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16. Abstract

The purpose of this document is to provide comprehensive guidelines on heat straightening repair techniques for damaged steel bridge members.

This Guide is a condensed and updated version of previous FHWA Report, FHWA-IF-99-004, "Heat-straightening Repairs of Damaged Steel Bridges, A Manual of Practice and Technical Guide", is proposed to become an AASHTO Guide, and is also listed as a standalone Manual in FHWA website

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GUIDE FOR HEAT-STRAIGHTENING OF DAMAGED STEEL BRIDGE MEMBERS

1. INTRODUCTION

Damage caused by overload, vehicle impact, handling, earthquake, or fire is a perennial problem associated with steel bridge structures. For almost half a century, heat-straightening techniques have been applied to bends and distortions in order to restore the original shape of steel elements. A few craftsmen, who have years of experience with heat straightening, perform the technique in the field with varying degrees of success. Some of these experts have mastered heat straightening, but the process is still considered more of an art than a science.

The ability to repair damaged structural steel members in place, often without the need for temporary shoring, has generated interest in heat straightening from the engineering profession. However, engineers have had to rely primarily on their own judgment and the advice of experienced technicians in applying heat-straightening techniques. Two key questions have often been raised: Do heat-straightening procedures exist which do not compromise the structural integrity of the steel? And if so, how can such repairs be engineered to ensure adequate safety of the repaired structure, both during and after repair? The primary goal of this guide is to answer these two questions.

This guide is intended for a general audience ranging from heat-straightening practitioner, to contractor, to inspector, and to bridge engineer.

1.1 History of Heat Straightening

The origins of heat straightening can be traced to the early days of welding. Steel fabricators observed how the heat from welding caused distortion in regular patterns. Some of these individuals began to experiment with ways to reverse this distortion by heating the steel in specific patterns to counteract the initial distortion. With experience, some of these technicians developed skills at not only removing weld distortion, but repairing other damage as well. These heating procedures developed as an art form passed from one practitioner to the next.

During this period, the use of curved steel members gained popularity for both practical and aesthetic reasons. Primary examples include horizontally curved bridge girders and camber to compensate for vertical curve and dead load deflections. Heat curving techniques were developed for these applications. While many of the heating techniques are similar to those used in heat straightening, there are distinctions between the two. Heat curving is typically performed on undamaged steel, usually in the controlled environment of the fabrication shop, and the typical radius of curvature for heat-curved members is quite large, meaning that the curvature is usually very gradual. On the other hand, heat straightening is used on damaged steel in which the yield stress has been exceeded, and often excessively, well into the strain-hardening range. Most heat straightening is conducted in the field, under highly variable weather conditions, and often with the members at least partially loaded. These differences mean that techniques and criteria for heat straightening may sometimes differ substantially from those of heat curving.

The earliest written information found was traced to Joseph Holt who defined some of the basic concepts of heat straightening in an unpublished manuscript in 1938. Over the years since, more publications began to appear which tended to be more qualitative than quantitative in nature.

Well into the 1980's, the use of heat straightening was so little understood that one-half the States did not allow heat-straightening repair of bridges (Shanafelt and Horn, 1984). At that time there were reasons why heat-straightening repair had not been widely accepted. First, the basic mechanism of heat-straightening was not well-understood in that the effects of both external restraints (jacking) and internal restraints (redundancy) were considered to be of minor concern rather than fundamental to the broad application of the process. Second, as a result of not identifying the importance of these parameters, there had been little documentation of the behavior of vee heated plates subjected to varying degrees of constraint and even less on rolled shapes. Third, while a fair amount of research indicated that most material properties are relatively unaffected by heat straightening, two important aspects had been overlooked: the influence of strain aging on ductility; and residual stress distribution. Finally, the research information available was predicated almost entirely on laboratory studies of simple elements. The reported field investigations were qualitative rather than quantitative and thus could not serve as a building block for validating heat straightening. A literature review of the technical material available through the late 1980's is available (Avent, 1989). Because of these voids in heat-straightening research, it was indeed true that the artesian practicing the trade was much more important than the engineer. Consequently, heat-straightening repair was often not considered on engineered structures.

In recent years, considerable research has been conducted to quantify the heat-straightening process. The technical data presented here represent a comprehensive evaluation of the heat-straightening process. A scientific basis is provided which will enable an engineering evaluation of heat-straightening repairs. In turn, the methodology for conducting actual repairs is also presented.

In the past, heat straightening has been more art than science. While the fundamental principles and basic methodology will be presented here, heat straightening 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.

1.2 Typical Types of Damage

The focus of this guide is on repairing damage to members of steel bridge structures. However, the principals are applicable to any type of steel structure. Damage to steel bridge members may result from a variety of causes. Among the more frequent are: vehicle impact, uncontrolled distortion during construction, fire, and earthquake. While damage in structures may appear random, certain patterns and characteristics are distinguishable. A convenient way to classify damage is to define the four fundamental damage patterns, although typical accidents often include a combination of these types. The fundamental damage categories are:

1.2.1 Category S

This type refers to damage as a result of bending about the "strong" or major axis. For rolled or built-up shapes, the web element is bent about its strong axis with one flange element in compression and one in tension. In addition to plastic deformation, the compression flange and web will sometimes exhibit local buckling due to the high compressive stresses. A typical example is shown in Figure 1.

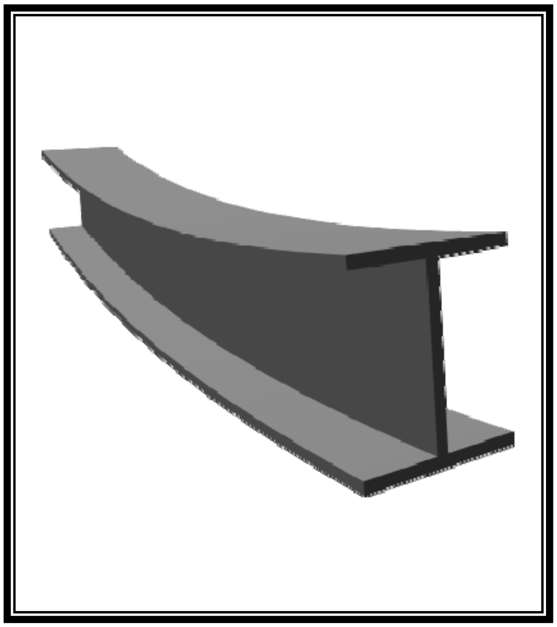


Figure 1. Graphic illustration of Category S damage.

1.2.2 Category W

This category refers to damage as a result of bending about the "weak" or minor axis. For rolled or built-up I-shapes the neutral axis is usually within, or near, the web. Consequently, the web may not yield or deform into the inelastic range. If neither is laterally restrained, the flange elements are bent about their strong axes and usually exhibit classical flexural yield patterns. Typical examples are shown in Figure 2.

1.2.3 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, if neither is laterally braced, 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 bridge girder), then the unconstrained flange element is subjected to plastic deformation and yielding may also occur in the web. Examples are shown in Figure 3**.**

1.2.4 Category L

This category includes damage that is localized in nature. Local flange or web buckles, web crippling and damage at bracing locations, and bends or crimps in plate elements of a cross section typify this behavior. An example is shown in Figure 4**.**

1.3 Classification Use

The importance of this classification system is that well-defined heating patterns can be established for each category. Once these patterns are understood, they can be used in combination for damage that includes multiple categories.

1.4 Objectives of This Guide

The goals of this manual are to:

- Describe and quantify the fundamentals of the heat straightening process.
- Address specific methods for repairing the basic damage categories.
- Provide guidelines for repairing more complex combinations of the basic damage categories.
- Provide detailed technical research data for engineers and scientists.

- Provide guidelines for conducting and supervising heat-straightening repairs.
- Provide model specifications for conducting heat-straightening repairs.

(a) Category W damage on a built-up double channel truss member. The damage was caused by a log falling from a truck on a bridge in North Louisiana.

(b) Category W damage to main girders during construction of a Louisiana bridge.

Figure 2. Examples of Category W damage.

(a) Category T damage to a composite wide flange beam. Damage was induced by a jack as part of an experimental program

(b) Category T damage on a composite bridge girder impacted by an over-height vehicle in Wisconsin.

Figure 3. Examples of Category T damage.

Figure 4. Category L damage showing flange buckles on wind bracing on Mississippi River Bridge in Greenville, MS.

2. HEAT STRAIGHTENING BASICS

2.1 What Is Heat Straightening?

Heat straightening is a repair procedure in which controlled heat is applied in specific patterns to the plastically deformed regions of damaged steel in repetitive heating and cooling cycles to gradually straighten 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 temperature of the steel does not exceed either (a) the lower critical temperature (the lowest temperature at which molecular changes 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.

A clear distinction should be made for two other methods often confused with heat straightening: hot mechanical straightening and hot working. Hot mechanical straightening differs from heat straightening in that external force is applied after heating 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 for non-load carrying elements when replacement or 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 structural 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.

2.2 Why Heat Straightening Works

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

- If steel is stretched or compressed past a certain limit (usually referred to as 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), it expands at a predictable rate and 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 5a. First, the bar is placed in a fixture, much stronger than the bar itself, and clamped snug-tight (Figure 5b). 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 5c. Since the bar is prevented from longitudinal expansion, it is forced to expand a greater amount laterally and transversely through it's 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 some yielding which does 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 remains even after the bar has completely cooled and the bar has shortened from its original length, Figure 5d. 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 significantly.

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.

The purpose of this chapter is to explain the basic techniques used in heat-straightening. There are three key elements to the heat-straightening process. The first is to select proper heating patterns and sequencing to fit the damage. The second is to properly control the heating temperature, and rate of heating and cooling. The third is to provide appropriate restraints during the heating cycle which can be relaxed or modified during the cooling cycle. The place to begin a discussion of heat straightening basics is with the first key: proper heating patterns and sequencing.

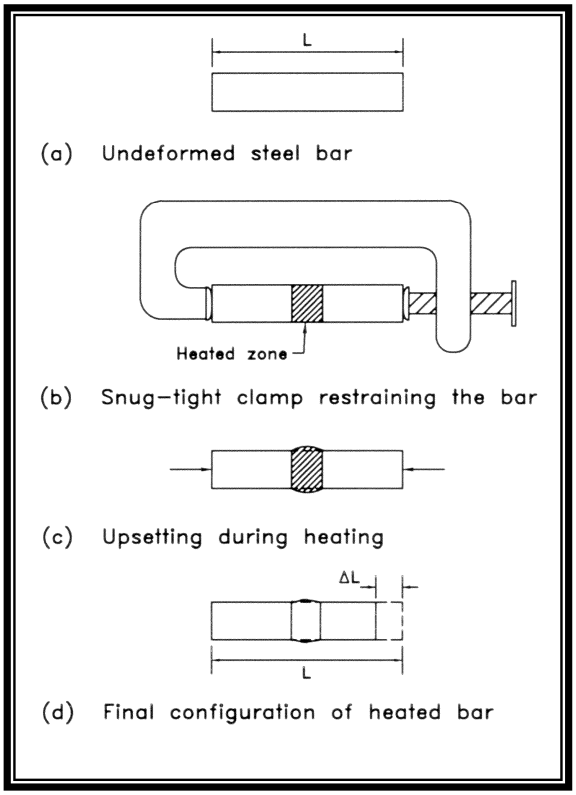


Figure 5. Conceptual example of shortening a steel bar.

2.3 Fundamental Heating Patterns

Several types of simple heating patterns exist. Effective heat straightening results when these patterns are combined into specific combinations,. As a starting point in understanding heat straightening, first consider a flat plate. Most steel bridge members are an assemblage of plate elements arranged to maximize strength and stiffness while minimizing material. Once an understanding of the heating patterns for a single plate is developed, these concepts can be extended to other shapes. There are several basic heating patterns used for flat plates.

2.3.1 Vee Heat

The vee heat is the most fundamental pattern used to straighten strong axis (category S) bends in steel plate elements. As seen in Figure 6, a typical vee heat starts with a very small spot heat applied 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^{o}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 6a) 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, 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 6b) 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. The net upsetting is proportional to the width across the vee, so the amount of upsetting increases from top to bottom of the vee.

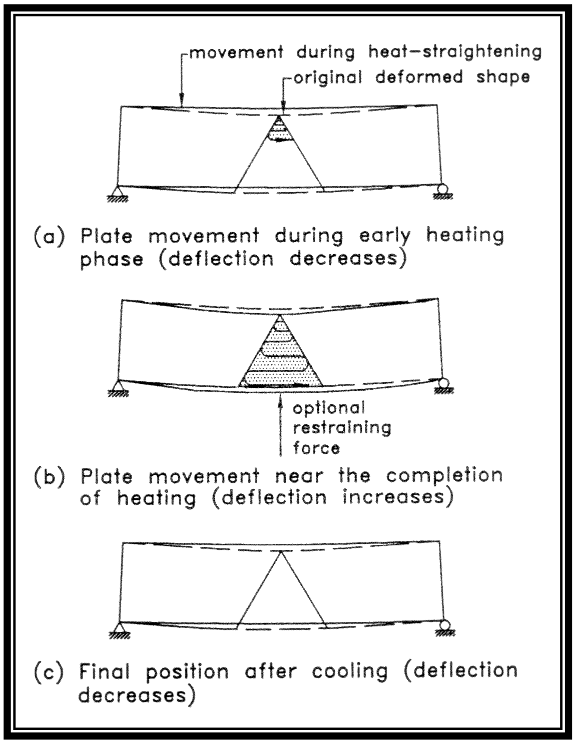


Figure 6. Stages of movement during vee heat.

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 6c). 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. The most typical partial depth vees are the three-quarter and half depth. Applications for partial depth vees will be discussed in later sections.

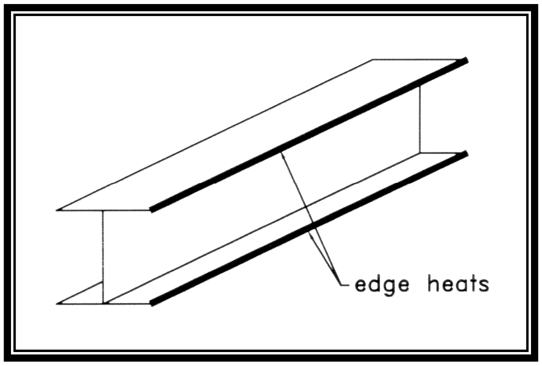


Figure 7. Schematic diagram of edge heats used to heat-curve a beam. (note that line heats are applied about 2 in. from edge for inelastically stretched edges and thermal cut flanges with small notches)

2.3.2 Edge Heats.

If a smooth gentle bend is desired, a line near the edge of the member is heated. The line may be continuous or intermittent, depending on the degree of curvature desired. This pattern is often used to heat-curve rolled shapes in the fabricating shop. A schematic is shown in Figure 7.

2.3.3 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 long narrow zones of yielding referred to as yield lines. A line heat consists of a single straight pass of the torch, Figure 8. The restraint in this case is often provided by an external force although some movement will occur without external constraints. This behavior is illustrated in Figure 9. A line heat is applied to the underside of a plate element subjected to bending moments produced by external forces (Figure 9a). As the torch is applied and moved across the plate, the temperature distribution decreases through the thickness (Figure 9b). The cool material ahead of the torch constrains thermal expansion, even if external 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 movement on the torch side of the plate similar to that shown in Figure 9d. 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 9c). Referring to a section through the plate transverse to the line heat (Figure 9c), 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 9d). 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

Figure 8. Line heat in progress on the web of a wide flange beam.

about the heated line.

2.3.4 Spot Heats.

For a spot heat, a small round area of the metal is heated by moving the torch in a slow circular motion increasing the diameter until the entire area of the metal is heated. A spot heat causes upsetting of the metal through the thickness due to the restraint provided by the cool surrounding material. On cooling, a spot heat leaves tensile stresses in all the radial directions across the heated area. During a spot heat, the torch should not be held at a particular point for too long, as the spot may get too hot and buckling may occur due to excessive thermal expansion on the heated side of the member. Spot heats are used to repair localized damage such as bulges, dents, bellies, or dishes in a plate element.

2.3.5 Strip Heats

Strip heats, also called rectangular heats, are used to remove a bulge in a plate element or 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, Figures 10 and 11. 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. This approach would minimize weak axis bending of the beam shown in Figure 11a. A second alternative with similar effect is shown in Figure 11b 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 11c. However, without restraints, this orientation may produce some

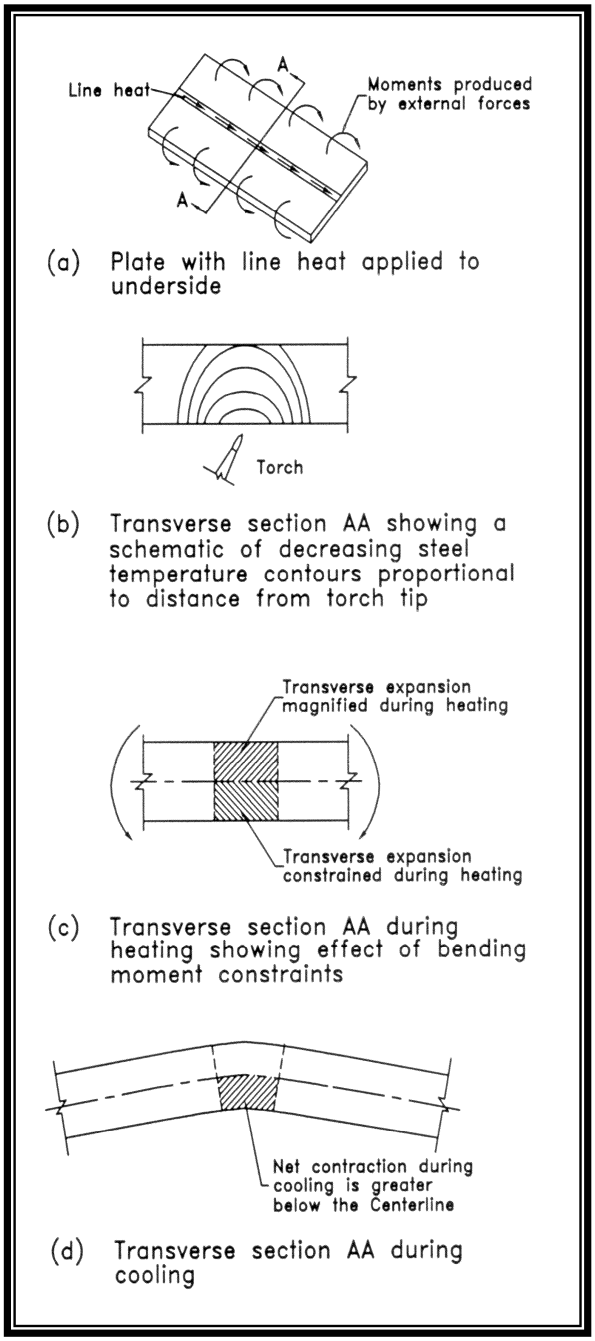


Figure 9. Schematic of line heat mechanism.

