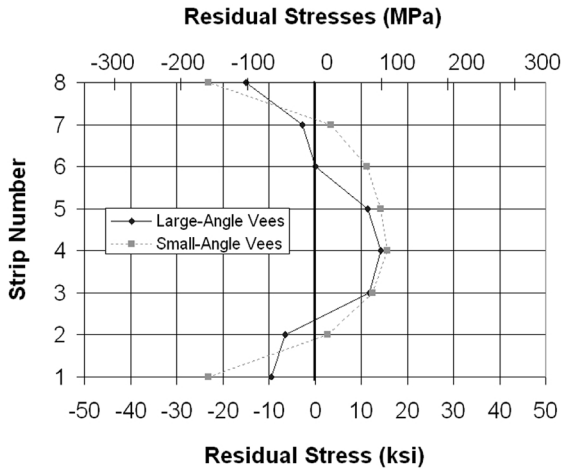


Fig. 15. Average residual stress values for vee heated plates which were originally undamaged.

to welded built-up members. Since U.S. codes use a single column curve concept, these members are all treated the same and no capacity reduction would be assumed. However, if multiple column curves are used (typical of many European countries), then heat straightened columns would fall in a lower strength curve after heating due to residual stresses. Consequently, there would be some loss of design strength.

Second, high tensile residual stresses may reduce the effectiveness of jacking forces by effectively canceling out the restraining compression associated with jacking. Movement could be reduced or even reversed, if the jacking force moment does not compensate for the residual stresses.

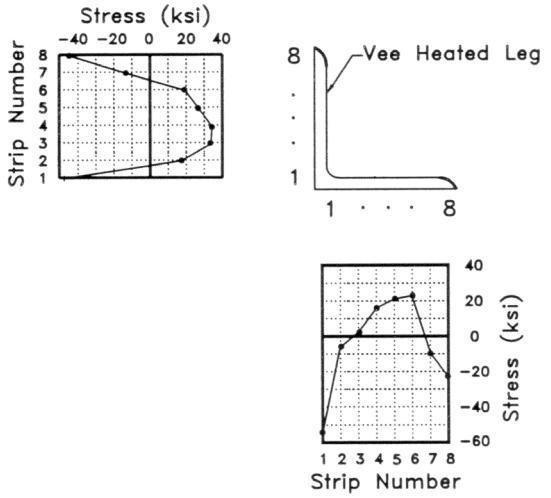


Fig. 16. Stresses in angle L4×4 (45° vee, apex at heel, M_j/M_p = 0.50, depth ratio = 1.00).

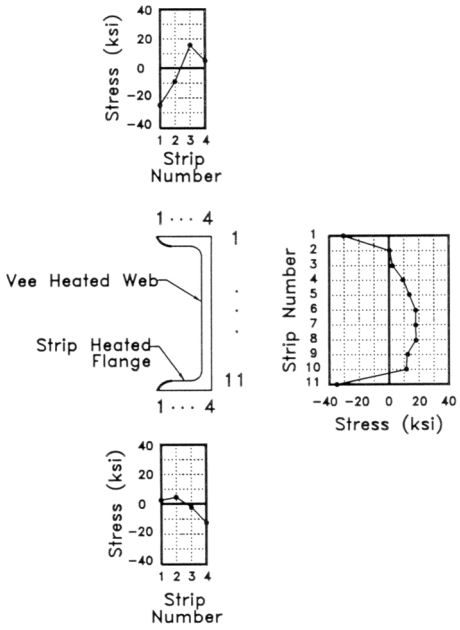


Fig. 17. Stresses in channel IX-6 (45° vee, M_j/M_p = 0.50, depth ratio = 1.00).

DOES THE DEPTH OF THE VEE INFLUENCE THE AMOUNT OF MOVEMENT DURING HEAT STRAIGHTENING?

Past researchers (Nicholls and Weerth, 1972; Roeder, 1985) have concluded that the plastic rotation (change in φ_d after one heating cycle) is proportional to the depth ratio, R_d, which is the ratio of vee depth, d_v to plate width, W. A review of Roeder's test data in the range of 650°C (±80°) or

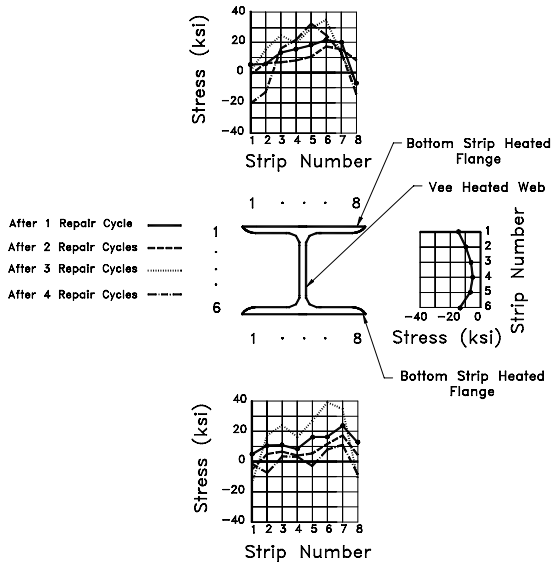


Fig. 18. Residual stress distribution damaged, Category W wide flange beams (assumed E *= 200,000 MPa or 29,000 ksi).*

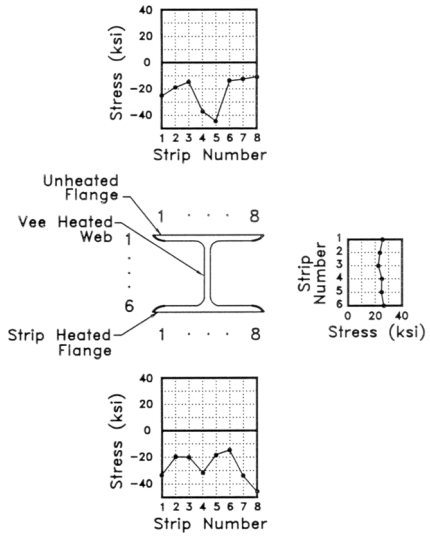


Fig. 19. Residual stresses in Category S damaged wide flange beam (45° vee, M_j/M_p = 0.50, depth ratio = 1.00).

1200°F (±150°) is inconclusive as to vee depth effect. Recognizing that the data was sparse, neither the depth ratio of 0.75 nor 0.67 produced plastic rotations that were consistently proportional to vee depth. To further evaluate this behavior, a series of tests was conducted for depth ratios of 0.5, 0.75, and 1.0 and vee angles ranging from 20° to 60°. At least three heats were conducted on initially straight plates for each case and the results averaged. The results are shown in Figure 20 for a combination of three depth ratios, three vee angles and two jacking ratios. The jacking ratios reflect that a jacking force was used to create a moment at the vee heat equal to either 25 percent or 50 percent of the ultimate bending capacity of the plate. As can be seen from Figure 20, the depth ratios of 75 percent and 100 percent track each other well. In fact the 75 percent depth ratio resulted in slightly larger plastic rotations in all but one of the six cases. The 50 percent depth ratio resulted in erratic behavior when compared to the other two. In three of the six cases the 50 percent depth ratio produced much smaller plastic rotations. In the other three cases, the plastic rotations were similar.

To further verify this behavior, a series of plates was damaged and straightened. The degree of damage was large enough that at least 20 heats were required for most of these plates. Therefore, more statistically significant average plastic rotations were obtained from these tests. Again the pattern of plastic rotations does not have a direct correlation to the vee depth ratios.

Therefore, even though it would seem intuitive that increasing the vee depth would increase the plastic rotation, there is no experimental justification for such a general statement. It can be concluded that the variation of vee depth ratio between 0.75 and 1.0 has little influence on plastic rotation. However, a vee depth ratio of 50 percent may reduce the plastic rotations.

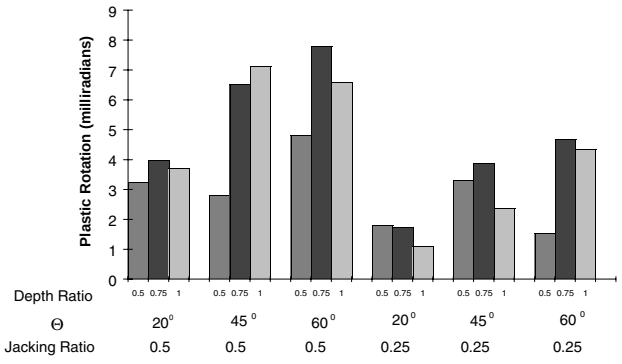


Fig. 20. Influence of vee depth on plastic rotations of originally straight plates for various vee angles and jacking ratios (heating temperature = 650°C or 1200°F).

HOW DOES THE GEOMETRY OF THE PLATE ELEMENT EFFECT HEAT STRAIGHTENING?

Researchers have generally considered plate thickness to have a negligible affect on plastic rotation. The only reservation expressed has been that the plate should be thin enough to allow a relatively uniform penetration of the heat through the thickness. The practical limiting value is on the order of 19 to 25 mm (¾ to 1 in.). Thicker plates can be heated on both sides simultaneously to ensure a uniform distribution through the thickness or a rosebud tip can be used. Similarly, researchers such as Roeder (1985) have heated plates of various widths while keeping other parameters constant. These tests showed no clear relationship between the plastic rotation and plate width.

CAN THE EFFECT OF HEATING TEMPERATURE ON DEGREE OF STRAIGHTENING BE QUANTIFIED?

One of the most important and yet difficult to control parameters of heat straightening is the through-thickness temperature of the heated metal. Factors affecting the temperature include: size of torch orifice, intensity of the flame, speed of torch movement, and thickness of the plate. In his experiments Roeder (1985) made careful temperature measurements of the heats produced by knowledgeable practitioners. He found that these individuals, when judging temperature by color, commonly misjudged by 56°C (100°F) and, in some cases, as much as 111°C (200°F). Thus, there are considerable variations in temperature control, even with knowledgeable users.

Assuming adequate control of the applied temperature is maintained, the question arises as to what temperature produces the best results in heat straightening without altering the material properties. Previous investigators have differed in answering this question. For example, Shanafelt and Horn (1984) state that heats above 650°C (1200°F) on carbon and low alloy steels will not increase plastic rotation. Rothman and Monroe (1973) concluded that reheating areas where previous spot heats were performed would not produce any useful movements. However, Roeder (1985) has shown that the resulting plastic rotation is generally proportional to the heating temperature up to at least 870°C (1600°F). To more clearly define the behavior suggested by a limited number of data points in Roeder's study, a series of heats were applied to plates in which the heating temperature was varied from 370 to 815°C (700° to 1500°F) in increments of 56°C (100°F). The results as shown in Figure 21 establish a clear and regular progression of increased plastic rotation with increasing temperature. Because increasing the temperature leads to more movement, practitioners sometimes tend to overheat. As discussed previously, it is important to limit the maximum

temperature in order to insure that the material properties remain unchanged.

HOW DOES THE LEVEL OF JACKING FORCE INFLUENCE THE DEGREE OF STRAIGHTENING PER HEAT?