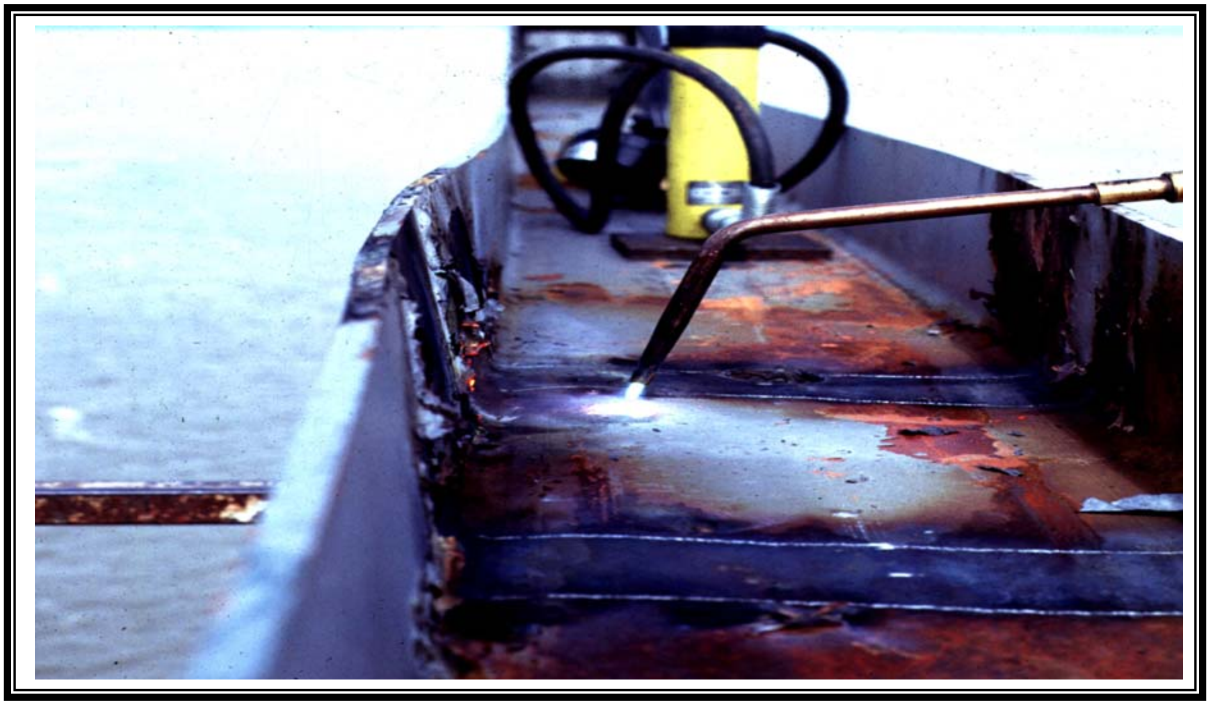


Figure 10. Strip heat in progress with a completed strip heat in the foreground.

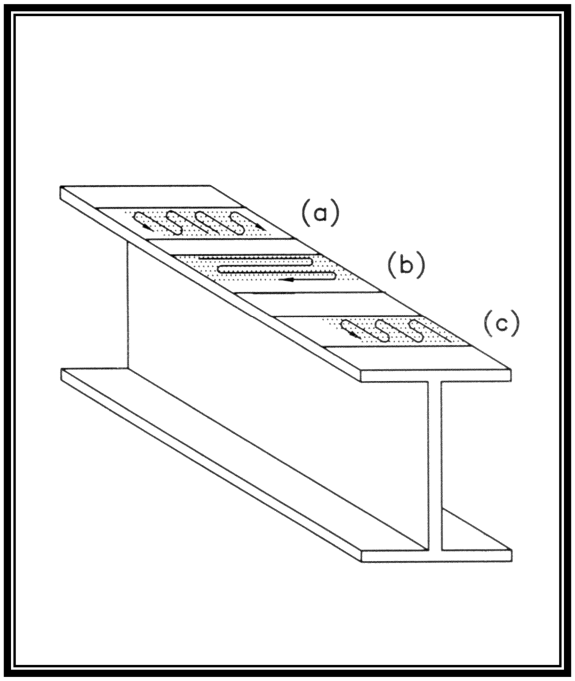


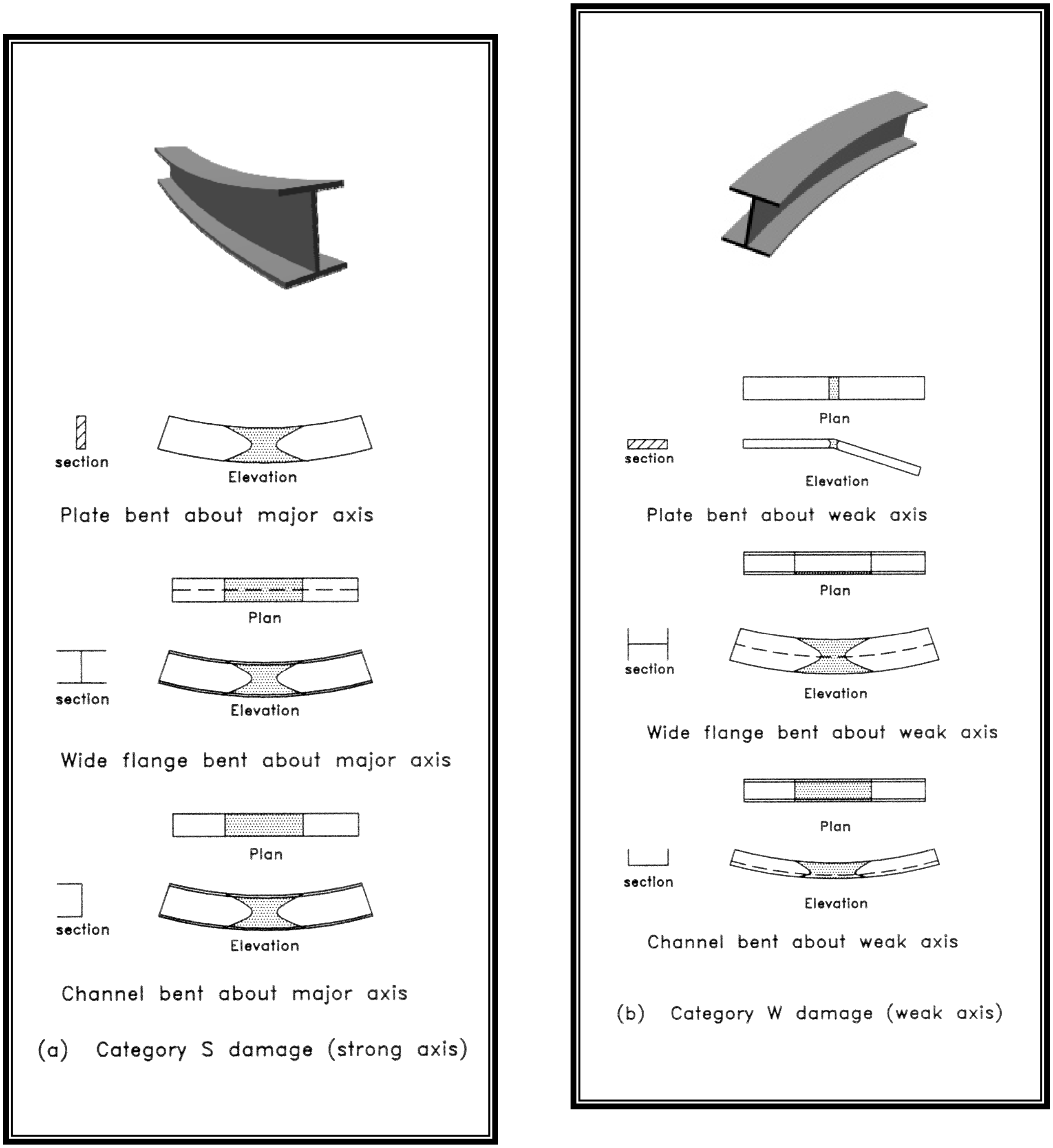
Figure 11. Schematic of strip heat on the flange of a rolled beam.

weak axis bending. By alternating the initiation point to opposite edges in successive heating cycles, the weak axis bending can be minimized.

2.4 Defining Basic Damage Patterns and Yield Zones

The fundamental damage categories have previously been defined. A yield pattern is associated with each damage category. The yield zone of steel is that area in which inelastic deformation has occurred. It is important to recognize the region of yielding because heat should only be applied in the vicinity of the yield zones. Typical yield zones are shown in Figure 12.

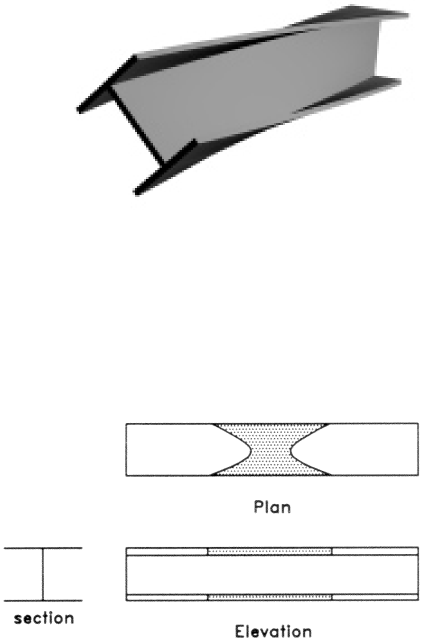
These sketches are schematic to depict the basic patterns. The yield zones may vary in length depending on the type of loading and degree of damage. Often, these zones can be



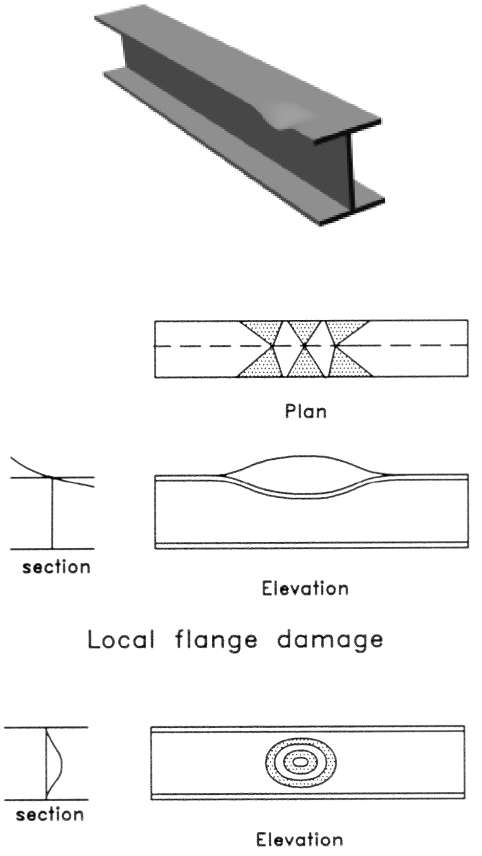
(a) Category S damage (strong axis)

(b) Category W damage (weak axis)

Figure 12. Yield zones for basic damage patterns.



(c) Category T damage (Torsional) for wide flanges



Local flange damage

Local web bulge

(d) Category L damage (Local)

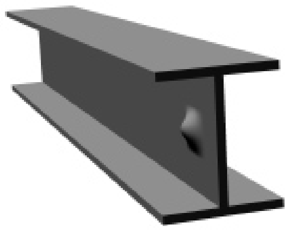


Figure 12. Continued.

determined by visual inspection and are identified by paint peeling or loosened rust and mill scale. Analytical methods are also available when necessary to accurately determine yield zones.

2.5 Basic Heating Patterns

The repair of damaged steel members often requires a combination of vee, strip, line, or spot heats. A series of such heats, applied consecutively as a group, is referred to as a heating pattern. The order in which these individual heats are conducted is referred to as the heating sequence. The process of conducting a complete heating pattern and allowing it to cool is referred to as a heating cycle. Structural steel shapes for bridges can be considered as an assemblage of flat plates. Almost invariably, damage to these shapes involves the bending of some of these plate elements about their own major axes. Consequently, the heat straightening of steel begins with the application of vee heats to such plate elements.

The application of a single vee heat to a flat plate has already been described. This basic vee heat is the building block upon which heat straightening of bridge members rest. The heating patterns used for the four fundamental damage categories are outlined in this section for typical rolled shapes.

The yield zone for category S damage to a wide flange beam is shown in Figure 13 along with the appropriate heating pattern.

2.5.1 Flat Plate Bent About the Major Axis (Category S)

The deformed shape of the typical bent plate is shown in Figure 14. The heating pattern is the full-depth vee as shown. Because the net change in curvature after one pattern of heats is small, cycles of heating and cooling are required to completely straighten a damaged plate. For each cycle, the vee (or vees) should be moved to a different location in the vicinity of the yield zone region as suggested by the dashed lines in Figure 14 so that the exact same spot is not continually reheated. More heats should be placed in the central part of the yield region and fewer near the extremities to reflect the difference in damage curvature. This principle applies for all heating patterns in the following sections.

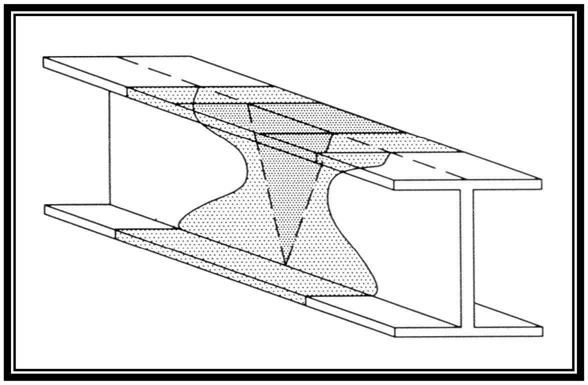


Figure 13. Yield zone and vee/strip heat layout for a category S damage to a rolled beam.

2.5.2 Structural Members Bent About Their Strong (Major) Axis (Category S)

As shown in Figure 15, the heating patterns for these cases consist of a vee and strip heat combination. 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 those damaged by bending about their major axes, such as the webs in Figure 15. The stiffening elements are those bent about their minor axes, such as the flanges in Figure 15. Typically, vee heats are applied to primary elements while strip, line or no heat at all may be applied to stiffening elements. For the case under consideration here, a 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.

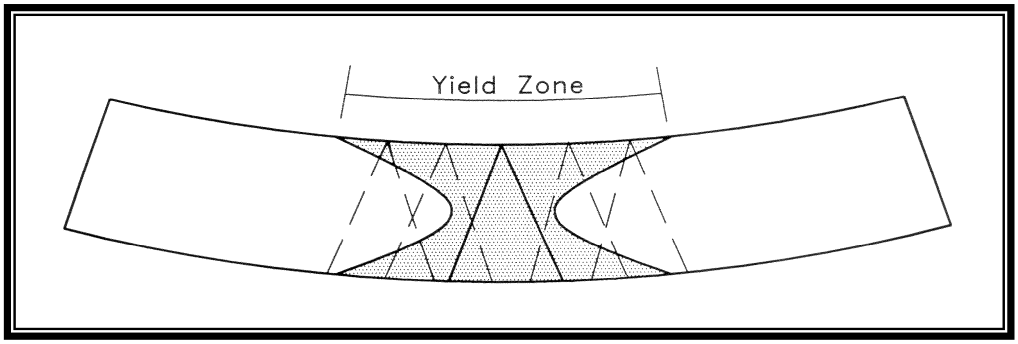


Figure 14. Plate vee heat pattern over yield zone.

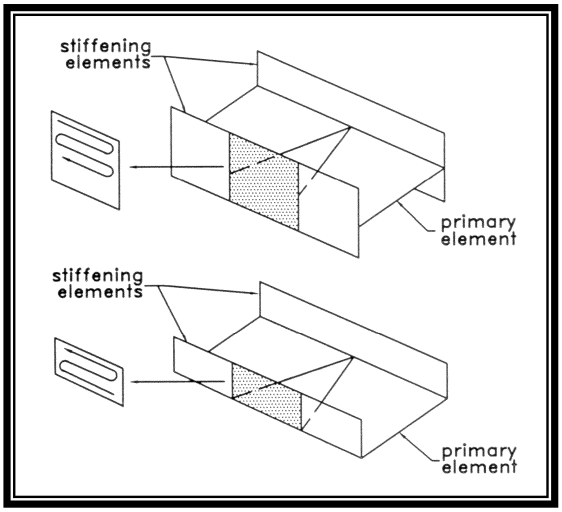


Figure 15. Heating patterns for wide flange beams and channels bent about their major axes (Category S).

The width of the strip equals the width of the vee 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.

2.5.3 Structural Members Bent About Their Weak (Minor) Axes (Category W)

The heating pattern for these cases 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 16. 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 within the vicinity of the yield zone until the member is straight.

2.5.4 Structural Members Subject to Twisting Damage (Category T)

The heating pattern for this damage case is shown in Figure 17. 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.

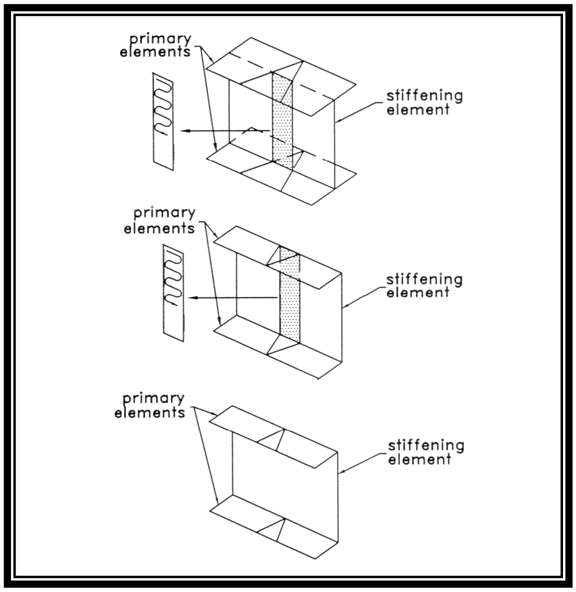


Figure 16. Heating patterns for wide flanges and channels bent about their minor axes (Category W).

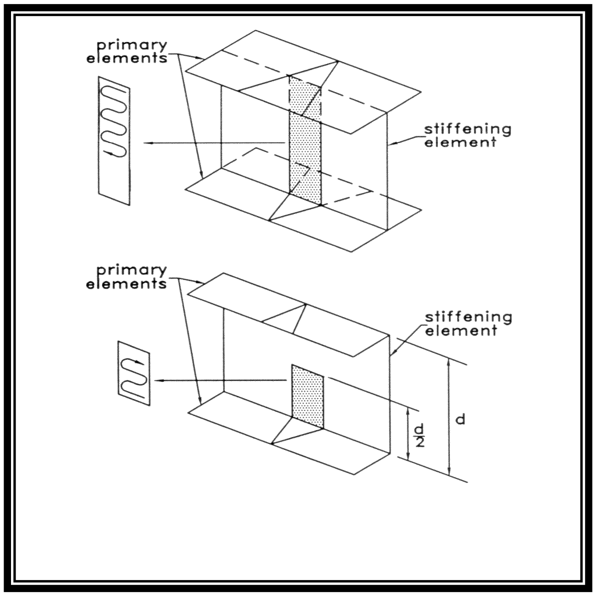


Figure 17. Wide flanges and channels with twisting damage (Category T).