While practitioners have long recognized the importance of applying jacking forces during the heat-straightening process, little research has been conducted to quantify its effect. A series of tests designed to evaluate this parameter involved applying a jacking force to a plate such that a moment is created about the strong axis in a direction tending to close the vee. This moment (at ambient temperature) is non-dimensionalized for comparison purposes by forming a ratio of the moment at the vee due to the jacking force, M_j, to the plastic moment, M_p, of the cross section, that is M_j/M_p. This term is referred to as the jacking ratio. The tests included jacking ratios ranging from zero to 50 percent with four different vee angles and the vees extending over either ¾ or full depth of the plate. The results shown in Figure 22 indicate how jacking can increase movement per cycle.

Roeder (1985) also studied the effect of the jacking ratio variation and found a similar pattern of behavior. However, the number of data points was limited. In general, the amount of movement is proportional to the jacking ratio. Experimental evidence indicates that this relationship is true for various cross sectional shapes. Several examples are shown in Figures 23 to 25. This data shows that the restraint necessary during heating can result from: jacking forces, the temperature gradient of the cool surrounding material, or a combination of both. For any combination producing the same restraint, the effect on the steel is similar. For example, in vee heated elements, advantage is taken of both material and jacking constraints. For line heats in plates (particularly thin plates), jacking dominates because thermal gradients are small.

CAN DAMAGED STEEL BE REPAIRED MORE THAN ONCE BY HEAT STRAIGHTENING?

A series of Category W damaged beams were re-damaged and straightened up to eight times, Avent, et. al., (1993a). The beams had a degree of damage of approximately 7°. While the beams were successfully straightened, material properties were noticeably affected by the fourth cycle of damage and repair. Both yield and tensile strength increased, especially in the vicinity of the apex of the vee heats. The difference between tensile strength and yield decreased with each damage-repair cycle indicating a trend toward more brittleness. Ductility also decreased significantly with successive damage-repair cycles. In another series of tests on composite girders (Avent, Madan, and Shenoy, 1993b), a crack formed along a line heat during the fourth damage-repair cycle.

Based on these results it is recommended that the same regions not be heat straightened more than twice if re-damaged. Should additional damage occur, the changes in mechanical properties as well as the possibility of cracking should be taken into account when deciding whether heat straightening is more viable than member replacement.

CAN THE AMOUNT OF STRAIGHTENING PER HEAT BE PREDICTED?

Two general approaches have been used to develop an analytical procedure for predicting member response during a heat-straightening repair. One approach involves finite element/finite strip thermal and stress analyses including

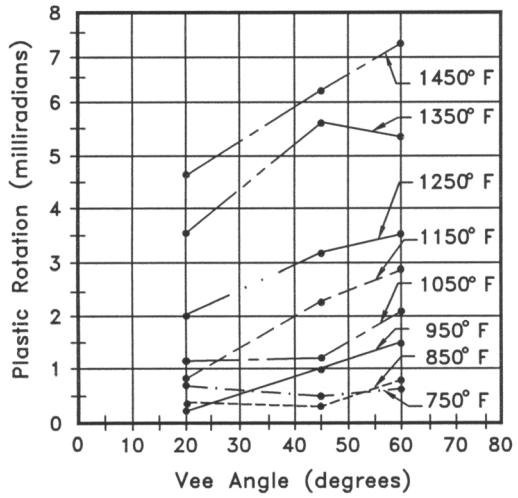


Fig. 21. Influence of heating temperature on plastic rotation for ¾ depth vee heats and a jacking ratio of 0.16.

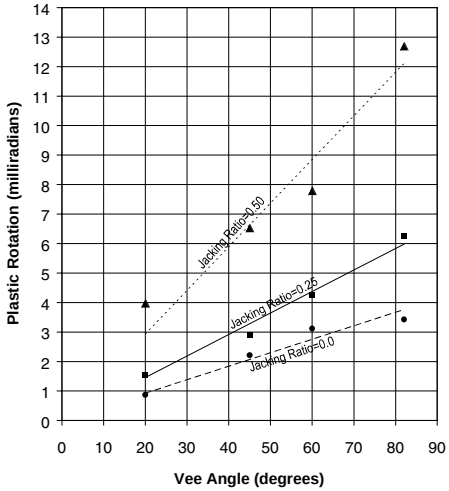


Fig. 22. Influence of jacking ratio on average plastic rotation for ¾ depth vee heats and 650°C (1200°F) heating temperatures (lines represent a least squares curve fit).

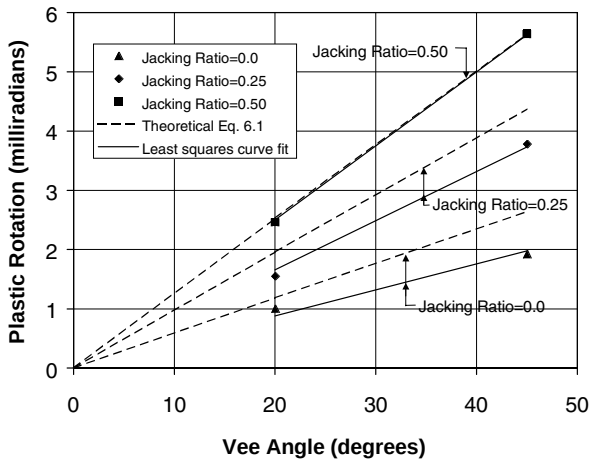


Fig. 23. Experimental and theoretical plastic rotations for a C 6x8 channel with Category S damage.

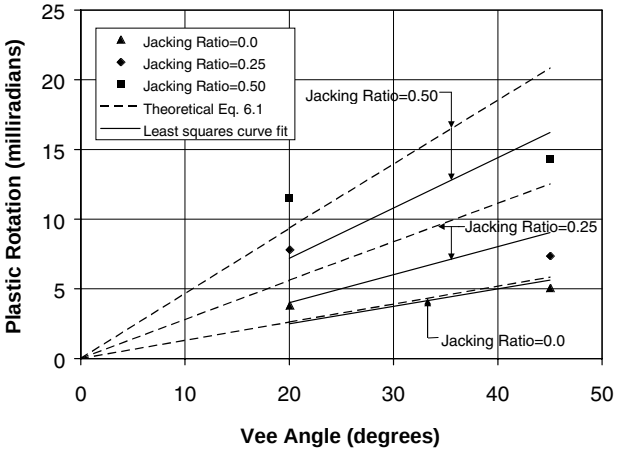


Fig. 24. Experimental and theoretical plastic rotations for Category W damage of a C 6x8.2 with the open end of vees at flange-web-juncture.

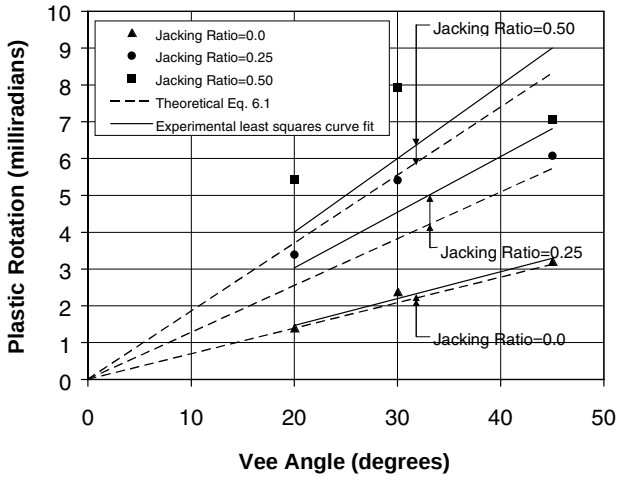


Fig. 25. Plastic rotation versus vee angle for W6x9 using the Category W heating pattern (Temperature = 650°C or 1,200°F).

inelastic behavior (Roeder, 1985). The stress and strain equilibrium is evaluated over small time steps and takes into account the influence of the non-uniform temperature distribution. This approach is a lengthy computational task, which is only possible using computer techniques and a typical analysis for a single vee heat can require extensive set up and computer time.

The other approach considers the global action of the vee. The Holt equation is based on such an approach and assumes that perfect confinement is provided at all times during the heating phase. As a result, longitudinal displacements through the vee are linear. With this equation the number of vee heats required to remove a bend in a steel member can be simply calculated. However, the Holt equation neglects the effect of restraining forces and temperature variation. A set of assumptions that are consistent with the observed behavior of vee heated flexural members include: (1) longitudinal plastic strain occurs only in the middle two-thirds of the vee heat zone (and in a reflected vee about the apex for partial depth vees); (2) at any specified distance from the neutral axis of the plate, the strains are constant in the longitudinal direction over the middle two-thirds of the vee; (3) the planes defined by the sides of the vee remain plane after heating and rotate about the apex of the vee; (4) the plastic rotation per heat varies linearly with the jacking ratio, M_j/M_p; (5) the degree of internal confinement (excluding any jacking force) equals 60 percent of perfect confinement; (6) the maximum heating temperature averages 1200°F (650°C); (7) the plastic rotation per vee heat varies linearly with the ratio of the product of the stiffening element width, b_s, and its distance from the apex of the vee, d_s, to the square of the vee depth, d; and (8) the movement per vee heat is a linear function of the ratio of plastic to elastic section modulus, Z/S, about the axis of bending. Using these assumptions, an expression for the plastic rotation, φ, per vee heat for Category S or W damaged wide flange beams or channels or angles bent about their x or y axis is given by

$$\varphi_p = F_\ell F_s F_a \varphi_b \tag{7}$$

where F_ℓ, the factor associated with the external jacking force is given by

$$F_\ell = 0.6 + 2\frac{M_j}{M_p} \tag{8}$$

F_s, a factor reflecting the shape of the cross section, is given by

$$F_s = 1 + \frac{1}{2}\left(\frac{b_s d_s}{d^2}\right) \tag{9}$$

F_a, a stress factor, is given by

$$F_a = 1 - 2\left[1 - \left(\frac{2}{3}\right)\left(\frac{Z}{S}\right)\right]\frac{M_j}{M_p} \tag{10}$$

and φ_b is the basic plastic rotation factor for a rectangular plate having no external jacking force and is given by

$$\varphi_b = 0.0147 \sin \frac{\theta}{3} \quad (11)$$

HOW DO AXIALLY LOADED COMPRESSION MEMBERS RESPOND TO HEAT STRAIGHTENING?

For columns and axially loaded members it is important to consider the *P*-Δ effect. If an axially compressed member is damaged by lateral loads as shown in Figure 26, a moment is generated which is equal to *P*Δ. This moment is in the opposite direction to the moment generated by a jacking force during the straightening process. The moment due to the *P*Δ will oppose the restoration movement during heat straightening.

A series of full-scale tests were conducted on both Category W and S damaged axially loaded columns (Avent and Mukai, 1998). Seven straightening procedures were conducted with at least 10 heats used for each set of parameters. The axial load imposed during the straightening process was typically 35 percent of the design allowable value. The jacking force was modified to cancel the *P*Δ moment effect in addition to providing the specified jacking ratio. The response for both cases was significantly less than that predicted for a wide flange beam without axial load. From these tests it is concluded that heat straightening is effective for axially loaded members using the same heating patterns as for cases without axial loads. However, the movement per heat will be somewhat smaller than if no axial loads are present.

WHAT HEATING PATTERN SHOULD BE USED FOR LATERAL IMPACT OF THE LOWER FLANGE OF A COMPOSITE GIRDER?