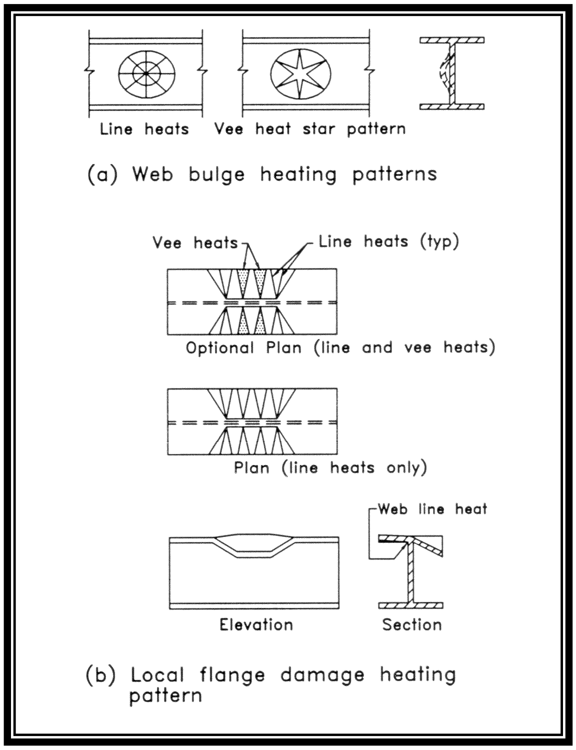


Figure 18. Typical heating patterns for local damage.

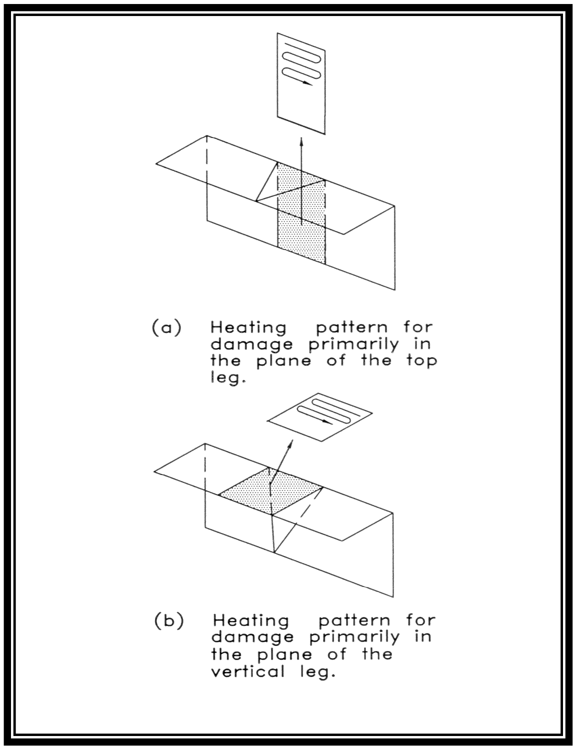


Figure 19. Heating patterns for angles.

2.5.5 Flanges and Webs with Local Buckles (Category L)

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 fig. 18. 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 ends 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 18b) 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.

2.5.6 Angles

Since angles usually do not have an axis of symmetry, the heating pattern requires special consideration. Typically, the heating pattern is similar to that of a channel. However, the vee heat on one leg of an angle will produce components of movement both parallel and perpendicular to the heated leg. Thus, the heating pattern shown in Figure 19 may need to be alternated on the adjacent leg. Another method to minimize out-of-plane movement is to use the strip heat patterns suggested in Figure 11.

2.6 Complex Damage

Most damage situations do not fit neatly into one of the fundamental damage categories. Rather, the damage is a combination of several of these categories. To repair these more complex cases, the damage should be viewed as a combination of the fundamental cases. The approach is to preplan the entire set of sequences, starting with the component of damage that is most severe. As straightening progresses, the process is redirected to other components, minimizing overlaps that counteract or unnecessarily reheat areas. By focusing on the fundamental damage categories in sequence, complex damage can be repaired by using the basic heating patterns described in the previous sections.

2.7 Equipment and Its Use

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. A regulator is used to reduce pressures to working levels of 100-140 kPa (15-20 psi). 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 20-25 mm (3/4 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 a rosebud or multiple orifice tip is recommended. The size may vary depending on the material thickness. The determining factor is the ability to raise the through-the-thickness steel temperature to the specified level. Note that whether single or multiple orifice, the torch should be a heating torch and not a cutting torch. The oxyacetylene fuel is preferred by many because it is a "hot" fuel. However, this fuel is also highly volatile. Some prefer a propane fuel, which is safer to handle. Since it does not burn as hot, a larger tip or rosebud orifice may be required. In either case the key is to be able to quickly heat a small area. Torch size and fuel must be adjusted to meet these criteria.

2.8 Safety Considerations

The fuel used in heat straightening is volatile and dangerous. Fuel tanks should always be handled with extreme care. Safety precautions include:

- Always place a protective cap on head of each tank before transporting. Always secure tanks prior to heat straightening.
- Examine tanks for damage prior to each use.
- Check lines and fixtures for leaks or damage prior to each use and that proper check valves are installed.

In addition, the technician using the torch must be safety conscious at all times. Precautions include:

- Wear protective goggles while heating (a no. 3 lens is recommended).
- Be careful of where the lighted torch is pointed at all times.
- Wear protective gloves and clothing.
- Always be in a stable, secure position prior to opening valves and lighting the torch.
- Follow proper procedures when using scaffolding and use safety harnesses when working above the ground. Secure tanks and hoses in safe positions prior to heat straightening.

2.9 Temperature Control

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. Early investigators had different opinions on temperature control. However, more recent comprehensive testing programs have shown that the plastic rotation produced is directly proportional to the heating temperature, up to at least 870°C (1600^{o}F).

The maximum temperature recommended by most researchers is 650°C (1200^{o}F) for all but quenched and tempered high-strength steels. Higher temperatures may result in greater rotation but out-of-plane distortion becomes likely and surface damage such as pitting will occur at 760°-870°C (1400^{o} to 1600^{o} F). Also, temperatures in excess of approximately 700°C (1300^{o}F) (metallurgically referred to as the lower phase transition temperature) may change the molecular composition, altering material properties after cooling. (See section 4.1 for a more detailed discussion justifying these temperature limits.) The limiting temperature of650°C (1200^{o}F) allows for about one hundred degrees of temperature variation, which was found to be a common range among experienced practitioners. AASHTO/AWS D1.5 (1996) specifies maximum heating temperatures of 590°C (1100°F) for quenched and tempered (Q&T) steels and 650°C (1200°F) for all others.

For A514 and non-HPS 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 Q & T 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. HPS Grade 70W produced by thermo-mechanically controlled processing (TMCP) is not Q % T, so 650°C (1200°F) applies.

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 include: visual observation of color of the steel (see 2.11.3); use of special temperature sensing crayons or pyrometers; and infrared electronic temperature sensing devices.

2.10 Restraining Forces

The term "restraining forces" can refer to either externally applied forces or internal redundancy and self-weight. These forces, when properly utilized, can expedite the straightening process. However, if improperly applied, restraining forces can hinder or even prevent straightening. In its simplest terms, the effect of restraining forces can be explained by considering the previous plate element as shown in Figure 6. The basic mechanism of heat straightening is to create plastic flow, causing expansion through the thickness (upsetting) during the heating phase, followed by elastic longitudinal contraction during the cooling phase. This upsetting can be accomplished in two ways. First, as the heat progresses toward the base of the vee, the cool material ahead of the torch prevents complete longitudinal expansion of the heated material, thus forcing upsetting through the thickness. However, as shown in Figure 6, some local longitudinal expansion occurs because the surrounding cool material does not offer perfect confinement. After cooling, the damage induced distortion is reduced in proportion to the confinement level from the internal restraints.

A second method of producing the desired upsetting (usually used in conjunction with the vee heat) is to provide a restraining force. The role of the restraining force is to reduce or prevent longitudinal plate movements associated with expansion during the heating phase. For example, if a restraining force is applied as shown in Figure 6, the upsetting effect will be increased by constricting the free longitudinal expansion at the open end of the vee. A restraining force is usually applied externally, producing a bending moment tending to close the vee. Caution must be used in applying external forces, since over-jacking may result in fracture of the member. To minimize the cracking potential, it is recommended that an external force be calculated and set prior to actual heating and not be increased until the cooling phase of the cycle is complete.

In essence, a restraining force acts in a similar manner to the cool material ahead of the vee heat torch movement. The material behavior can be viewed as shown in Figure 20. A small element from a plate, when constrained in the *x*-direction and heated, will expand and flow plastically primarily through the thickness (Figure 20c).

Secondary plastic flow will occur in the *y*-direction. However, this movement will be small in comparison with that of the *z*-direction, because the plate is much thinner than its *y*-dimension and offers less restraint to plastic flow. Upon cooling with unrestrained contraction, the final configuration of the element will be smaller in the *x*-direction and thicker in the *z*-direction (Figure 20d) than its original size. Regardless of the cause of the constraint, either cooler adjacent material, self weight, or an external restraining force, the plastic flow occurs in an identical manner.

Sometimes the structure itself provides additional restraint through redundancy. For example, if the simply supported beam depicted in Figure 6 were fixed at the supports, the member stiffness increases by 33 percent. This increased stiffness would provide additional restraint over the simply supported case.

In order to stay within the criteria for heat straightening, the restraint forces must not produce stresses greater than yield in the heated zone. At a heating temperature of 650°C (1200°F), the yield stress is reduced by approximately 50%. Therefore, a restraining force producing stresses of 50% yield (at ambient temperature) in the heated section would result in stresses at near initial yield when heated. Anything higher pushes the procedure into the hot mechanical straightening range. Therefore limit forces due to self-weight and applied restraint to those producing a maximum moment of 50% of the member capacity (in the heated area) at ambient temperature. This recommendation is somewhat conservative since the entire cross section is never at 650°C (1200°F). Rather, just the immediate area around the torch is at that temperature and the remainder of the cross section has already begun to cool (behind the torch) or is not yet heated (ahead of the torch). Thus, limiting the moment to 50% of member capacity keeps the procedure within the heat straightening zone. Another reason for limiting the force is that higher jacking forces increase the risk of fracture. This aspect is discussed in section 4.4.

In light of this, a set of criteria for restrain forces can be developed. These criteria apply for internal as well as external constraints.

1. Constraints should be passive during the heating phase; that is, they should be applied before heating and not increased by external means during heating or cooling.
2. Constraints should not impede contraction during the cooling phase.
3. Constraints should not cause local buckling of the compression element during the heating phase.
4. Constraints should not produce an unstable structure by either the formation of plastic hinges or member instability during the procedure.
5. Constraints should be limited such that the maximum moment in the heated zone does not cause stresses that exceed 50% of yield at ambient temperature.

From a practical viewpoint, these criteria mean that (a) the vee angle should be kept small enough to avoid local buckling, (b) the external restraining forces must be applied before heating and be self-relieving as contraction occurs, and (c) the maximum level of any externally applied forces must be based on a structural analysis of the complete structure that includes the reduced strength and stiffness of a member due to the heating effects.

2.11 Practical Considerations

This description of the heat straightening process provides the basic methodology. However, the proper application of heat is a skill requiring practice and experience: at this juncture, the art of heat straightening meets the technology. The practitioner needs to understand the variables involved in the process and how to control them. Some of the more important variables are discussed here.

2.11.1 Torch Tip Size and Intensity

The amount of heat applied to a steel surface is a function of the type of fuel, the number and size of the orifices, the fuel pressure and resulting heat output at the nozzle tip. Selecting the appropriate tip size is primarily a function of the thickness of the material. The goal is to rapidly bring the steel in the vicinity of the torch tip to the specified temperature, not just at the surface, but throughout the thickness. Once this condition is obtained at the initial heating location, the torch should be moved along the path at a rate that brings successive sections of steel to the specified temperature. A tip that is too small for the thickness will result in insufficient heat input at the surface that does not penetrate effectively through the thickness. If the tip is too large, there will be a tendency to input heat into the region so quickly that it is difficult to control the temperature and distortion. Table 1 is a general guide for selecting a tip size. Intensity of the torch, ambient temperature, steel configuration, access, and fabrication details influence the choice of tips. Adjustments can also be made in the torch intensity to improve the heating response. A hotter flame is helpful if the configuration of the steel tends to draw heat away from the spot of heating. A less intense flame allows for a slower pace as the torch is moved along the path. The intensity may be adjusted so as to compensate for variables encountered in the field.

2.11.2 Material configuration

The pace of moving the torch along the path will be a function of the configuration of the member, location of damage and pattern selected. At the initiation of heating, the torch typically remains on a single spot as the temperature rises. Once the heating temperature is reached, a steady movement along the path of heating can usually be maintained. Practice heats will allow technicians to develop a feel for how to vary the torch speed over various configurations.

Attachments such as stiffeners may serve as a heat sink requiring the slowing of the torch movement over certain zones. One typical example is the heating of the flange of a rolled beam where the web-flange juncture must be heated more slowly since the web draws heat away from the flange.

Sometimes the pace must be quickened to maintain a uniform heat. A common example is the conclusion of a vee heat at a free edge. By the last pass along that edge, the wave of heat moving down the vee almost overtakes the torch. As a result, the last pass is usually conducted very quickly.

2.11.3 Judging the Temperature

In theory, control of temperature may seem easy: watch the color of the steel and use temperature crayons. In practice, temperature control is quite difficult. First, the satiny silver color of steel indicating 650°C (1200°F) is often obscured. The torch flame often reacts with surface impurities including paint, oil or previous temperature crayon marks themselves. When the flame hits these, it may burn bright yellow or orange and hide the surface near the tip. Additionally, the surface temperature directly under the flame will briefly exceed specified limits in order to convey heat into the metal. Therefore, temperature should not be checked until the flame leaves the area for a 3 to 5 second "soak time". The available light also influences observations. In daylight or bright indoor light, the silver color is easier to read and no dull red can be seen. However, in dark shadow zones or on overcast days or with limited artificial light, the steel will emit a dull red glow at the same temperature. No. 3 goggles may mask subtle colors so an observer without goggles may be needed. As a general rule, if red is visible in normal lighting, the steel is too hot. When heat straightening is done properly, the steel is not heated above its lower phase transition temperature and its properties will not change significantly. Overheating may create brittle, fracture sensitive zones, which could result in a sudden failure. Constant attention is required to maintain the heating temperature in the correct range. Practice is essential to recognize and control the temperature.

2.11.4 Jacking Forces

Earlier, a clear distinction was made between hot mechanical straightening and heat straightening. The technique of hot mechanical straightening consists of lowering the yield strength by heating and then applying sufficient jacking loads in a single application to straighten the damage by inelastically deforming the section. Heat straightening on the other hand, requires that the restraining forces result in stresses not exceeding yield at the elevated temperature. Movement occurs as a result of plastic deformations during contraction, not by mechanical overload. Therefore, initial restraining forces are an integral part of heat straightening.

First, one should know how much external force is being applied to the system. Thus, all jacks should be gauged and calibrated. Second, the maximum jacking force should be calculated to insure that over-stress at elevated temperatures will not occur. Often, these computations require a structural engineering analysis, but for frequently encountered cases, some rules of thumb can be established. The practitioner must be aware that over-jacking may cause over-correction, buckling or a sudden fracture during the process. It might also result in difficult to detect micro-cracks which could severely reduce fatigue resistance.

2.11.5 Heating Patterns

One key to heat straightening is selecting appropriate heat patterns to fit the yield zones of the steel. Basic patterns were illustrated in Figures 14-19. Yield zones, where the steel has inelastically deformed, occur in regions of sharpest curvature. Some practitioners have a tendency to heat in a broader zone, but this again is a case of more being less. Stay with the recommended patterns and do not expand them. Heat straightening is a cyclic process and the movement occurs gradually by contraction during cooling. Sometimes 20 or more heating cycles may be required to straighten a damaged member. Since a heating pattern usually covers only a portion of the yield zone, the pattern should be shifted on a cycle-by-cycle basis. The significant portion of a heating pattern array should be in the yield zone with fewer heating cycles having patterns near the edges and more near the center where curvature is the sharpest. Also, do not duplicate continuous passes through a given zone during one heating cycle. Going back and reheating before the material has cooled interrupts the contraction process. The heat straightening

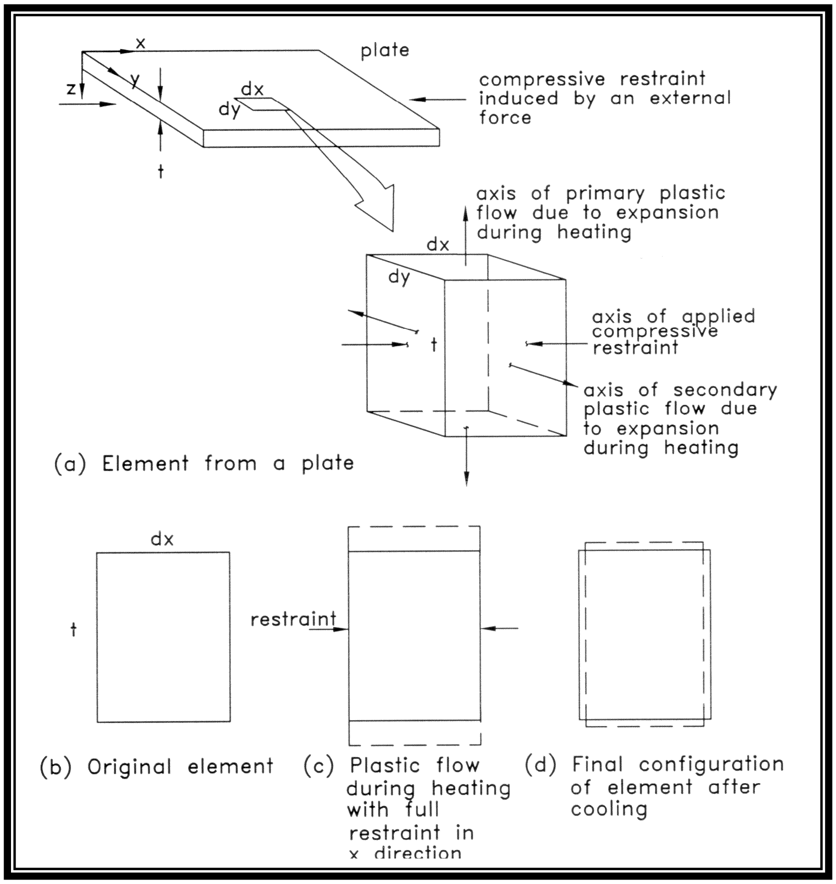


Figure 20. Characteristics of plastic flow and restraint during heat straightening.

Table 1. Recommended torch tips for various material thicknesses.

Steel Thickness		Orifice Type	Size
(in)	(mm)		
< ¼	6	Single	3
3/8	10	Single	4
½	13	Single	5
5/8	16	Single	7
¾	20	Single	8
1	25	Single Rosebud	8 3
2	50	Single Rosebud	8 4
3	75	Rosebud	5
> 4	100	Rosebud	5

predictability and effectiveness is consequently reduced.

2.11.6 Sequencing of Heats

When a combination of vee, strip and/or line heats are 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 15.