Perhaps the most typical type of damage found on steel bridge members results from impact of vehicles or freight on the beams or girders of composite deck-girder bridges. Heat straightening is an attractive repair alternative because of its low cost and minimal disruption of traffic (Avent and Brakke, 1996). Typical damage includes: (1) a flexural yield zone at the impact point in the lower flange due to bending about the strong axis of the flange; (2) a yield line or yield zone in the web due to bending of the web element about its weak axis; (3) reverse curvature flexural yield zones in the lower flange at diaphragms on either side of the impact point; and (4) localized bulges in the lower flange and web. Conceptually, vee heats are used to repair plate elements with plastic bending about the major axis, while line heats are applied to repair plate elements with flexural damage about the minor axis. Hence, a vee heat on the bottom flange in conjunction with a line heat on the web, applied to their respective plastically yielded portions, are the proper heat patterns to repair composite beams impacted by high loads (Figure 27). Care must be taken to continually adjust the span of the line heats, so that only those portions of the web are heated that show plastic curvature after the last heating cycle. Similarly, the vee heats are confined to the portion of the bottom flange with plastic deformations. In addition, a half-depth web strip heat is applied. The purpose of this heat is to reduce the differential shortening between web and flange. By heating the web with a half-depth strip, the web can deform and relieve some of these stresses. The application of strip heats on the web do not influence the average plastic rotations appreciably but, does tend to reduce the buckling of the web near the center of damage.

HOW CAN THE LIMIT FOR SAFE JACKING FORCES BE DETERMINED FOR DAMAGED COMPOSITE BEAMS?

When a jacking force is applied to the lower flange of a composite beam, the internal redundancy makes it difficult to calculate the stress in the lower flange. Such difficulties may occur on other types of indeterminate structures as

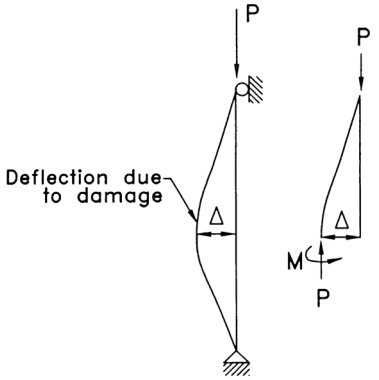


Fig. 26. PΔ effect on an axially loaded column.

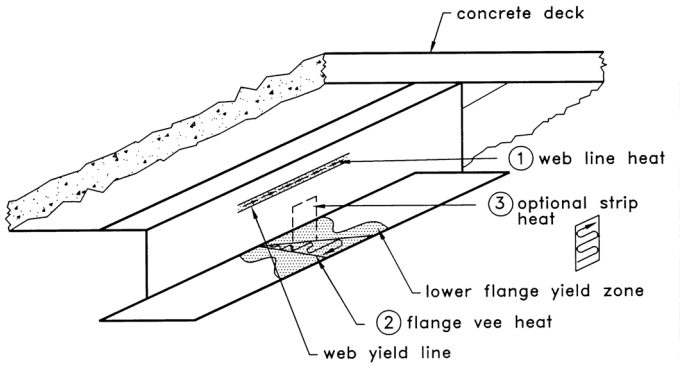


Fig. 27. Heating patterns for composite girder.

well. The question is: how much of the jacking force is translated into lower flange moment and how much is transferred through the web and into the deck? When applying a lateral load to the bottom flange near the center of the composite girder, the moment produced is transferred to the end reactions by two mechanisms: the bottom flange acts as a flexural beam supported at the ends, and the web acts as a flexural plate (and, at large deformations, a membrane plate) supported by the deck and end diaphragms. As demonstrated by Avent and Fadous (1989), a shallower girder has greater stiffness and thus lower flange moments than that of the deeper girder subjected to the same lateral load. By adopting a jacking ratio definition which assumes that all of the applied force is transferred into a lower flange moment, M_j, which is resisted only by the plastic moment of the bottom flange, M_p, the implication is that most of the lateral stiffness is provided by the bottom flange. This apparent jacking ratio can be misleading (Avent et al., 1993b). It is more relevant to use an effective jacking ratio, M_f, which reflects the actual moment in the flange to its plastic capacity, M_p. This relationship has been developed as a function of the ratio of beam depth, d, to web thickness t_w in the form

$$M_f = \gamma\ M_j \tag{12}$$

where

$$\gamma = \frac{d/t_w}{10{,}000}(15 + 2.75\, d/t_w) \tag{13}$$

Based on sudden fractures that have occurred at higher jacking ratios, it is recommended that the jacking ratio M_f/M_p be limited to one-third.

CAN THE MOVEMENT PER HEAT OF COMPOSITE BEAMS BE PREDICTED?

An equation for plastic rotation has been developed by Avent and Mukai (1998) in the form of that for rolled shapes, Equation 7, where φ_b is defined by Equation 11, $F_s = 1.0$, γ by Equation 13, and

$$F_a = \left(\frac{d/t_w}{46}\right)^2 \tag{14}$$

and

$$F_\ell = \left(0.6 + 2\frac{M_f}{M_p}\right) \tag{15}$$

or

$$F_\ell = 0.6 + 2\gamma\frac{M_j}{M_p} \tag{16}$$

HOW CAN LOCALIZED DAMAGE BE QUANTIFIED?

The focus of past heat straightening research has been on various aspects of repairing global damage. However, it is a rare situation when localized damage doesn't occur concurrently with global damage. Yet, little published information has been available on how to repair local damage by heat straightening. As a result, localized damage is often repaired improperly by cold mechanical straightening and hot mechanical straightening, as well as heat straightening.

Local damage patterns display two main characteristics: large plastic strains (usually tensile) in the damaged zone, and bending of plate elements about their weak axis. If the local damage is to be repaired, shortening must be induced in the damaged area equal to the elongation caused when the element was damaged. In addition, the distortion along the yield lines must be removed as part of the repair process. Studies on global damage repair have shown that vee heated regions shorten significantly during cooling and that line heats can be used to induce bending about the yield lines. Thus a combination of line and vee heats can be used to repair localized damage. It is helpful to separate localized damage into two distinct categories: Category L/S denoting bulges in plate elements with stiffening elements on two sides (such as a web), and Category L/U denoting bulges in plate elements having one unstiffened edge (such as a flange). Examples are shown in Figure 28.

HOW SHOULD LOCALIZED DAMAGE TO UNSTIFFENED ELEMENTS BE HEAT STRAIGHTENED?

While every damaged unstiffened plate element will have its own unique shape, there is a set of common characteristics, which can be used to determine the heating pattern.

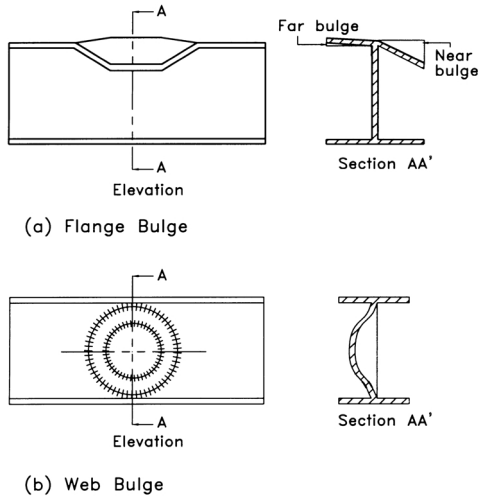


Fig. 28. Typical localized damage classified as Category L.

Category L/U damage is commonly caused by impact to a flange on one side of the web. An idealized zone of damage is shown in Figure 29. The impacted side of the damaged flange will be referred to as the near side (N). The non-impacted side of the flange on the other side of the web will also typically incur damage. This damage on the far side of the flange (F) has geometry similar to that of type N but usually of lower magnitude. The damaged flange typically undergoes rotation about a clearly defined yield-line near the fillet of the web. The impacted side of the flange (side N) usually deforms in a folded plate pattern. This flange is shown deforming toward the web in Figure 29b. The deformation usually results in yield lines, which define the edges of the folded plate (Figure 29c). In some cases, particularly in regions of high curvature, the deformation pattern may be one of a flexural yield zone rather than a series of yield lines. These zones result from plate element flexure and tend to spread over the surface as the degree of damage increases. Such zones will be referred to here as yield surfaces. The other half of the same flange usually deforms in a similar pattern in the opposite direction, even if not directly impacted. The folded plate pattern, Figure 29d, tends to have smaller deformations, thus $\delta_n > \delta_f$. Because the web is thinner than the flange, a yield line often forms in the web near the fillet. The section shown in Figure 29b illustrates this behavior. The tee section at the flange/web juncture remains a rigid right angle. The yield line forming in the web fillet allows this tee to rotate through an angle θ_w. The yield line at the flange fillet on the impacted side of the flange (side N) results from the additional rotation, θ_n, thus the total rotation of the N flange is $\theta_w + \theta_n$. The other half of the flange (side F) tends to act as a reaction against rotation thus a second flange yield line may form at the F side fillet. The angle formed by this yield line is θ_f and the rotation of the F flange is $\theta_w - \theta_f$. The identification of these yield lines is important in the repair procedure.

The heating/jacking pattern to straighten this damage will depend on how the geometry changes as heat straightening progresses. It is usually most effective to have jacking forces on both the near and far sides of the flange. However, straightening can be conducted with jacking only on the near (impacted) side. The specific steps are:

1. Restraining forces

Place jacking forces on both the near and far sides of the damaged flange in the direction tending to restore the flange to its original condition. As shown in Figure 30a, a convenient arrangement on the near side is to place a jack, P_n, between the top and bottom flange. The far side jack, P_f, requires a clamping type force which is often more difficult to arrange in field applications. If the clamping force cannot be anchored from the opposite flange, a spreader beam arrangement can be used, as shown in Figure 30d, to anchor the reaction to the straight portions of the far side flange. An alternative is to only jack from the near side.

However, the average movement per cycle tends to be lower than similar cases jacked on both sides. Care should be taken to limit the magnitude of jacking forces used.

2. Vee heats

Although vee heats may not be necessary, a limited num-

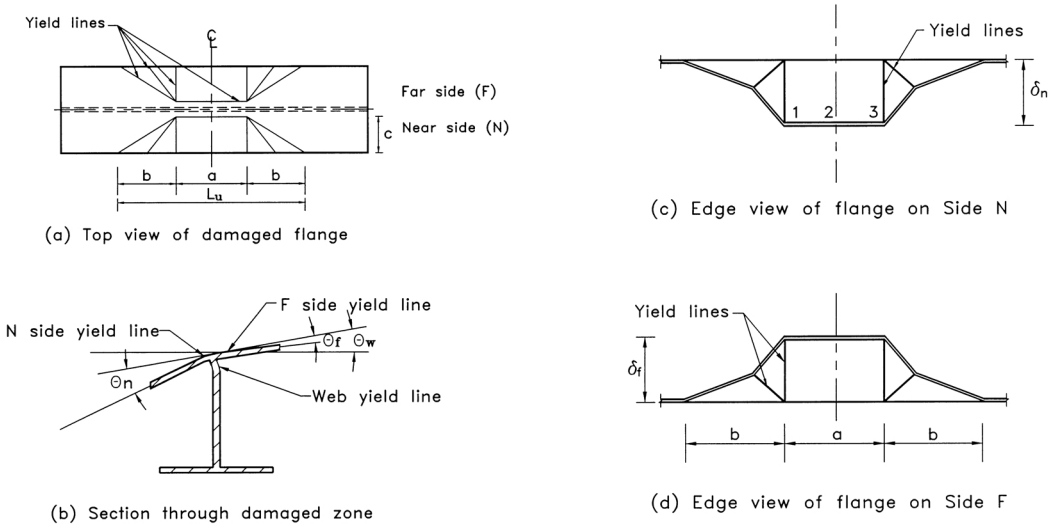


Fig. 29. Heat straightening local flange damage (Category L/U).