A common sequence is to heat the vee first, followed immediately by the strip. The available research data and difference sequences used in practice indicates that more than one sequence can be successful. At this time there is not adequate documentation to mandate one sequence for a particular heating pattern. The experience of the practitioner is the most reliable guide to proper sequencing. The sequencing patterns shown in this manual are based on those often successfully used in practice.

2.11.7 Lack of Movement

One of the more perplexing aspects of heat straightening is that sometimes there is no movement. Should this happen, perform several cycles, making sure to shift to new locations within the yield zone after each cycle. Sometimes there is an existing residual stress pattern or restraint imposed by the structure tending to oppose movement. Several heating cycles will tend to redistribute or dissipate these opposing stresses and may lead to the desired movement. Should the problem persist, the jacking forces may be too low. A re-analysis of the jacking layout is recommended, particularly in light of redundancies that may exist. Finally, check the heating patterns to insure they are consistent with the damage. For example, neglecting to heat all separate yield zones during one heat cycle could prevent movement. The key point is that if the steel doesn’t move, there is a reason. It is a matter of finding the reason. Difficult problems may require a consultant more experienced in heat straightening or replacement of the element. Over-heating or over-jacking is not a solution.

2.11.8 Cooling the Steel

Ambient air cooling is the safest method. Rapid cooling is dangerous if the steel has been over-heated and may produce brittle “hot spots”. However, once the steel has cooled below the lower phase transition temperature, rapid cooling is not harmful. Many practitioners allow the surface of the steel to cool below 315°C (600°F) prior to accelerating cooling. Such a surface temperature reduction insures that the interior steel temperature has dropped. One approach to accelerated cooling is to use compressed air blown on the heated surfaces. Faster cooling can be obtained with water mist cooling. However, the steam generated could result in burns and the water runoff could lead to a clean-up problem especially if it covers areas which must be subsequently heated. The following cautionary measures should be taken when considering this option: (1) a mist applicator which allows the technician to remain at a safe distance; (2) protective clothing and goggles; and (3) a method for safely disposing of the waste water.

3. ASSESSING, PLANNING AND CONDUCTING SUCCESSFUL REPAIRS

As with other types of repair, a successful heat-straightening repair requires assessment, planning and design. Several procedures should be considered as part of the process. Critical aspects include: determination of degree of damage, location of yield zones and regions of maximum strain, limitations for heat-straightening repair, selection of heating patterns, and selection of jacking restraints. Each requires the exercise of engineering judgment. Outlined in this chapter are some key aspects of assessing, planning and designing a repair. One of the primary keys is ongoing coordination between the engineer, field supervisor or inspector, and the contractor conducting the repair.

3.1 Role of Engineer, Inspector and Contractor

The engineer is responsible for selecting the most appropriate repair technique for the specific damage. Alternatives must be evaluated and the most effective solution determined. The key considerations include: cost, implementability, adequate restoration of strength, longevity of repair, time to complete repair, aesthetics, and impact on traffic. These aspects constitute the concept referred to as design.

Although frequently overlooked, repairs should be designed in a similar manner to new structures. The typical process includes: selecting a trial repair scheme, conducting a structural analysis (which may require assumptions of certain geometric or material properties), defining the parameters of the repair (or verifying the capacity after repair), possibly re-analyzing and re-designing, evaluating alternate repair or replacement schemes, and finally, providing complete details and specifications for the system selected.

Heat-straightening repair is not the solution for every damage situation. The engineer's role is to assess its specific applicability. Aspects to consider are: current condition of the rest of the structure and other anticipated repairs, degree of damage, presence of fractures, cause of damage and likelihood of repetitive damage, accessibility, and the repair method’s impact on material properties. Once the heat straightening alternative is selected, then the repair parameters such as traffic control, contractor access and work areas, permitted hours of work, typical heating patterns, maximum restraining forces and locations, and maximum heating temperature must be chosen. Finally, plans and specifications should be developed which generally define how the repair is to be accomplished.

Since most heat-straightening repairs are conducted by contractors, the field inspector, representing the bridge owner, has major responsibilities to insure that the repair is being conducted according to plans and specifications. Of particular importance is insuring that procedures are followed which are not detrimental to the steel.

The third member of the team is the contractor who actually executes the repair. The ultimate success of the project hinges on the skills and understanding for the project by the contractor’s personnel. While others may have designed the repair plan, the details of execution lie with the contractor. Important considerations may include: (1) scaffolding arrangements; (2) selection of proper heating equipment; (3) implementing the restraint plan with appropriate jacks and come-alongs; (4) placing the heats in proper patterns and sequences; and (5) analyzing the progress of the repair. The contractor must be alert to the response of the structure and be prepared to suggest changes to ensure stability and expedite the process. In spite of our current knowledge and analytical capabilities, movements during heat straightening cannot always be predicted accurately

The primary reasons for this difficulty are that: (1) damage patterns are often a complex mixture of the idealized cases and require experience to determine the details of the heating process; and (2) residual stresses and moments which may have been locked into the structure during both original construction and also the damage phase are difficult to predict and may prevent or increase the expected movement. The contractor must be able to assess the reaction of the structure to the planned repair and suggest modifications if the structure is not performing properly. These modifications may range from changes in heating patterns and jacking arrangements to decisions on whether to remove secondary or bracing members during the repair. Perhaps most important is that the engineer, the inspector and the contractor maintain open and clear channels of communication. This interaction of the three key players in a heat-straightening repair will go a long ways toward insuring a successful project.

3.2 Keys to a Successful Repair

A successful repair requires the control and selection of certain specific parameters. The first key is the selection of the heating patterns and sequences. The combination of vee, line and strip heats must be chosen to fit the damage patterns. Heat should only be applied in the vicinity of those regions in which yielding of the material have occurred. Typically, vee heats should be relatively narrow. A good rule of thumb is to limit the open end of the vee to 250 mm (10 in) for one inch thick plates. However, a smaller limit should be considered for progressively thinner plates. These limits will minimize distortion which might occur due to local buckling of the plate element.

The second key is to control the heating temperature and rate. Temperatures should be limited to 650°C (1200°F) for non-quenched and tempered steels, 590°C (1100°F) for A514 and A709 Grade 100 and 100W quenched and tempered steels and 565°C (1050°F) for A709 Grade 70W quenched and tempered steel. Higher heats may adversely affect the material properties of the steel and lead to a weaker structure.

The third key is to control the applied restraining forces during repair. Research has shown that the use of jacks to apply restraint can greatly shorten the number of heating cycles required. However, over-jacking can result in buckling or a brittle fracture during or shortly after heat straightening. To prevent such a sudden fracture, as illustrated in Figure 21, jacking forces should be limited. The recommended procedure is to calculate the plastic moment capacity of the damaged member and limit the moment resulting from the combination of initial jacking forces and dead loads to one-half of this value. If practitioners do not take this precaution, brittle fractures or excess deformation may occur. It is strongly recommended that jacks be gauged and calibrated, then set for the maximum force computed. Of course, the jacking forces should always be applied in the direction tending to straighten the beam.

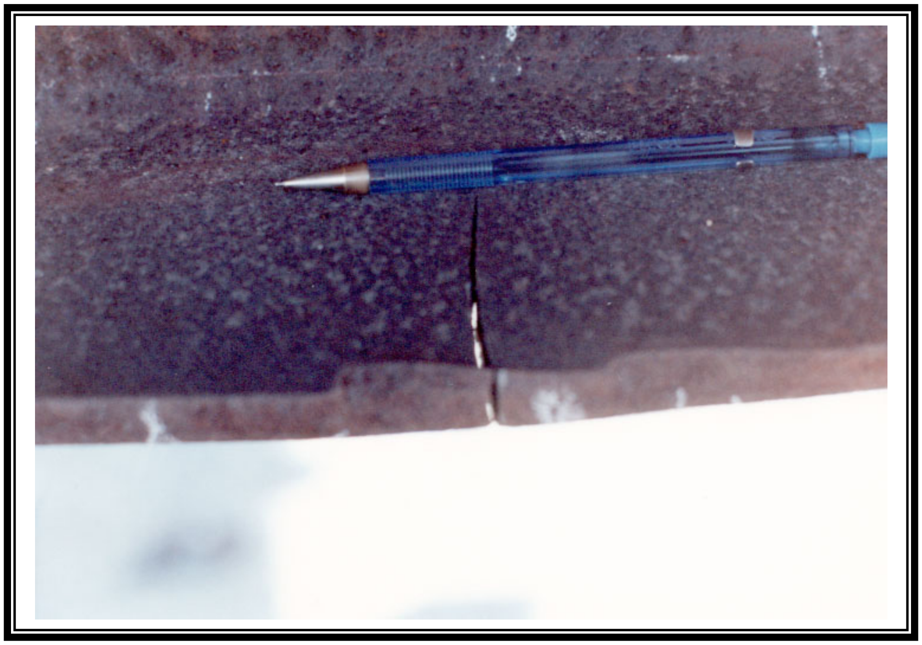


Figure 21. Brittle fracture during heat straightening.

The execution of a heat-straightening repair that incorporates these keys must begin with the assessment of the damaged structure.

3.3 Steps in the Assessment Process

Many incidents resulting in damage to steel bridges produce an emergency situation. The first step in the rehabilitation process is a site investigation to assess the degree of damage and the safety of the existing structure. The purpose of this section is to provide guidelines for damage assessment in the form of steps required for a complete assessment. All aspects may not be required in each case, so judgment must be used when deciding if, and when, to eliminate a part of the process.

3.3.1 Initial Inspection and Evaluation for Safety and Stability

The purpose of the inspection is to protect the public, employees of the owner and repair personnel. This inspection is often visual and conducted with special concern for safety. The major aspects of damage are recorded and documented with photographs and measurements. During this inspection, a preliminary list of repair requirements and options should be made. Particular attention should be paid to temporary needs such as shoring, traffic control, access and other short-term considerations. A part of this evaluation may require a review of the design drawings and computations to determine the safety and stability of the bridge. The specific cause of damage may also influence the final decision on repair and should be investigated if possible. Typical damage causes are: (1) over-height or over-wide vehicle impact; (2) overweight vehicles or overloads; (3) out-of-control vehicles or moving systems; (4) mishandling during construction; (5) fire; (6) blast; (7) earthquakes; (8) support or substructure movement; and (9) wind or water-borne debris.

3.3.2 Detailed Inspection for Specific Defects

Applicability of a heat-straightening repair depends on the type and degree of damage. Three aspects should be carefully checked: (1) signs of fracture; (2) degree of damage; and (3) material degradation.

3.3.2.1 Signs of Fracture

While some fractures are quite obvious, others may be too small to visually detect. However, it is important to determine if such cracks exist since they may propagate during the heat-straightening process. When in doubt, one of the following conventional methods can be utilized: (1) dye penetrant, (2) magnetic particle, (3) ultrasonic testing, or (4) radiographic testing.

3.3.2.2 Degree of Damage

Degree of damage can be evaluated using two different criteria. One is the angle of damage, φ_d, which is a measure of the change in curvature. The other is the strain ratio, μ, which is a measure of the maximum strain occurring in the damaged zone. For either case an evaluation of the degree of damage requires measurements to be taken. Two types of damage are quantified by measurements: (1) Overall bending or twisting of a member; and (2) localized bulges or sharp crimps. These measurements can be used to compute the maximum damage-induced strain, μ, or to determine the angle of damage, φ_d.

For determining angle of damage, the usual procedure is to begin by measuring offsets from a taut line, laser beam or straight-edge. A typical layout is shown in Figure 22 showing the definition of φ_d. This layout may be done by either using the unyielded adjacent regions on either side of the damage as reference lines, since their curvature is small in comparison to the plastic zones, and determining the included angle between them, or by establishing a base line and finding the offsets in the damage zone. For the first case, tangents from the straight portions define the angle or degree of damage between the tangents. If the offsets are taken in the elastic zone on either side of the damage as shown in Figure 22b, the degree of damage, φ_d, can be computed.

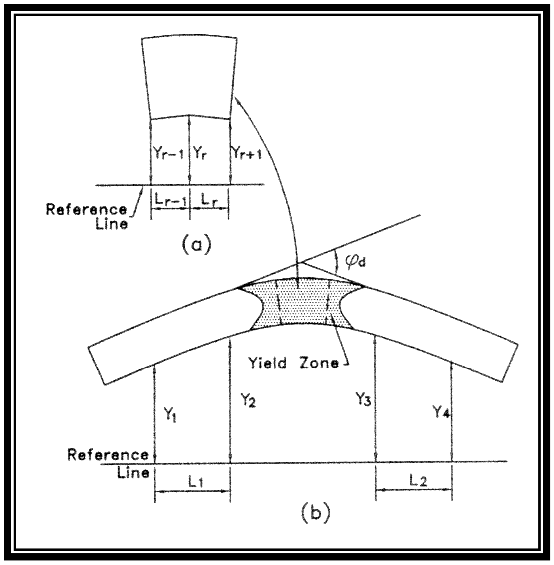


Figure 22. Offset measurements to calculate degree of damage and radius of curvature.

Based on measurements taken at the site, degree of damage can be calculated as follows:

$$\varphi_d = \tan^{-1}\left(\frac{y_2 - y_1}{L_1}\right) + \tan^{-1}\left(\frac{y_3 - y_4}{L_2}\right) \qquad \text{(Eq. 3.1)}$$

where φ_d is the angle of damage or angle of permanent deformation at the plastic hinge and y_i is a measured offset as shown in Figure 22b.

In some cases direct measurements of φ_d can be made from a photograph. If a photograph can be taken perpendicular to the plane of curvature, then tangents can be laid out and measured directly. For small zones of damage, two straight edges can be used to produce the tangent intersections. Again, the angle of damage can be measured with a protractor. While this method may seem somewhat crude, a reasonable degree of accuracy can be obtained.

For the case where the offsets are taken in the damage zone (see Figure 22a). The radius of curvature, R, can be approximated as

$$\frac{1}{R}=\frac{y_{r-1}-2y_r+y_{r+1}}{L^2} \qquad \text{(Eq. 3.2)}$$

The degree of damage can then be calculated from:

$$\sin\frac{\varphi_d}{2}=\frac{L}{R} \qquad \text{(Eq. 3.3)}$$

or $$\varphi_d = 2\sin^{-1}(\frac{L}{R}) \qquad \text{(Eq. 3.4)}$$

Where $L_{r-1} = L_r = L$

Approximations are involved in using these equations. The assumption is made that the radius of curvature is constant over the entire length of the damage although it usually varies. If the damage curve is smooth, this assumption is fairly accurate. If the curve is irregular, the assumption becomes more approximate. For highly irregular curvatures, measure only the worst portion of the damaged region using the three-point offset procedure and the calculation of radius of curvature from Eq. 3.2. In general, the approaches described here give an adequate estimate of the radius of curvature and angle of damage.

In order to calculate the maximum strain ratio, the maximum curvature should be measured as previously described. Shown in Figure 23 is a damaged beam of uniform curvature. The radius of the bend is defined as radius of curvature, R. Strain is proportional to curvature and curvature can be computed from field measurements, so the radius of curvature to the yield curvature, R_y, may be expressed as

$$R_y = \frac{Ey_{\max}}{F_y} \qquad \text{(Eq. 3.5)}$$

where E = modulus of elasticity, F_y = yield stress, and $y_{\max}$ = the distance from the centroid to the extreme fiber of the element.

The radius of curvature is related to the strain by

$$\varepsilon_{\max} = \frac{1}{R}y_{\max} \qquad \text{(Eq. 3.6)}$$

where R is the actual radius of curvature in the damaged region.

Since damage measurements are taken at discrete locations, the radius of curvature can be approximated from Eq. 3.2. Once the smallest radius of curvature is determined in the damaged region, the maximum strain can be computed from Eq. 3.6 and compared to the yield strain

$$\varepsilon_y = \frac{F_y}{E} \qquad \text{(Eq. 3.7)}$$

From Eqs. 3.6 and 3.7, the strain ratio is

$$\mu = \frac{Ey_{\max}}{RF_y} \qquad \text{(Eq. 3.8)}$$

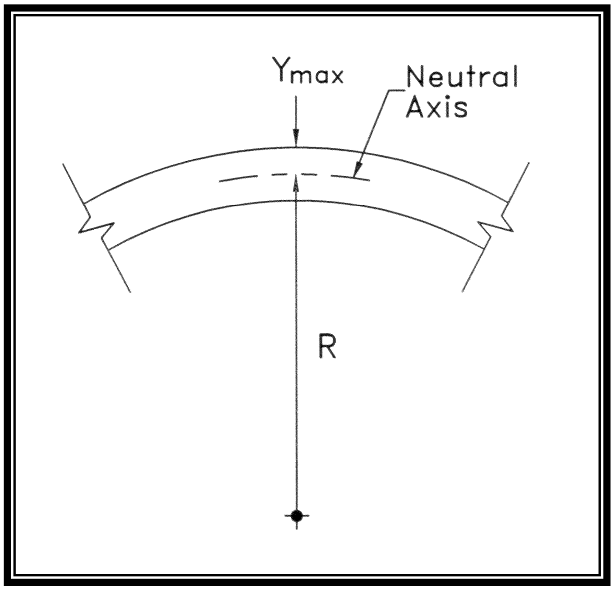


Figure 23. Radius of curvature for a damaged beam of curvature and cord length.

Research data has shown that heat straightening can be successful on steel with plastic strains up to 100 times the yield strain, ε_y. There is reason to believe that even larger strains can be repaired. However, since no research data exists beyond the $100\varepsilon_y$ range, engineering judgment is required.

3.3.2.3 Material Degradation

Certain aspects of material degradation will influence the decision to heat straighten. Nicks, gouges and other abrupt discontinuities in the damage zone will be stress risers during the repair when jacking forces and heat are applied. Such discontinuities should be noted and ground to a smooth transition prior to heat straightening.

A second concern is exposure to high temperature (such as a fire) when the damage occurred. As long as the steel temperature did not exceed either the tempering temperature or the lower phase transition temperature, no permanent degradation would be expected from the heating. However, if the damaged steel reached higher temperatures, metallurgical tests should be performed to ensure material integrity before heat straightening is applied. Tests that should be considered include: (1) a chemical analysis; (2) a grain size and micro structure analysis; (3) Brinell hardness tests; (4) Charpy notch toughness tests; and (5) tensile tests to determine yield, ultimate strength, and percent elongation. In-place, non-destructive tests (Brinell, appearance) avoid removing material that must be restored. Charpy and tensile tests require significant removal of material straight enough to machine specimens from damaged and undamaged areas for comparative results.

Several visual signs may suggest exposure to high temperature including: melted mill scale, distortion, black discoloration of steel, and cracking and spalling of adjacent concrete. Tests can then be conducted at suspicious regions. For example, a significant increase in Brinell hardness, in comparison to undamaged areas of the same member, indicates potential heat damage. Or, for the Charpy V Notch test, a significant reduction in values over those from an undamaged specimen may indicate damage. The most definitive test is usually a metallurgical comparison of microstructure between damaged and undamaged areas. Evidence of partial austenization and recrystallization into finer grain size indicates heating above the lower phase transition temperature.

3.3.2.4 Geometry of the Structure

Often the design drawings are available to confirm the structure's original configuration, design parameters and type(s) of steel.. If drawings are not available, then enough measurements should be taken so that a structural analysis can be conducted if required.