ber may be used to assist in the flange shortening effort. The vees should be approximately half depth and applied to both the near and far sides of the flange to eliminate global curving of the member. The vee should be narrow with an angle of 20° or less and the open end of the vees should be at the flange tips. It is best to place the vee heats in regions where no line heats are required. No more than two vees should be used (preferably only one) in one heating cycle. The location should be shifted with each heating cycle so the same location is not re-heated for at least three cycles. A typical arrangement is shown in Figure 31b.

3. Line heats

A pattern of line heats should be placed so that the line heats correspond to yield lines. These should be heated on the convex surface if possible. A typical pattern is shown in Figure 31a. For yield surfaces of continuous plastic strain, such as often occurs in regions such as ABC in Figure 31a, line heats should be spaced over the section at a spacing of approximately $b_f/4$ where b_f is the flange width. Similarly, line heats may also be used instead of vee heats on section BCDE. The order of heating the yield lines tends to have a minor impact although it is good practice to heat the ones at the largest damage locations first. It is also recommended to heat the near side lines prior to the far side.

4. Web line heat

The web yield line should be heated last. It is typically located at the fillet as shown in Figure 31c.

These four steps complete the cycle. The cycle should be repeated until the flange is straight.

Quite often this procedure can be used to nearly straighten the section. However, the progress of the movement should be observed to insure that over-straightening does not take place. If the near flange movement progresses too quickly, then θ_n may become zero prior to θ_w. This situation is shown in Figure 30b. Should this behavior occur, a modification should be made in Step 3 for line heats. Rather than heating all lines on the near side (31a), line 4 should not be heated.

If straightening progresses to the point that $\theta_f = \theta_w$, then the far flange may over-straighten with the continuation of heating. The pattern should be changed. The situation is depicted in Figure 30c. The modification is to reverse the direction of the far side jacking force while continuing the pattern. The force P_f will prevent over-

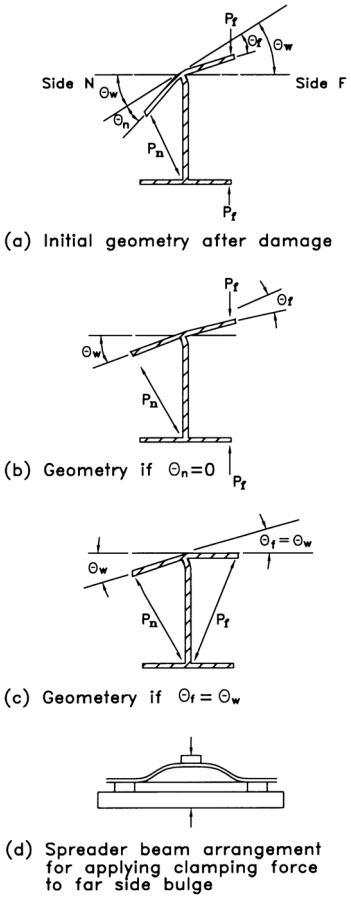


Fig. 30. Arrangement of restraining forces during various stages of repair.

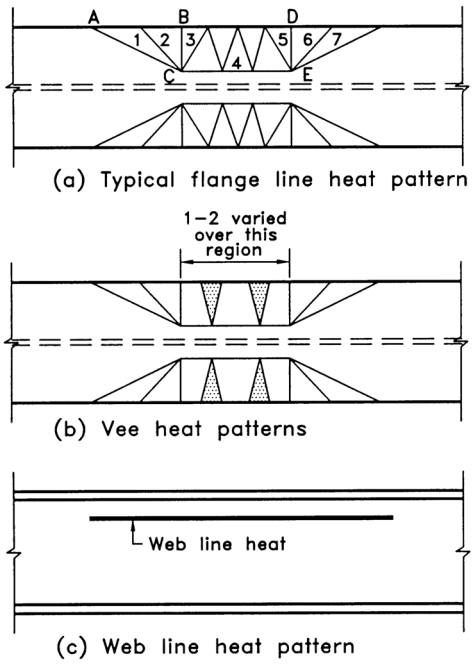


Fig. 31. Arrangement of vee and line heats.

straightening while allowing the near flange and web to continue corrective movement. Judgement is required in selecting the number of line heats to fit the specific damage. As straightening progresses, the number of lines may be adjusted to fit the changing shape of the damage.

HOW SHOULD LOCALIZED DAMAGE TO STIFFENED ELEMENTS BE HEAT STRAIGHTENED?

Stiffened elements of a beam are defined as those supported on both sides by perpendicular elements. The web of a wide flange beam is a typical example in that the two flanges provide the support or stiffening effect. When stiffened elements are damaged, the pattern formed is usually a dish shaped bulge. This damage frequently approximates a shallow spherical shell.

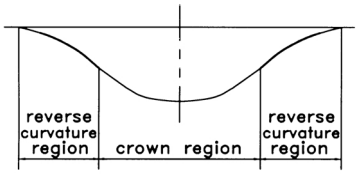
Judgement is required when selecting the heating patterns for damaged stiffened elements. Heating the regions of sharpest curvature with combinations of lines and/or narrow vees is the most effective approach. Always follow the practice of heating only in the vicinity of regions with plastic curvature. As straightening progresses, this region may become smaller. The following methodology is recommended for bulges in stiffened elements. The jacking force is typically applied at the crown of the bulge using a spreader plate.