3.4 Steps in the Planning and Design Process

Once the damage assessment is complete, the repair can be designed. The following steps may be required as part of this planning and design process:

- Analyze the degree of damage and maximum strains induced.
- Conduct a structural analysis of the system in its damaged configuration.
- Select applicable regions for heat straightening repair.
- Select heating patterns and parameters.
- Develop a constraint plan and design the jacking restraint configuration.
- Estimate heating cycles required to straighten members.
- Prepare plans and specifications.

Each of these will be discussed in the following sections

3.4.1 Analysis of Degree of Damage and Determination of the Maximum Strain due to Damage

Heat-straightening repairs have been conducted for strains up to $100\varepsilon_y$, or $\mu=100$. Repairs may be successful at even greater strains. But research studies have not focused on such strains so engineers should use judgment in straightening beyond this range.

Fire damage involving high temperature may be an exception to this limit. If the distortion is due to diminished strength at high temperature material properties have probably been detrimentally affected. Repair decisions should then be based on metallurgical analysis and expert opinion as well as the $100\varepsilon_y$ strain limitation.

3.4.2. Conduct a Structural Analysis of the System

A structural analysis may be necessary to evaluate the damaged structure. This analysis serves one of two purposes: (1) to determine the capacity in its damaged configuration for safety purposes; and (2) to compute residual forces induced by the impact damage which may effect safety and influence the level of applied restraining forces during heat straightening (see ref. 1 for an example of calculating residual moments). The analysis can be based on the undeformed geometry except when the displaced geometry of the frame or truss system (after damage) results in changes in internal forces by more than 20 percent. However, even if undeformed geometry is used in the analysis, the deformed geometry should be used when computing the member stresses. The allowable stresses should be based on the original properties of the material. When a member has a significant change in shape due to damage, the section properties should be modified when calculating stresses. While each specific application must be considered on an individual basis, some general guidelines can be developed. Assuming that no fractures have occurred, bending and compression members are the most critical to evaluate. Forces due to applied loads in tension members tend to straighten out-of-plane damage (and are thus self-correcting), while such forces in bending or compression members tend to magnify the damage.

3.4.3. Select Regions Where Heat Straightening is Applicable

While the primary consideration for allowing heat-straightening repair is the degree of damage limitation, other criteria may also influence the decision. Of particular importance is the presence of fractures or previously heat straightened members. A fracture may necessitate the replacement of part, or all, of a structural member. In some cases it may be feasible to heat straighten the suspect region and then repair it in-place by mechanical connectors. In other cases a portion of the member may be replaced while the remainder is repaired by heat straightening.

An example of combining heat straightening with replacement is when one or more girders are impacted by an overheight vehicle. This type of accident often displaces the bottom flange. If the impact point is near diaphragms, the diaphragms are often severely damaged. An example is shown in Figure 24. It is usually much more economical to simply replace a diaphragm rather than taking a lengthy time to straighten it. The recommended procedure is to remove the diaphragm (especially if it would restrain desired movement of the member) heat straighten the girder, and then replace the diaphragm with a new one.

In general, heat straightening can be applied to a wide variety of structural members. However, some have cautioned about straightening fracture critical members (Shannafelt and Horn, 1984). Although there is no research data to support a ban on heat straightening fracture critical members, practically no fatigue testing has been conducted. If heating temperature (including the limits imposed by section 12.12 of the AASHTO/AWS D1.5 Bridge Welding Code) is carefully controlled, jacking forces are maintained, and notches and nicks are ground smooth there is no reason to expect unusual problems. Additional care is warranted for fracture critical members to insure that the heat straightening is properly conducted.

3.4.4. Select Heating Patterns and Parameters

The fundamental heating patterns have been described in Chapter 2. Since typical damage is often a combination of these fundamental damage types, a combination of heating patterns is often required. The key is to select the combination of patterns to fit the damage. When in doubt, concentrate on one of the basic heating patterns at a time. For example, remove the Category W damage prior to addressing the Category L damage.

3.4.4.1 Vee Depth

In general, the vee depth should be equal to the width of the plate being straightened. Partial depth vees do not reduce member-shortening as some have speculated. The primary application for half depth vees is the repair of local damage.

3.4.4.2 Vee Angle

The angle of the vee is usually limited by practical considerations. It should be as large as practical for the specific application. If the open end of the vee is too wide, out-of-plane distortion often occurs. Likewise the vee area should be small enough to heat quickly so that differential cooling is limited. A good rule of thumb is to limit the open end of the vee to approximately one-third to one-half the plate width but not greater than 254 mm (10 in). These limits translate roughly to 20-30° vee angles. If the width of the open end of the vee, V, is selected, the vee angle is

Figure 24. Diaphragm damage due to vehicle impact on girder.

$$\theta = 2\tan^{-1}\frac{V}{2W} \qquad \text{(Eq. 3.9)}$$

where W is the plate width.

3.4.4.3 Number of Simultaneous Vee Heats

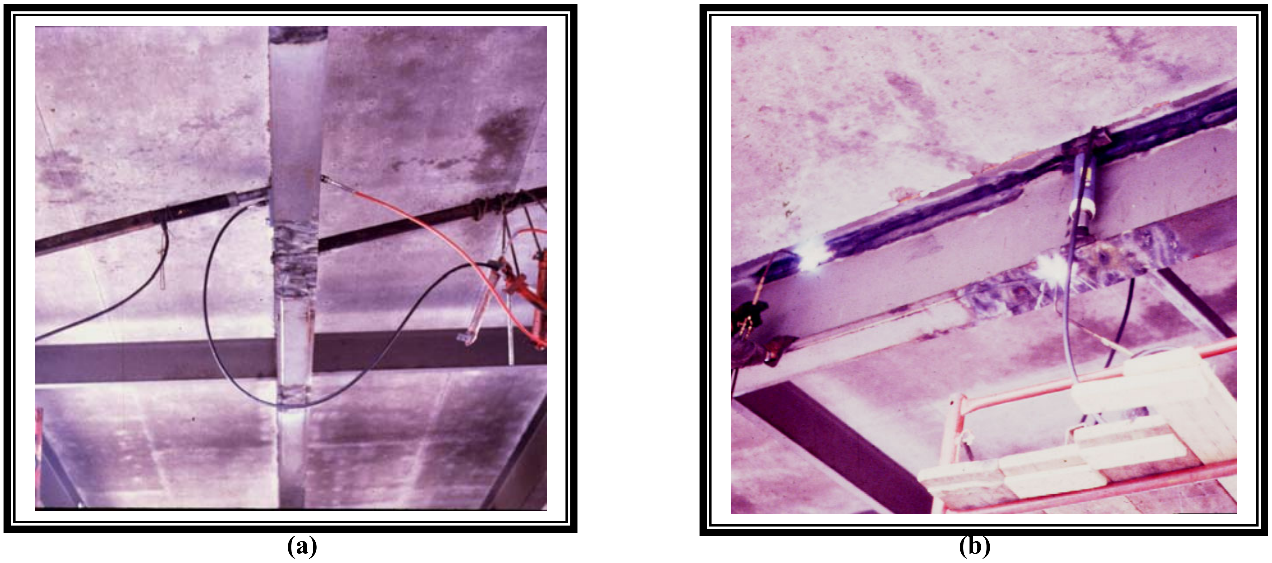
Simultaneous vee heats may be performed with proper spacing. It is recommended that the vees be spaced at least one plate width, W, apart. Also, if multiple plastic hinges occur, each hinge may be heated simultaneously.

3.4.5. Develop a Constraint Plan

Since jacking forces can expedite repairs, such forces should be utilized. Jacks should be located to produce the maximum effect in the zones of plastic deformation. Jacks must be gauged and calibrated prior to use and properly secured so they will not fall out as pressure subsides during cooling. The loads applied to the structure should be controlled and the limiting values established. A jacking arrangement for a composite girder bridge is shown in Figure 25. Lateral forces are utilized on the lower flanges, Figure 25a, while jacks between flanges are used for local damage, Figure 25b.

For cases where residual moments are small, the jacking moment, M_j, should be limited to

$$M_j \leq \frac{M_p}{2} \qquad \text{(Eq. 3.10)}$$



(a) (b)

Figure 25. Jacking arrangements for global and local damage on a composite girder bridge.

where M_p is the plastic moment capacity of the member or damaged element (such as the lower flange of a composite girder). Methods of computing jacking forces for various member configurations are available (Avent and Mukai, 1998). Any residual moments will be relieved during the first few heats. Rather than computing residual moments, an alternative is to use a jacking moment of only ¼ M_p during the first two cycles.

On occasion, a hairline fracture will occur or become visible during heat-straightening repair. The causes are believed to be: (1) excessive restraining forces being applied during the heating process; (2) successive repairs of a re-damaged element; and/or (3) the growth of micro cracks initiated during initial damage. Item (1) is the primary cause, so restraining forces should be specified at safe limits and be monitored during actual repair. For item (2), heat straightening material should be limited to only two damage repairs.

3.4.6 Estimate the Heats Required to Straighten the Members

The estimate of number of heats provides a time line for the project. Comparing the estimated movement with the actual movement as it progresses also indicates whether the heating is being properly done. The number of heats, n, can be estimated as

$$n = \frac{\varphi_d}{\varphi_p} \qquad \text{(Eq. 3.11)}$$

where φ_p is the predicted plastic rotation per heat and φ_d is the degree of damage. Formulas for the plastic rotation associated with various structural shapes and damage conditions are provided in a later section of this guide.

3.4.7 Repair Plans and Specifications

The final step is to prepare plans and specifications for the project. These plans will be the inspector's guide as well as the contractor's directive. Suggested specifications are given in Appendix I. As noted in 3.1, the owner provides quality assurance inspectors to verify the contractor complies with contract requirements. The contractor is responsible and must provide both quality control and supervisors to satisfy the contract.

3.5 Supervision of Repairs

3.5.1 Monitoring the temperature

Excessive temperatures may cause surface damage or lead to increased brittleness. Temperature can be monitored in several ways. One of the most accurate is to use temperature-sensing crayons. These crayons melt at a specified temperature and are available in increments as small as 14°C (25^{o}F) (Figure 26). By using two crayons that bracket the desired heating temperature, accurate control can be maintained. The crayons and their marks will burn if exposed directly to the flame of the torch, and heat needs a few seconds to penetrate and provide representative readings. Therefore, the torch must have just exited the area tested or be momentarily removed (one to four seconds) before the crayons are struck on the surface. An alternative for thinner material is to strike the crayon on the backside at the point being heated.

Another temperature monitoring method is to use a contact pyrometer. This device is basically a thermocouple connected to a readout device. It can be used in a matter similar to a temperature crayon by placing it on the surface. Because the pyrometer relies on full contact with a smooth surface, the readings vary with position and pressure, typically underestimating the actual temperature. It is recommended that the pyrometer be calibrated with temperature crayons prior to using.

Infrared devices are probably the most convenient to use. These devices record the temperature with a digital readout and can be used from a distance to minimize disruption of the heating process. However, the torch still needs to be beyond the area or momentarily removed while taking the reading.

To complement the crayons, pyrometer, or infrared devices; visually observe the color of the steel at the torch tip. Under ordinary daylight conditions, a halo will form on the steel around the torch tip. At approximately 650°C (1200°F) this halo will have a satiny silver color in daylight or bright lighting. The observation of color is particularly useful for the technician using the torch to maintain a constant temperature. However, this is the least accurate method of monitoring temperature and is approximate at best.

3.5.2 Controlling restraining forces

Another concern for the heat-straightening supervisor is the control of restraining forces. Typically hydraulic jacks are used to apply restraining forces (see Figure 27 as an example) and should be calibrated so that the force being exerted can be determined. Mechanical jacks should only be permitted if they are calibrated to control applied loads. The maximum allowable force should be computed as part of the design process and specified in contract documents.

3.5.3 Review of Proposed Heating Patterns

The inspector should review and accept the heating patterns and torch paths proposed by the contractor. The general patterns can be part of the repair plan.

Figure 26. Temperature sensing crayons.

Figure 27. Jacks in place on a Wisconsin bridge.

3.5.4 Checking Tolerances

A significant concern is the tolerance for the completed repair. The contract documents should specify the allowable tolerances and the inspector should verify that these limits either have been met or where (and why) exceptions were accepted. While tolerance levels may be similar to that of new construction, often a greater tolerance is specified to reduce the number of heat cycles required, especially in restricted areas and to minimize the cost of the repair. This decision should be made as part of the design process. Recommended tolerances are given in Appendix I.

3.5.5 Safety

The above items relate specifically to heat straightening. The contractor's supervisor exercises normal control of the job site, as with any construction project, including monitoring of safety procedures.

3.5.6 Checklist of Procedures for Supervisors and Inspectors

Remember that the goal is not just to straighten the damage, but to straighten it safely. There are a number of critical items for the supervisor to verify as the repair progresses.

1. Heating patterns are submitted, reviewed and accepted prior to initiating the repair.
2. Periodically check the jack gauges to insure that excessive force is not being applied before heating.

3. Periodically monitor the heating patterns, torch motion and temperature.
4. Observe the color of the steel at the torch tip. In normal daylight lighting, the steel should have a satiny silver halo at the tip. In low light, a slight dull red glow may be visible.
5. Establish reference points to measure movements. A taut line is useful although it must be moved aside during heating. In small regions, a straight edge may be used. Sometimes it is convenient to measure from a part of the adjacent structure which will not move during the straightening process.
6. Be sensitive to worker and public safety issues since work is usually performed with at least some traffic nearby. Insure that jacks and other equipment are secured from falling.
7. Final acceptance should be based on meeting the specified dimensional tolerances without exceeding temperature or restraint limitations.

4. EFFECTS OF HEAT STRAIGHTENING ON THE MATERIAL PROPERTIES OF STEEL

4.1 Introduction

The potential for detrimental effects from heating damaged steel has limited the implementation of heat straightening. However, with an understanding of the properties of steel, heat straightening can be safely conducted. Heating steel reduces the yield stress as well as the elastic modulus but the coefficient of thermal expansion increases with temperature. The behavior of these parameters complicates attempts to understand the response of steel to heat straightening. In addition to these short-term effects, heat can result in long-term consequences which may be detrimental.

Most structural steel used for bridge construction in the United States is classified as low carbon, high strength low alloy (HSLA) or quenched and tempered (Q & T) steel. At ambient temperature, these steels have three major constituents: ferrite, cementite and pearlite. The iron-carbon equilibrium diagram shown in Figure 28 illustrates the relationship of these components. Ferrite consists of iron molecules with no carbon attached, cementite is an iron-carbon molecule, (Fe_3C); and pearlite is a mixture of cementite (12 percent) and ferrite (88 percent). A low carbon steel has less than 0.8 percent carbon, too little to develop 100 percent pearlite, resulting in pearlite plus free ferrite molecules. High carbon steels (carbon content between 0.8 and 2.0 percent) have more carbon than required to form pearlite, resulting in steel with partial cementite. Low carbon steels tend to be softer and more ductile, characteristics of ferrite, but cementite is hard and brittle so high carbon steels are harder and less ductile, poor properties for bridges.

Temperatures greater than about 700°C (1300°F) begin to produce a phase change in steel. This temperature is often called the lower critical (or lower phase transition) temperature. The body centered cubic molecular structure begins to assume a face centered cubic form. With this structure, a larger percentage of carbon will be carried in solution. When steel cools below the lower critical temperature, it attempts to return to its body centered structure. Since this retransformation requires time, rapid cooling may not permit the complete change to occur and a hard, brittle phase called martensite occurs. This form has reduced ductility and is 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 815-925°C or 1500-1700°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.

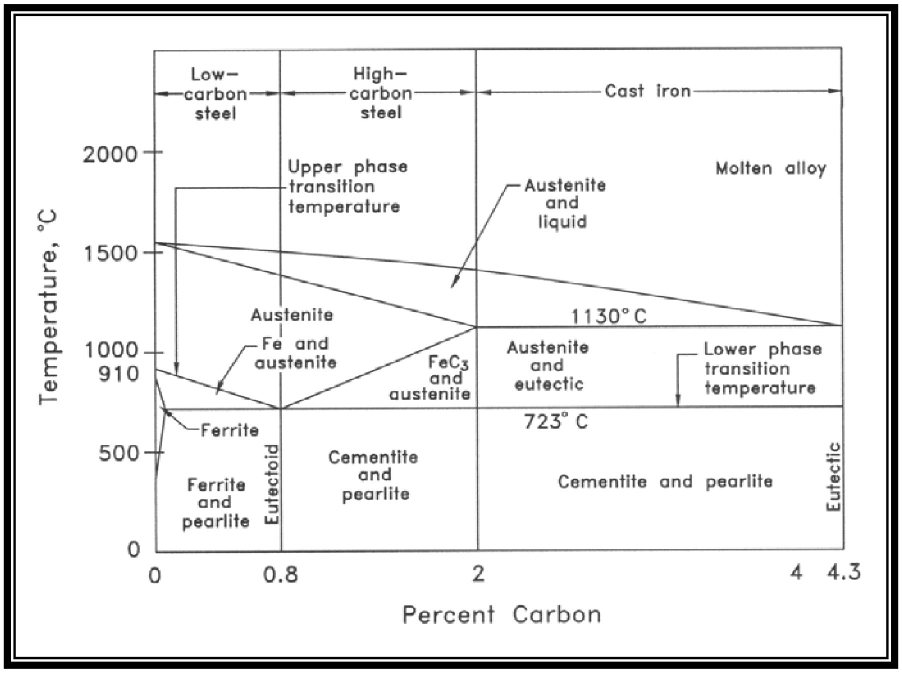


Figure 28. Iron-carbon equilibrium diagram.

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 is this concern that has limited the application of heat straightening in many cases.

A related issue is the question of residual stresses. When heated steel cools, the surfaces having the most exposure to the cooling environment contract more rapidly. This unequal contraction produces residual stresses found in most steel shapes and it is important to understand how heat straightening affects these patterns. The purpose of this chapter is to provide a summary of how heat straightening affects material properties and residual stresses.

4.2 Residual Stresses in Heat-straightened Steel

Significant residual stresses occur in most structural steel members. Such stresses usually result from differential shrinkage during cooling in the manufacture of both rolled and welded built-up shapes. However, the cutting and punching process during fabrication may also produce residual stresses. Residual stresses in fabricated steel can be quite high and may reach 50 percent of yield for some rolled shapes and approach yield for some welded members. With one exception, residual stresses have been neglected in code requirements governing steel design. The reasons for neglecting residual stresses relate to two characteristics: (1) The ductility of steel allows for a moderating redistribution of residual stresses when a member is subjected to large loads, and (2) since residual stresses are self-equilibrating, large compressive stresses at one location on a cross section are balanced by tensile stresses at another location. As a consequence, the stresses at a specific cross section produced by applied loads is additive to the residual stresses at some points and are subtractive at others so the ultimate strength of a member is usually not affected. The exception is compression members in which high residual stresses may reduce the buckling strength. American design codes account for residual stresses in compression members by assuming an average residual stress value of 50 percent of the yield stress. This assumption may lead to somewhat conservative designs for rolled shapes (which have smaller residual stresses) and slightly less conservative designs for welded built-up shapes (which have larger residual stresses). European codes have adopted the multiple column curve approach in which different formulas are used depending, on the magnitude of residual stresses. For these codes the level of residual stress affects the design capacity.