1. Initial Heating Pattern

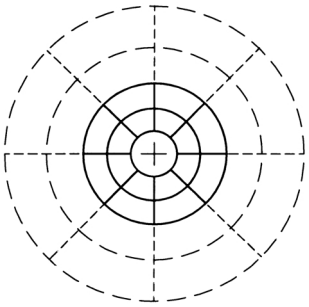
The typical bulge will have reverse curvature bending as shown in Figure 32. The crown region should be heated first with the torch on the convex side. As movement progresses, the heating patterns can be expanded into the reverse curvature region again with the torch on the convex side. The initial heating patterns should consist of radial and ring line heats as illustrated in Figure 32. The exact number of ring heats will depend on the size of this region. It is recommended that the diameter of the smallest ring be no less 51 mm (2 in.) and that spacing between rings be at least 51 mm (2 in.). For large bulges the ring spacing should be larger than 51 mm (2 in.). For cases where the curvature is relatively uniform, equally spaced rings may be used. However, a ring heat should be placed at locations where sharp changes in curvature are indicated. Heat the outer ring on the convex side first and work inward. After the rings are heated, the radial lines should be heated. Again, work from the outside in but do not run the radial lines inside the last ring. Continue this pattern cyclically until the crown region begins to flatten. Allow the steel to completely cool between heating cycles.

2. Final Heating Pattern

As the crown section flattens, the heating pattern should be expanded into the reverse curvature regions. One alternative is to expand the number of ring heats and extend the radial heats as described in Step 1 and shown by dashed lines in Figure 32b. The second alternative is to use four-point star vee heats along with ring heats instead of radials. The star vee pattern is shown in Figure 33. The vees are heated first, working from tip to center. However, the central portion past where adjacent



(a) Reverse curvature regions of a bulge



(b) Ring and line heating patterns

Fig. 32. Curvature and line heating patterns for category L/S damage.

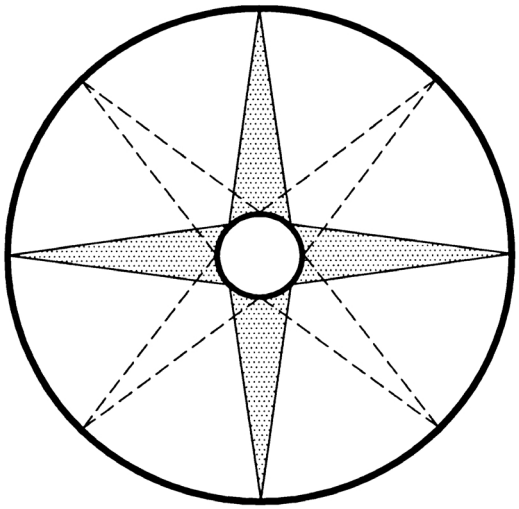


Fig. 33. Star vee heat pattern.

Table 1. Recommended Tolerances for Heat Straightening Repair		
Member Type	Recommended Minimum Tolerance[1,2]	
	English (in.)	SI (mm)
Beams, Truss Members, or Columns: overall sections including impact point	 ½ in over 20 ft ¾ in over 20 ft	 13 mm over 6 m 19 mm over 6 m
Local Web Deviations	*d*/100 but not less than ¼ in.	*d*/100 but not less than 6 mm
Local Flange Deviations	*b*/100 but not less than ¼ in.	*b*/100 but not less than 6 mm
[1]Units of member depth, *d*, and flange width, *b*, are inches and millimeters, respectively, for English and SI units [2]Tolerances for curved or cambered members should account for the original shape of the member		

vees intersect should not be heated. Vees should be narrow with an angle of 20° or less. After star vee heating, the rings should be heated, starting with the outermost ring. A maximum of three ring heats should be used at one time with the star vees. Rotate the star vee pattern 30° after each cycle so that the same vees are not repetitively heated. Rings may be repetitively heated or shifted, depending on the degree of plastic curvature. The steel should completely cool before the next heating cycle begins.

WHAT TYPE OF TOLERANCES SHOULD BE USED IN HEAT STRAIGHTENING?

In most cases any desired tolerance level can be obtained by heat straightening. One approach to specifying the tolerance for heat straightening repair is to use a standard specification for manufacturing or fabrication. One commonly referenced standard is the American Welding Society Bridge Welding Code (1996 or latest edition). Member dimensional tolerances are given in Section 3.5 and flat plate tolerances are given in Section 9.19. The use of this or similar construction standards for heat straightening tolerances may be too limiting for the following reasons: (1) The tighter the tolerances, the longer the repair will take. Costs and delays in using the structure will thus increase. (2) In many cases, the area of damage is small and not necessarily located at the most highly stressed region. Less restrictive tolerances can safely be used in such instances since the engineer can assess the specific structural configuration. (3) The steel in the vicinity of impact may have material distortions, such as changes in thickness, which may preclude highly restrictive tolerances. As a consequence, engineering judgement for the specific situation is recommended as the most effective approach in setting tolerances.

In order to provide some general guidelines, a set of recommended tolerances is given in Table 1. These tolerance levels are less restrictive than specified in the Bridge Welding Code.

SUMMARY AND CONCLUSIONS

The goal of this paper has been to summarize the state-of-the-art in heat straightening repair of damaged steel. The format used was to list the commonly asked questions and to provide the answers based on the latest research and development. The principles discussed here can also be applied to heat curving members to produce camber, sweep or curved beams. Heat straightening is a safe and economical repair procedure when properly executed. It is a skill requiring practice and experience. The proper placement and sequencing of heats combined with control of the heating temperature and jacking forces distinguishes the expert practitioner. In the past, heat straightening has been more art than science. With the information presented here, the practicing engineer will have guidelines quantifying the most suitable procedures.

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