Avent, et. al. (2001) conducted research to assess whether heat straightening produces some negative effects due to residual stresses. The distribution of residual stresses for vee heated plates is shown in Figure 29 and those for various heat-straightened rolled shapes are shown in Figures 30-34.

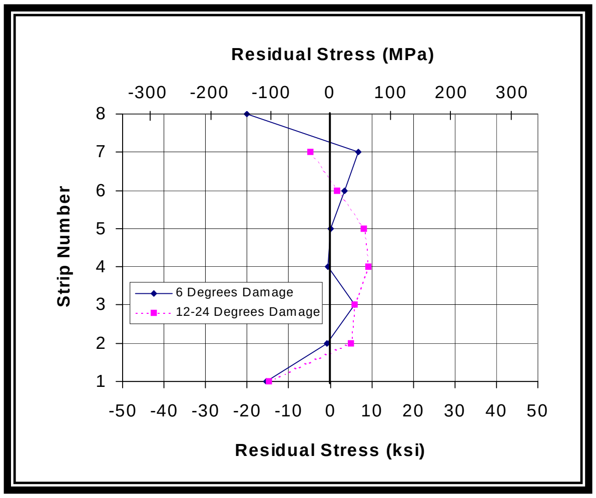


Figure 29. Residual stress distribution for plates damaged and then vee heated

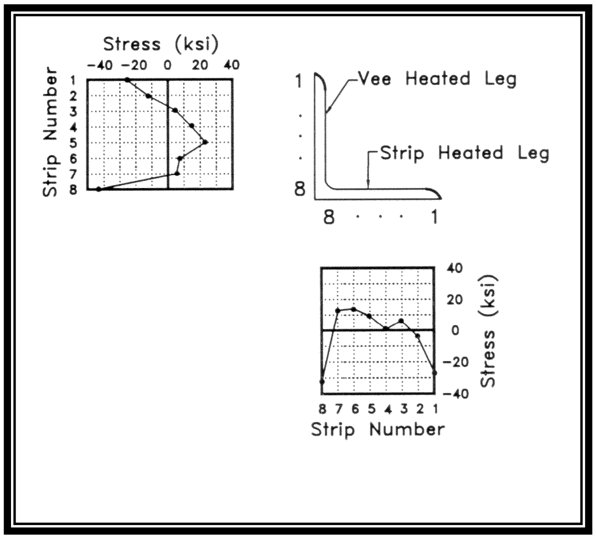


Figure 30. Typical residual stress distribution for a heat straightened angle

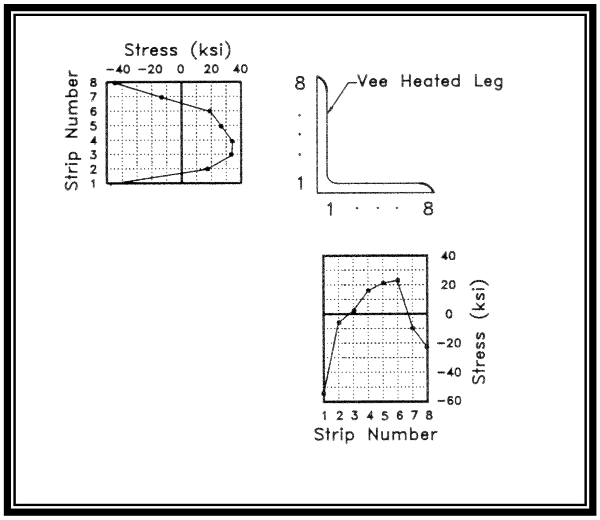


Figure 31. Typical residual stress distribution for a heat straightened angle

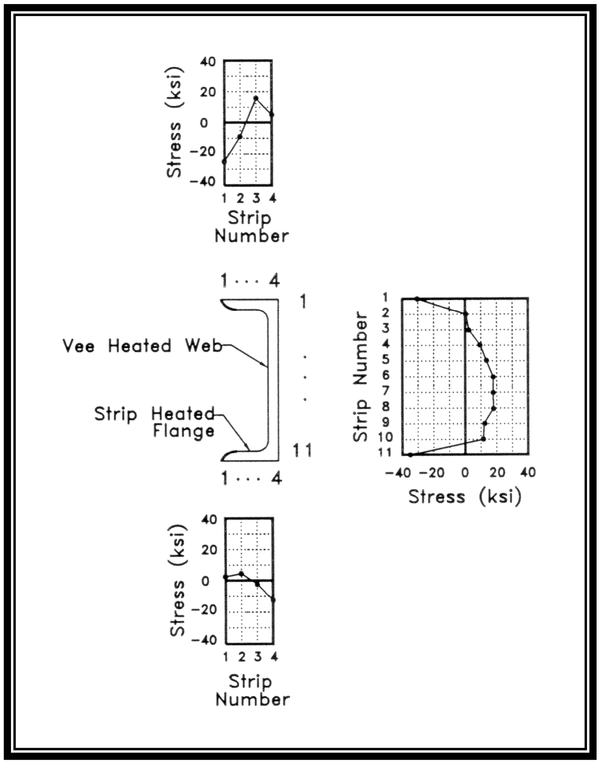


Figure 32. Typical residual stress distribution for a heat straightened channel

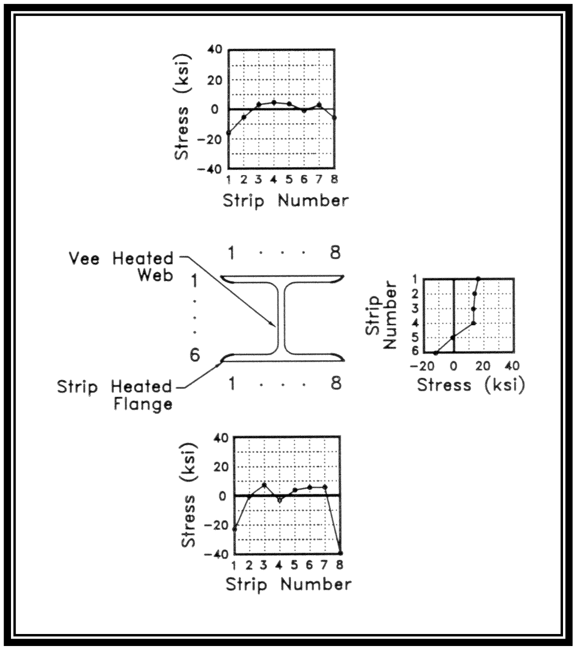


Figure 33. Typical residual stress distribution for a Category S wide flange beam

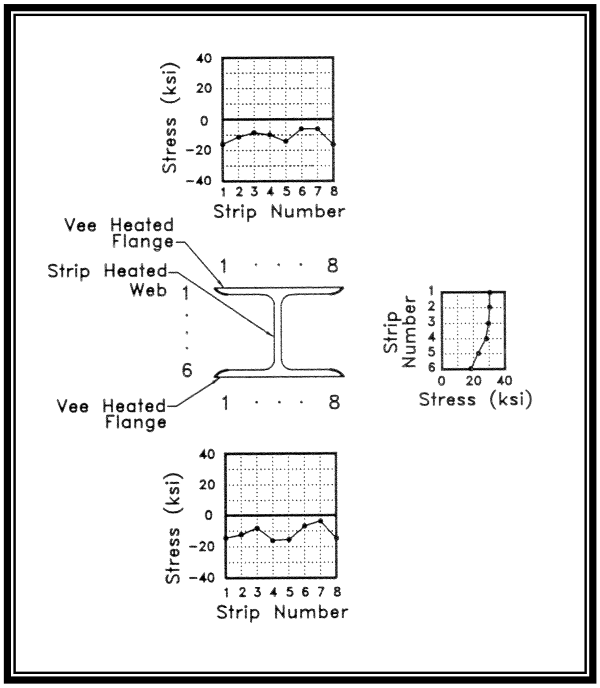


Figure 34. Typical residual stress distribution for a Category W heat straightened wide flange beam

In summary, the residual stresses in heat-straightened plates are fairly consistent having maximum compression stresses of about 150 MPa (20 ksi) at the edges and tension stresses of about one-half that value at the center of the plate. Residual stresses in heat-straightened angles and channels tend to have maximum values approaching yield in compression at the toes and heel. Relatively high tension stresses are found near the middle of each leg. Maximum residual stresses in wide flange beams approach the yield stress in compression at the flange edges.

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 to welded built-up members. Since U.S. codes use a singe column curve concept, these members are all treated the same and no capacity reduction should be assumed. Second, high tensile residual stresses reduce the effectiveness of jacking forces by effectively canceling out compressive stresses in areas where externally applied forces would cause them. Movement could be reduced or even reversed, if the jacking force moment does not compensate for the residual stresses.

Finally, large compression residual stresses may produce bulges in the compression elements of a cross section during heat straightening. Special heating patterns and sequences may be required to prevent this effect.

4.3 Effect of Heat Straightening on Material Properties of Steel

Research data (Avent, Mukai and Robinson, 2000) indicate that heat straightening affects the mechanical properties of steel. Early researchers used undamaged steel and a small number of heats to conclude that property changes after cooling were minimal. However, tests on damaged and subsequently heat-straightened plates and beams indicate that some property changes may be of significance. The modulus of elasticity may decrease by over 25% in some heated regions.

Yield stress may increase by as much as 20% in some cases, especially in the vicinity of the apex of vee heats. Specimens heated for various lengths of time, cooled both by air and by quenching with a mist, and subjected to various superimposed loads and residual stresses have been tested. None of theses variables had significant effect on the yield stress with the possible exception of the quenched and tempered steel. In the case of quenching, the yield stress was, on the average, unchanged from the original yield. Overall, the data indicates that the long term effects of the heat straightening process on yield stress are small but generally increase it.

Tensile strength also increases but at only half the rate of yield stress. The ductility as measured by percent elongation typically decreases by one-third.

In general, the fatigue-crack initiation threshold increases with tensile and yield strengths, but tensile strength increases in the heat-straightened plates were relatively small, when compared to ductility losses. Thus, improvement of the fatigue-crack initiation threshold, based solely on tensile strength could possibly be more than offset by the reduced stress redistribution permitted by the ductility loss. Some reduction in the fatigue limit might occur as a result.

Similar to ductility, fracture toughness (a value proportional to the energy consumed during plastic deformation) may decrease as a material's yield strength changes during heat straightening. Research data indicates that considerable variation may occur in Charpy vee notch tests before and after heat straightening. However, no clear relationships have been established for first time heat straightening repairs.

Most research on material properties effects has been limited to strain ratios of 100 or less. This range of strain ratios includes a majority of typical bridge damage. Of particular significance is that, within this range, changes in mechanical properties after heat straightening are not a function of degree of damage as measured by angle of damage or strain ratio. However, for strain ratios over 100, yield stress is directly proportional and elongation is inversely proportional to strain ratio. Thus, except for high degree of damage areas, material properties should not be the primary determining factor when contemplating the use of heat straightening.

An important issue is how many times a girder can be damaged and heat straightened. Changes in all the material properties become more evident with the increasing number of damage/repair cycles. These changes are particularly significant at the region associated with the apex of the vee. After two damage/repair cycles, the property changes remain relatively modest. But after four damage cycles, the increase in yield and tensile strengths and the loss in ductility were much more pronounced (Figures 35-37). Because the variation in yield is larger, the gap between yield and tensile strengths decreases as the number of damage/repair cycles increase. The ratio of yield-to-tensile strength is around 68% for undamaged steel. That ratio typically increases to 78% after one damage/repair cycle and to 88% after eight cycles. The elongation after one or two damage/repair cycles (31-32 percent) followed the trend of results for a single repair with about a one-third reduction. However, for four or eight cycles the elongation and ductility are proportionally reduced as shown in Figure 37. This behavior with each damage/repair cycle results in an increasingly brittle material. These data illustrate why over-jacking may result in brittle fracture after a number of damage/repair cycles in the same zone.

The point at which loss in ductility becomes dangerous is case-specific. However, the extreme losses encountered in the repetitively damaged beams show that there is probably a limit to the number of times that any given member should be repaired. Material property changes were usually acceptable after two cycles. Thus, a condition that is safe to straighten once could usually be safely straightened twice. The changes become significantly greater after four and eight damage/repair cycles, respectively. These findings are further substantiated by the fact that during one full-scale study (Avent and Fadous, 1989), one girder exhibited brittle behavior by cracking during a heat in its fourth damage/repair cycle. Based on this research, re-damaged members at the same location should not be subjected to heat straightening more than twice. Connor, Kaufmann and Urban (2008) reached the same conclusion in their full-scale testing to evaluate fatigue and fracture performance.

4.4 Limits on Jacking Force to Minimize Risk of Fracture

The recommended maximum jacking force is 50% of the member capacity as discussed in Section 2.9. The basic concept is to keep the stresses due to jacking below the yield stress at the elevated temperature. For bending members the computation of capacity is straight-forward and computed as the plastic moment capacity, M_p. While some small zones of yielding may occur under the conditions of jacking equal to 50% of M_p, the majority of the cross section remains below yield. However, when considering local damage (Category L) or composite girders, the computation of capacity is not well-defined. For local damage the best way to determine the capacity is experimentally such as applying a jacking force in an undamaged low stress area until initial yielding is reached. For composite girders, refer to Avent and Mukai (1998) for computation methods.

Little research has been conducted on the effects of higher jacking forces. Avent and Mukai (1998) conducted some large scale repairs on damaged girders. One case included using jacking forces producing moments greater than 50% M_p. In this case, the movements observed during heat straightening were excessive and indicated that some hot mechanical straightening had taken place. During the 7th heating cycle, the lower flange of the composite beam fractured as shown in Figure 21. The fracture occurred on edge of the lower flange compressed by the force which induced the damage. Similar fractures have also been observed in actual field repairs. In each case the fracture occurred on the flange edge compressed when damaged. During the heat straightening repair, the jacking force induced tension in the area that fractured. This case indicates that excessive jacking forces increase the risk of sudden fractures.

Recent research by Sharma (2005) has provided insight as to why such fractures occur. A series of plates were bent about their weak axes and heat straightened using line heats. Jacking forces producing plastic moments of 50, 70 and 90 percent of capacity were used. As expected, the plate movement during heat straightening was directly proportional to the level of jacking force. Material properties tests showed that the level of jacking force had little effect on yield stress, tensile strength, modulus of elasticity, or ductility. However, there were significant differences in material properties on the side compressed by damage. Comparing material properties from the areas placed in tension and compression by the damage, the compression side had significantly: (1) higher yield stress, (2) lower ductility, and (3) less toughness based on Charpy tests. These results indicate that the compressed side is more brittle and thus more likely to fracture during repair with large jacking forces.

4.5 Limits on Maximum Damage Strains

The body of research indicates that heat straightening can be used without significantly compromising the material for strain ratios less than 100. Sharma (2005) also conducted weak axis plate tests that included damaged plates with strain ratios of 65, 150 and 200. He found the following relationships: (1) plate movement during heat straightening was inversely proportional to the strain ratio, (2) the increase in yield stress after heat straightening was directly proportional to the strain ratio, and (3) ductility after repair was inversely proportional to the strain ratio. This behavior indicates that the likelihood of fracture during heat straightening is directly proportional to the strain ratio, particularly when the strain ratio is greater than 100. Thus, the risk of fracture increases with strain ratios greater than 100.

4.6 Fatigue and Fracture Performance

Connor, Kaufmann and Urban (2008) conducted the first major study on fatigue and fracture performance of heat-straightened steel. Their full-size tests led to the conclusion that damage and repair cycles did not have a significant effect on fatigue life of girders at stiffeners and cover plates. However, live load stresses may be magnified by residual local damage (even within normal tolerances) after heat straightening. They recommend stress adjustment factors be applied to ensure that the residual damage will not cause an unacceptable increase in live load stress that would result in a fatigue failure.

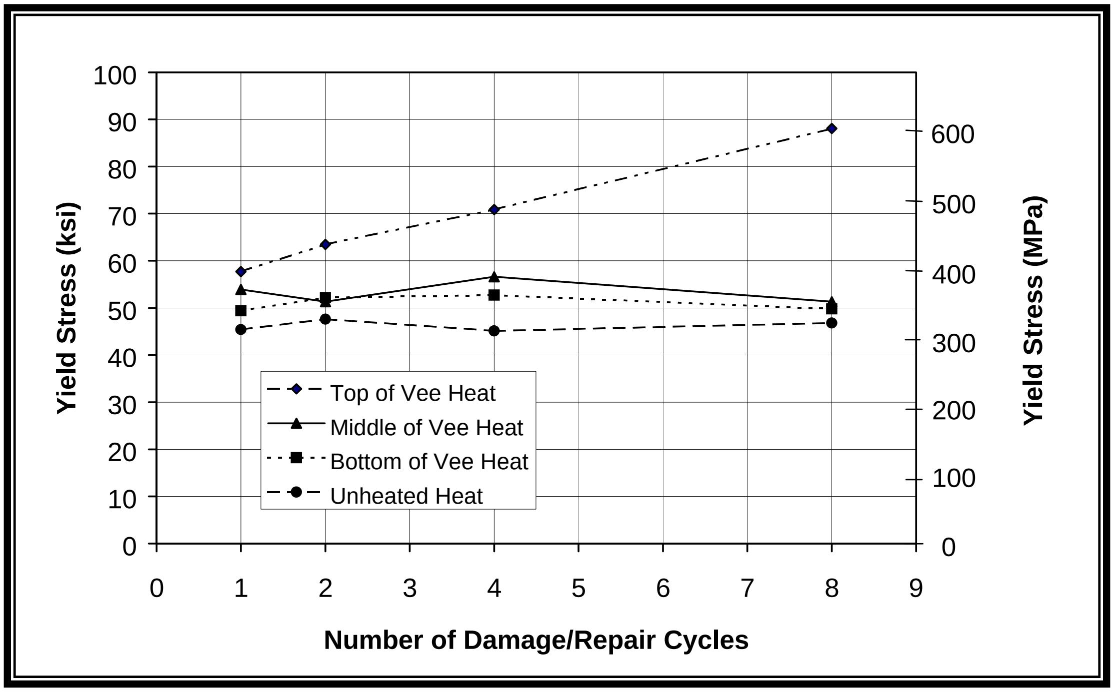


Figure 35. Yield stress versus number of damage/repair cycles for heat straightened beam

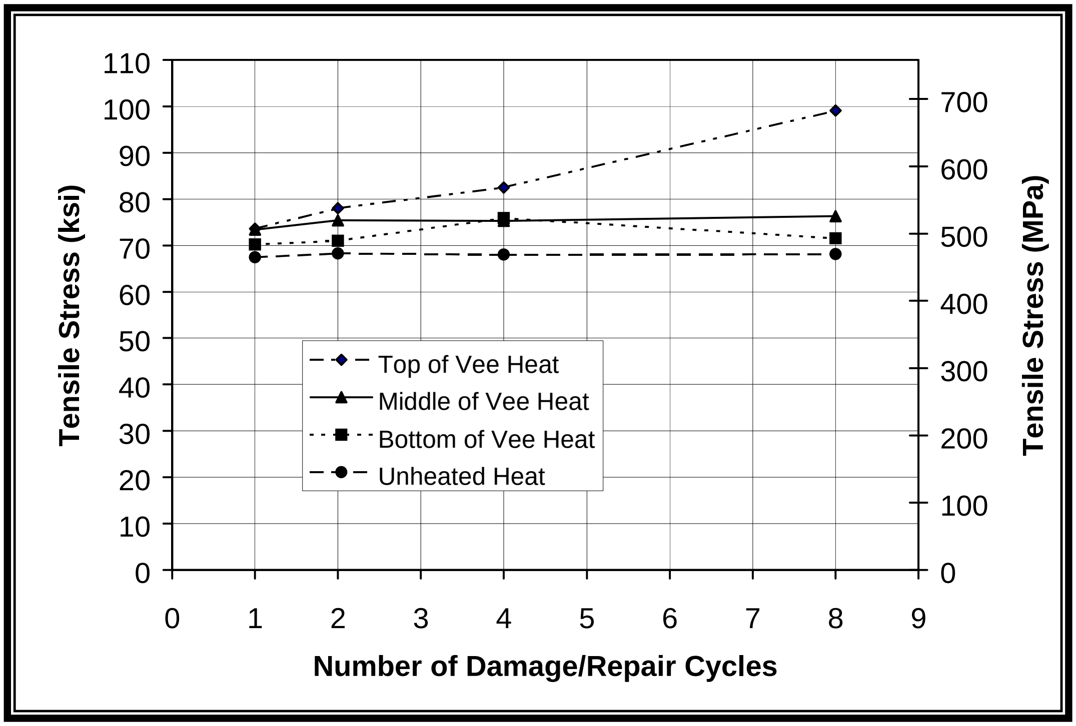


Figure 36. Tensile stress versus number of damage/repair cycles for heat straightened beam.

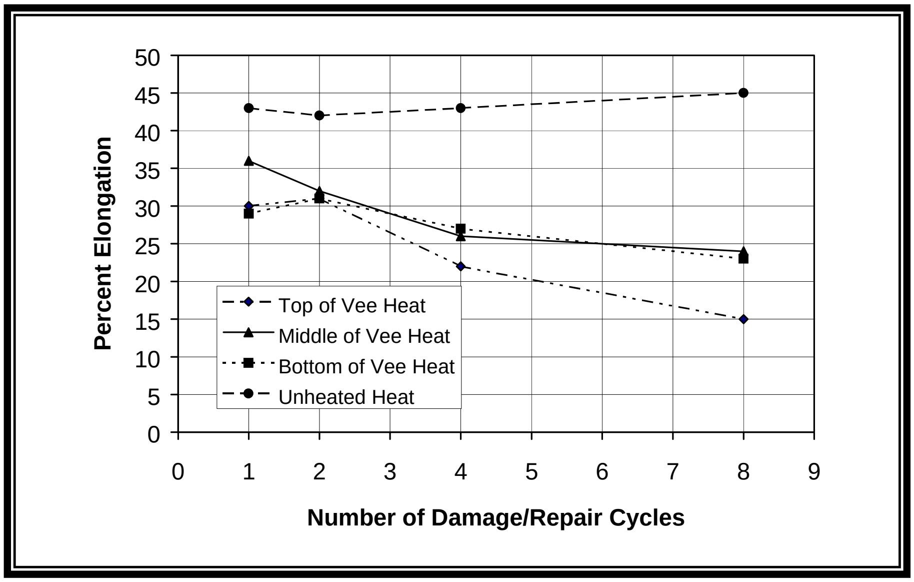


Figure 37. Percent elongation versus number of damage/repair cycles for heat straightened beam.

5. HEAT STRAIGHTENING OF FLAT PLATES

5.1 Introduction

The fundamental element of any structural steel shape is the flat plate. Damage to bridge structures involves combinations of these plate elements, bent about their strong and/or weak axes. Understanding the behavior of plates during heat straightening is fundamental to the heat straightening process.

Two studies (Roeder, 1986 and Avent, et. al. 2000)) helped define the factors affecting heat straightening of plates. As a result the following observations can be made.

- 650°C (1,200°F) is a practical and safe upper temperature limit for non-Q & T steel.
- Changes in material properties are relatively small when the temperature remains below the phase transition temperature of approximately 720°C (1330°F).
- Plastic rotation, defined as the change in angle of tangents located on either side of the damaged zone of a plate after the completion of a vee heat, is the basic measurement of movement during heat straightening.
- The rotation produced by a vee heat on an otherwise unrestrained plate is directly proportional to vee angle and heating temperature.
- Plastic strain during straightening occurs primarily within the vee heat region.
- Plastic strain is somewhat sensitive to geometry of the plate. However, much of this sensitivity can be attributed to differences in rate of heating and heat flow.
- Due to the difficulty in controlling the many variables associated with heat straightening, the magnitude of movements for individual heats may vary considerably.
- Varying the vee depths between 75-100 percent of the plate width has little influence on the plastic rotation of a vee heated plate.
- Plate thickness and width do not significantly influence plastic rotations, provided sufficient heat is applied to generate a specified consistent temperature within the vee.
- External restraints can significantly increase the movements per vee heat with the movement being related to the restraint force.
- The movement associated with each of the initial heat cycles is often larger than subsequent cycles due to internal restraints developed when a member is damaged severely enough to require a high number of cycles.
- Axial forces can be used as constraining forces, but bending moments are usually more efficient in producing movement.
- The influence of yield stress on plastic rotation is small for mild steel having an F_y between 230-345 MPa (33-50 ksi).

5.2 Variables Affecting the Movement of Heat-straightened Plates

5.2.1 Temperature

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: number and size of torch orifices, temperature of the flame, speed of torch movement, and thickness of the plate. Studies have shown that knowledgeable practitioners commonly misjudged the heating temperature by 55°C (100°F) and, in some cases, as much as 110°C (200°F). Thus, there is considerable variability in temperature control, even with experienced users.

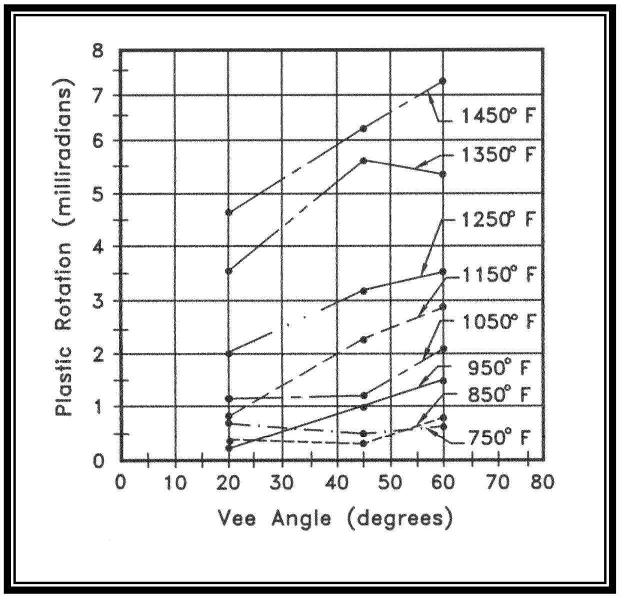


Figure 38. Influence of heating temperature on plastic rotation for 3/4 depth vee heats and a jacking ratio of 0.16.

The effect of heating temperature can be seen in Figure 38 in which the heating temperature was varied from 370-815°C (700° to 1500°F) in increments of 56°C (100°F). The results establish a regular progression of increased plastic rotation with increasing temperature.

The maximum temperature recommended by most researchers is 650°C (1200°F) for all but the quenched and tempered high strength steels. Higher temperatures may result in greater rotation; however, out-of-plane distortion becomes likely and surface damage such as pitting will occur at 760-870°C (1400-1600°F). Also, temperatures in exceeding 700°C (1300°F) may cause molecular composition changes which could detrimentally change material properties after cooling. The limiting temperature of 650°C (1200°F) allows for a safety factor in this regard. For the quenched and tempered steels, the heat-straightening process can be used but the temperature should be limited to 595°C (1100°F) for A514 and A709 (grades 100 and 100W) and 565°C (1050°F) for A709 grade 70W to ensure that the properties are not adversely affected.

5.2.2 Effect of Vee Angle

The results shown in Figure 38 and 39 also illustrate the effect of the vee angle when heat straightening. The amount of movement is approximately proportional to the vee angle.

5.2.3 Restraining Forces

The term "restraining forces" can refer to externally applied forces, self weight or internal redundancy. These forces, when properly utilized, can expedite the straightening process. However, if improperly applied, restraining forces can hinder or even prevent straightening.

The proper procedure for applying a restraining force is to create a moment tending to compress the stretched area. The ratio of the moment at the vee due to the jacking force, M_j, to the plastic moment, M_p, of the cross section, is M_j/M_p. This term is referred to as the jacking ratio. The effect of jacking ratios ranging from zero to 50 percent with four different vee angles are shown in Figure. 39. It can be concluded from this data that plastic rotation is generally proportional to the jacking ratio and the proper use of external loads greatly expedites the heat-straightening process.

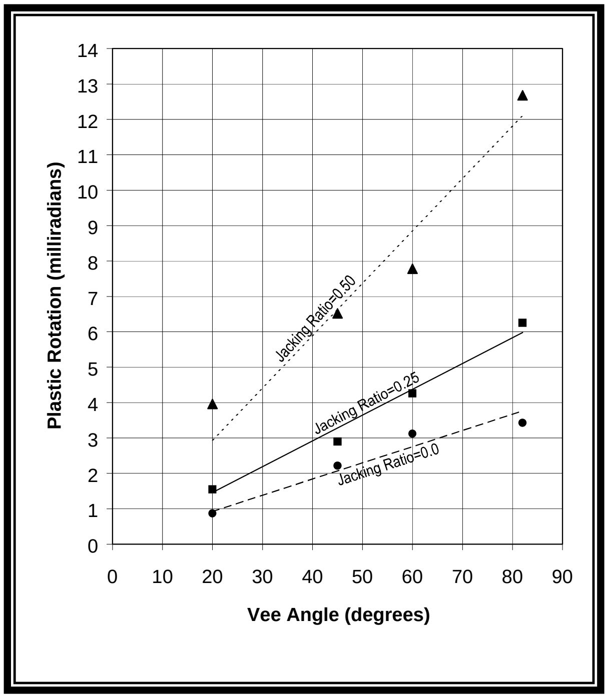


Figure 39. Influence of jacking ratio on average plastic rotation for 650°C (1200°F) heating temperatures (lines represent a least squares curve fit).

In summary, parameters which have an important influence on the plastic rotations produced by vee heats are: (1) vee angle, (2) steel temperature, and (3) external restraining force. In the usual range of three-quarters of the plate width or greater, the depth of the vee appears to have little effect.. Likewise, the plate dimensions are of minor significance as long as the heating patterns attain the desired temperature.

5.3 Analytical Development

Two general approaches have been used to develop an analytical procedure for predicting member response during a heat-straightening of a plate damaged by bending about the major axis. One approach involves finite element/finite strip thermal and stress analyses including inelastic behavior. The stress and strain equilibrium is the summation of small steps and considers the influence of the non-uniform temperature distribution. This approach is lengthy, 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 goal of the analytical development is to obtain an equation which can be used to predict the angle of plastic rotation produced by a vee heat. Avent, et. al. (2000) developed this type of model using the following assumptions: (1) longitudinal plastic strain occurs only in 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 in the longitudinal direction are constant over the zone of the vee; (3) the planes defined by the sides of the vee remain planes after heating and rotate about the apex of the vee; (4) confinement during heating is not perfect single axis along the longitudinal direction (i.e., some longitudinal movement during heating is assumed): (5) the permanent strains occur within the inner two-thirds of the vee with an effective vee angle of two-thirds the actual angle, (6) the plastic rotation varies linearly with jacking ratio, (7) perfect confinement is equivalent to a 20 percent jacking ratio, (8) the zero jacking force equals 60 percent of the perfect confinement case and (9) the heating temperature is 650°C (1200^{o}F). The resulting formula for plastic rotation, φ, (angle change due to a single vee heat) with zero jacking force is

$$\varphi = 0.0147 \sin \frac{\theta}{3} \qquad \text{(Eq. 5.1)}$$

where θ is the vee angle. The jacking force is incorporated by the introduction of a jacking force factor

$$F_\ell = 0.6 + 2\frac{M_j}{M_P} \qquad \text{(Eq. 5.2)}$$

and the plastic rotation is

$$\varphi_p = F_\ell \varphi \qquad \text{(Eq. 5.3)}$$

The formula compares well to the experimental data and is the first simple formula available that includes the parameters of heating temperature of the steel and magnitude of restraining force (jacking force). The form of this approach also lends itself to the behavior of rolled shapes, axially loaded members, and composite and non-composite girders.

6. HEAT STRAIGHTENING ROLLED SHAPES

6.1 Fundamental Damage Patterns

The process of heat straightening damaged rolled shapes is based on a logical extension of the straightening of plates. Rolled shapes can be viewed as an assemblage of flat plate elements. When damaged, some elements are bent about their strong axis, some about their weak axis and some about both. The overall effect on a member results in damage which is a combination of one or more of the fundamental damage categories described in Chapter 1.

To develop a methodology for heat straightening complex damage on rolled shapes, understanding the behavior of such shapes when subjected to single fundamental types of damage is necessary. Focusing on categories S and W, a distinction will be made between a cross sections's primary elements and stiffening elements. The primary elements are the plate elements subjected to bending about their local strong axes. The stiffening elements are perpendicular to the primary elements and bent about their own local weak axes.

For example, consider the channel shown in Figure 40, which has been plastically deformed about its major axis, resulting in Category S damage. The web of this channel, a plate element bent about its major axis, is therefore a primary element. The two flanges are bent about their minor axes and are thus stiffening elements.

For rolled shapes with flexural damage, the pattern of yielding usually differs for the primary and stiffening plate elements. Typically, the primary plate elements develop plastic hinges, a state of stress in which the entire cross-section has reached yield (F_y): Tensile yield in one region and compressive yield in the other.

The stiffening elements of a damaged rolled shape may exhibit one of several conditions. In the first, yielding does not occur because the stiffening element is located near the neutral axis of the cross section, e.g., when a wide flange beam is bent about its minor axis, the web may not reach yield. In the second case, the stiffening element is located near the extreme fibers of flexural yielding (such as the flanges of the channel shown in Figure 40). In this situation the flanges yield due to axial stress (either tension or compression). In the third case, the stiffening element is yielded in weak axis bending in which a region of yield is formed as shown in Figure 41. The results are a narrow strip of flexural yielding often referred to as a yield line.

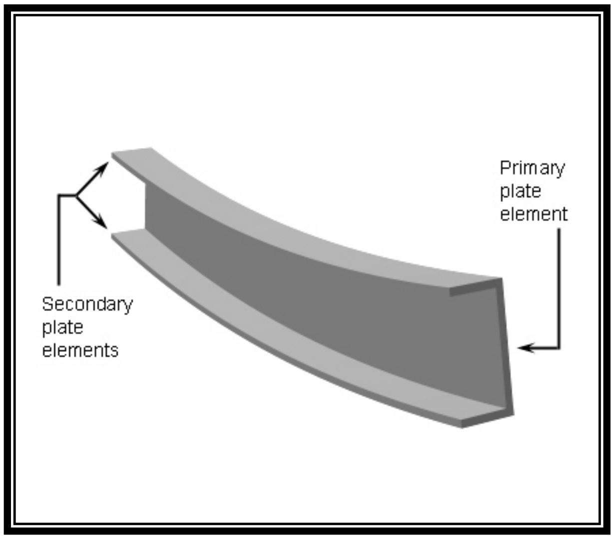


Figure 40. Primary and stiffening plate elements for a channel bent about its major axis (Category S damage).

With the various patterns of inelastic deformation which occur in damaged rolled or built-up shapes, the heating pattern for repair must be tailored to fit. While the vee heat is generally used on primary elements of a section bent about their major axes, the stiffening elements may require a strip heat, line heat or no heat at all. Multiple heating patterns introduce additional variability, so the time to complete a heat may be considerably longer than heating a single plate. Considerable cooling may occur at the initial heating locations before the last element is heated, retarding expected movement due to increased internal restraints. A good practice to minimize the heating time is using more than one torch for complex patterns.

In addition to the jacking force factor, the various combinations of plate elements found in structural steel shapes introduces two other parameters that may affect the member's behavior during heat straightening. The first is a shape factor and the second is a stress factor. It is obvious that the shape may influence behavior, but the stress factor requires an explanation.

When jacking forces are applied prior to heat straightening, the distribution of stress over the heated section due to jacking will vary according to the shape of the cross section and the restraint conditions. As the torch moves over the section, the steel temperature rises and then falls in a manner somewhat analogous to a wave moving across calm water. The heat variation produces continuous and complex changes in the combined stress distribution. As a consequence, stress distributions may be quite different between two members of different configurations.

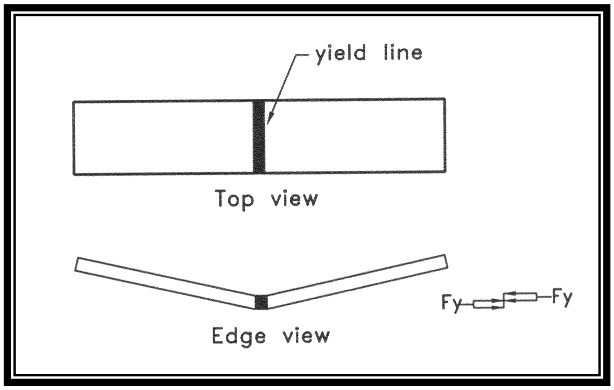


Figure 41. Weak axis bending resulting in a yield line in the plate element.

One measure of this effect is the ratio of plastic moment, M_p, to the moment at initial yield, M_y. For a constant yield stress this ratio is Z/S where Z is the plastic section modulus and S is the elastic section modulus. Since the moment due to jacking is usually expressed as a percentage of M_p, the degree of yielding during heating is often a function of this ratio. For example, $Z/S = 1.5$ for a rectangular plate and is only about 1.12 for typical wide flange beams. In other words, yielding is initiated at two-thirds of ultimate capacity for a plate but does not occur until 90 percent of capacity for most wide flange members. For a moment due to jacking in the range of 35-50 percent of M_p, some localized yielding will occur during heat straightening. The amount, and consequently the degree of straightening, will depend on the stress factor as a function of Z/S.

The model for predicting movement during heat straightening is a modification of the plate equation, Eq. 5.3. For mild steel, the equation for plastic rotation of a structural shape can be expressed as

$$\varphi_p = F_\ell F_s F_a \varphi_b \qquad \text{(Eq. 6.1)}$$

where F_ℓ is the factor associated with the external jacking force, F_s is a factor reflecting the shape of the cross section, F_a is the stress factor, and φ_b is the basic plastic rotation factor derived for a rectangular plate (see Eq. 5.3) and expressed as:

$$\varphi_b = 0.0147 \sin\frac{\theta}{3} \qquad \text{(Eq. 6.2)}$$

The stress factor can be written as

$$F_a = 1 - 2[1 - (\frac{2}{3})(\frac{Z}{S})]\frac{M_j}{M_p} \qquad \text{(Eq. 6.3)}$$

Where Z/S is the ratio of plastic to elastic section modulus for bending about the major axis (except for angles in which the ratio is multiplied by F_s).

The jacking force factor is identical to that developed for plates, that is

$$F_\ell = 0.6 + 2\frac{M_j}{M_p} \qquad \text{(Eq. 6.4)}$$

The shape factor is

$$F_s = 1 + \frac{1}{2}(\frac{b_s d_s}{d^2}) \qquad \text{(Eq. 6.5)}$$

Where

b_s = width of stiffening element;

d_s = distance from apex of vee heat on primary member to intersection of stiffening element; and

d = depth of the vee heated elements (assuming a vee depth (d_s) of at least three-quarters of this depth).

6.2 Composite Deck-Girder Bridges

Two primary parameters affecting heat straightening—vee angle and heating temperature—have been discussed in previous chapters. However, three additional parameters have also been shown to play a central role in the heat-straightening process. One factor relates to the influence of restraining forces, a second to the heating patterns used, and a third to the damage-induced pattern. A typical damage pattern is shown in Figure 42. Typically, a lateral jacking force is applied to the lower flange during heat-straightening repair. However, the determination of the jacking ratio is complicated for composite girders due to the internal redundancy of the system. First, when a lateral jacking force is applied to the lower flange, only a portion of that force produces a moment in the flange. Part of the force follows a load path through the web into the upper composite flange and is resisted by the concrete deck. The determination of the actual moment in the lower damaged flange is required to prevent overstress during jacking and to predict the expected movement. Second, the moment capacity due to a laterally applied load is also influenced by the load path transfer making it difficult to compute the plastic moment capacity, M_p.

The most effective combinations of heating patterns and restraining forces are ones that minimize any internal constraints

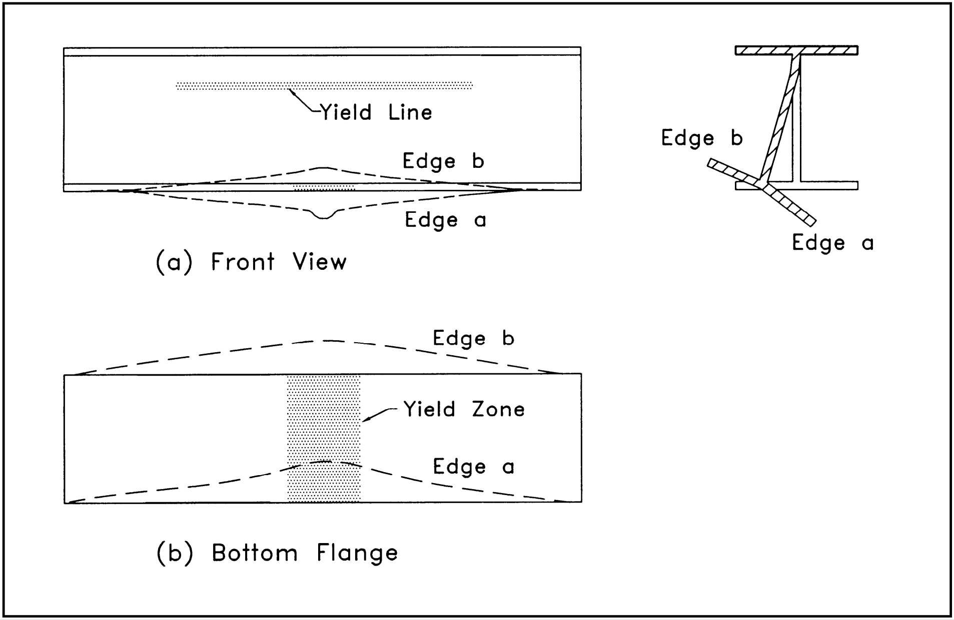


Figure 42. Typical deformed shape and yield zones in damaged composite girders.

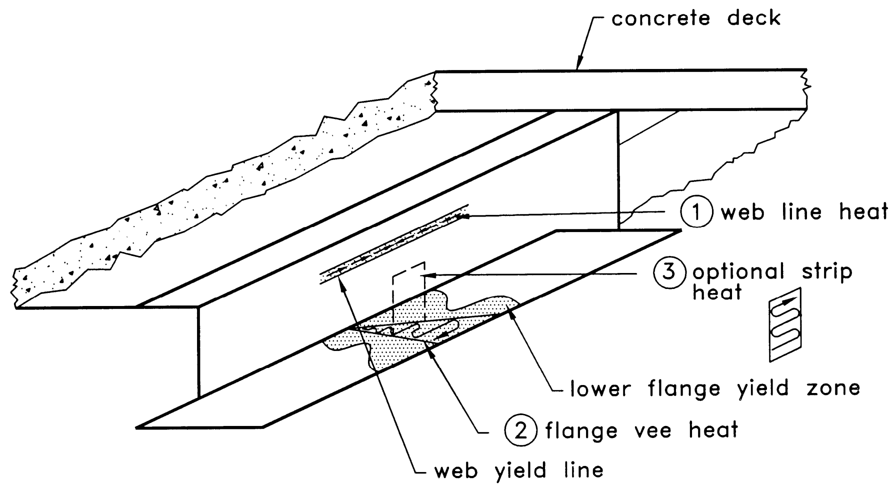


Figure 43. Heating patterns for composite girder.

inhibiting the straightening while maximizing the positive external constraint effect. For any damage condition, an analysis of these factors is required to optimize straightening effects. For Figure 43, the wide flange can be analyzed in terms of its web and bottom flange plate components as interacting elements

Each has plastically deformed so attempting to straighten the first component independently of the second leads to the second component acting as a negative constraining force rather than a positive one.

6.2.1 Factors Affecting Heat-Straightening Behavior of Composite Girders

6.2.1.1 Heat Patterns

The term “heat patterns” refers to the combination and layout of vee heats, line heats, and strip heats used to conduct the heat-straightening repair. 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 a composite beam in Figure 43. Care must be taken to iteratively adjust the span of the line heats, so only portions of the web are heated that show plastic curvature after the previous 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 usually required. 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 strip heat tends to reduce the buckling of the web near the center of damage.

6.2.1.2 Residual Moments

A characteristic of each damaged girder is the presence of residual moments. When damage is induced, the web acts as a spring resisting the movement. While a yield line typically occurs near the top of the web, there is also an elastic component of stored energy, often referred to as internal redundancy. During the first heat cycle, this restoring force acts as an additional jacking force tending to straighten the girder. Unless the external jacking ratio is reduced, the plastic rotation during the first heat cycle is magnified. The initial plastic rotation relieves the majority of this stored force, so, it doesn’t influence successive heats. If the girder is externally indeterminate in the impact direction, residual moments are also created during the damage phase. For either case this behavior should be considered when developing a constraint plan. A reduced jacking force is recommended during the first two heating cycles to minimize internal force effects and the possibility of cracking.

6.2.1.3 Restraining Forces

The simplest way of providing restraining forces is to allow the unheated portion of the member to restrict thermal expansion by suitable heat pattern locations. This is a form of an internal constraint. Internal constraint may also be imposed by the self-weight, axial loading, or static indeterminacy of the member. Frequently, external restraining forces are used to complement or even negate the internal constraints to enhance the heat-straightening.

6.2.1.4 Stiffening Effect of Web

When a lateral restraining force is applied to the damaged lower flange of a composite girder, the purpose is to generate a restraining moment in the lower flange. Due to the web interaction between the lower flange and the completely restrained upper flange, some of the applied force is transferred through the web into the deck rather than into the lower flange. For deep girders most of the force goes into the lower flange. However, for more shallow depths, an increasing amount of the force does not go into the lower flange. Only the fraction of the total force that is directly carried by the bottom flange provides external restraint to the vee heat. Hence, a jacking ratio assuming that the lower flange provides the total resistance does not reflect the true bending moment in the bottom flange and may be considered only as a nominal jacking ratio. It is more relevant to calculate the jacking ratio using the actual bending moment transferred to the bottom flange. This ratio is the effective jacking ratio.

6.2.2 Model for Heat-Straightening Response

Avent and Mukai (1998) developed a model to determine the amount of the applied lateral jacking force that is actually distributed to the lower flange as opposed to that which is transferred through the web to the composite deck. The stiffness of the system includes both the effect of the lower flange and the web stiffening effect due to connectivity with the upper composite flange. Thus, only a portion of the moment generated by the jacking force (effective jacking force) is actually distributed to the lower flange.

The equation for the change in angle, φ_c, due to a single vee heat on the lower flange is

$$\varphi_c = F_a F_\ell \varphi_b \qquad \text{(Eq. 6.6)}$$

Where

$$F_a = (\frac{d/t_w}{46})^2 \qquad \text{(Eq. 6.7)}$$

$$F_\ell = 0.6 + 2\gamma \frac{M_j}{M_p} \qquad \text{(Eq. 6.8)}$$

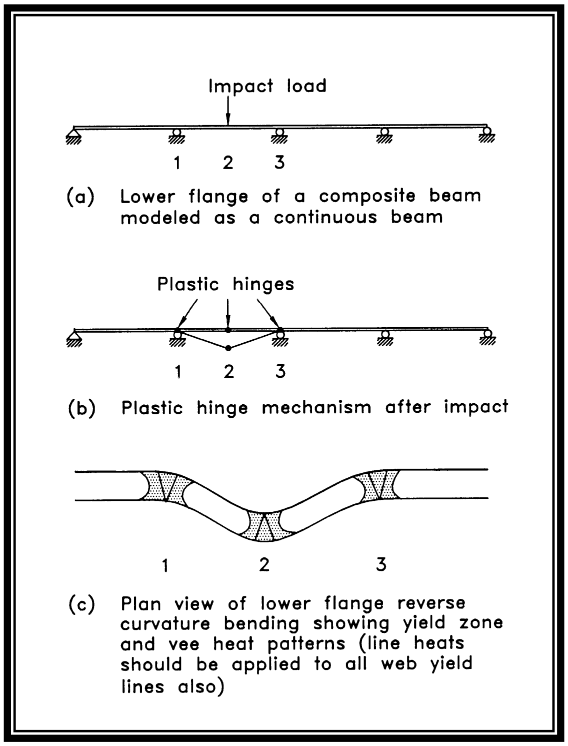
$$\gamma = \frac{d/t_w}{10{,}000}(15 + 2.75\, d/t_w) \qquad \text{(Eq. 6.9)}$$

$$\varphi_b = 0.0147 \sin\frac{\theta}{3} \qquad \text{(Eq. 6.10)}$$

and d/t_w is the web depth-to-thickness ratio, M_j is the jacking moment if the lower flange carried the load independently of the web (apparent jacking force), and M_p is the plastic moment of the lower flange.

6.2.3 Modeling Statically Indeterminate Spans with Intermediate Diaphragms

Practically all steel spans over roadways have intermediate diaphragms. When the lower flange is impacted, its behavior resembles that of a beam continuous over several supports with the diaphragms acting as these supports, Figure 44a. The impact usually produces a plastic hinge mechanism as shown in Figure 44b. The three plastic hinges produce reverse curvature bending and yield zones at the impact point and adjacent supports a shown in Figure 44c. The vee heat patterns are also shown in Figure 44c. Both the positive and negative curvature sections should be heated either simultaneously or in quick succession so rotation will occur at all three locations with reduced restraint from adjacent plastic hinges. Consequently, the model for the single span case should provide a reasonable approximation of this more complex situation. Important considerations for composite girder repair are the residual stresses induced during both the damage and the repair phase.



(a) Lower flange of a composite beam modeled as a continuous beam

(b) Plastic hinge mechanism after impact

(c) Plan view of lower flange reverse curvature bending showing yield zone and vee heat patterns (line heats should be applied to all web yield lines also)

Figure 44. Diaphram stiffened composite girder

6.3 Trusses and Axially Loaded Members

6.3.1 Introduction

The stress condition of a member plays a major role in its behavior during heat straightening. In some cases the loads on a structure can be reduced to the point that member stresses are a minor factor. But for other cases, even after the removal of live loads, the dead loads produce significant stresses. A primary case in point is the truss bridge. Typically, the dead load stresses on such structures may range from 25-50 percent of maximum service load stresses in some members. It is thus necessary to examine the stress distribution of a structure prior to initiating heat straightening.

For the beam shown in Figure 45, dead loads produce bending about the minor axis of the wide flange beam. The dead load can have a neutral, positive or negative effect on repairs depending on the type of damage. For example if the damage is a result of bending about the beam's major axis in Figure 45, but dead loads produce moments about the minor axis, a web vee heat is in a region of nearly zero dead load stress based on the original cross section. The dead load stress will have little effect on movement about the major axis after heating. If the damage is the result of bending about the weak axis (in the direction of the dead loads), then the flange vee heats will be working against the dead loads. Without the use of jacking forces to overcome the dead load moments, the straightening will be reduced or possibly be zero. If the damage was opposite to the direction of the dead load, the movement after heat straightening would be enhanced by the dead load.

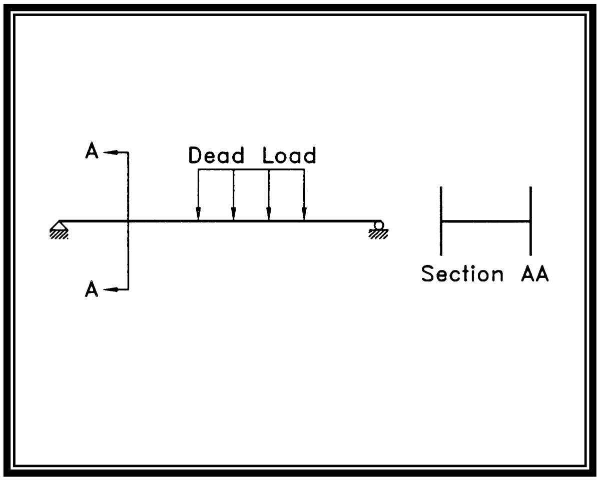


Figure 45. Dead load conditions on a simply supported beam.

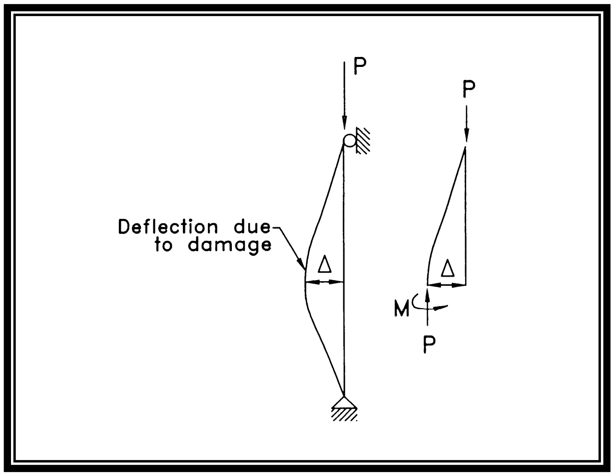


Figure 46. PΔ effect on an axially loaded column.

For columns and axially loaded members, the P-Δ effect must be considered. If an axially compressed member is damaged by lateral loads as shown in Figure 46, 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. If the lateral deflection is large, the moment due to the P-Δ effect could retard or prevent the restoration movement during heat straightening, or create instability when heating reduces steel strength..

6.3.1 Response of Columns to Heat Straightening

With the axial load applied, a moment in the member is created due to the PΔ effect. This moment tends to impede the heat straightening process as it acts to magnify the damage. The approach recommended is to cancel out this moment with the application of the lateral jacking force. The jacking force should be adjusted to impose the specified jacking ratio plus inducing a moment to cancel out the PΔ moment at the center of damage. For each heating cycle the jacking force should be reduced to compensate for the reduced PΔ moment.

To generalize, for a simply supported beam-column with the damage at an arbitrary location, the applied jacking force, P_a, is

$$P_a = P_j + P_{ec} \qquad \text{(Eq. 6.11)}$$

where P_j is the jacking force to create a specified moment at the damage location as a percentage of M_p, or

$$P_j = \frac{R_\ell \ell M_p}{ab} \qquad \text{(Eq. 6.12)}$$

and ℓ = column length, a and b = distances from end supports to the applied jacking load, and R_ℓ = the jacking ratio, M_j/M_p. P_{ec} is the additional jacking force required to cancel the eccentric moment due to the axial load, P, or

$$P_{ec} = \frac{\ell P \Delta}{ab} \qquad \text{(Eq. 6.13)}$$

Test results (Avent and Mukai, 1998) indicate that heat straightening can be successfully applied to axially loaded compression members. The results are plotted in Figure 47. Also shown is the theoretical curve for the beam without axial load based on the same parameters. The plastic rotations varied linearly with the jacking ratio, but they tended to be smaller than those predicted for the same beam without axial compression (Eq. 6.1). The axial force reduces the expected values compared to those without axial loads. Similar behavior was found for axially loaded compression members with Category S damage plastic rotations.

In summary, heat straightening is effective for axially loaded columns using the same patterns as for cases without axial compressive loads. The movements after heating will tend to be smaller than with zero axial loads on the same member. The jacking forces used should include, as a minimum, a component producing a moment at the damaged section equal and opposite to the moment produced by the axial compressive force acting through the deflection at the damaged section.

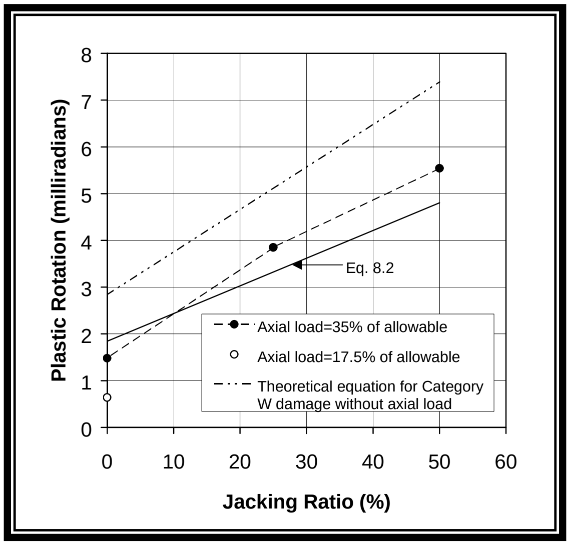


Figure 47. Plastic rotation versus jacking ratio for axially loaded Category W column.

7. HEAT-STRAIGHTENING REPAIR OF LOCALIZED DAMAGE

7.1 Damage Classification

Damage in steel members can be broadly classified as global and local damage. Different methods are required for the heat-straightening repair of these types of damage. Global damage entails deformation of both primary and stiffening elements well beyond the point of impact. Local damage is characterized by plastic strain occurring only in the region of impact. It includes small bulges, bends or crimps in single elements of the cross section. The two most frequently encountered patterns can be categorized as flange bulges and web buckles as shown in Figure 48. Flange bulges are associated with local damage to unstiffened cross section elements such as a flange of a girder. Web buckles are associated with local damage to stiffened cross section elements such as the web of a girder. All are classified as Category L damage, but two sub-classifications will be used: Category L/U for local damage to unstiffened elements, and Category L/S for damage to stiffened elements.

The focus of past heat-straightening research has been on various aspects of repairing global damage, but localized damage usually occurs concurrently with global damage. Yet, little published information has been available on heat straightening local damage. As a result, localized damage is often repaired improperly by various combinations of cold mechanical straightening and hot mechanical straightening, as well as heat straightening.

Local damage patterns display common characteristics: large plastic strains (usually tensile) in the damaged zone, and bending of plate elements about their weak axes. 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.

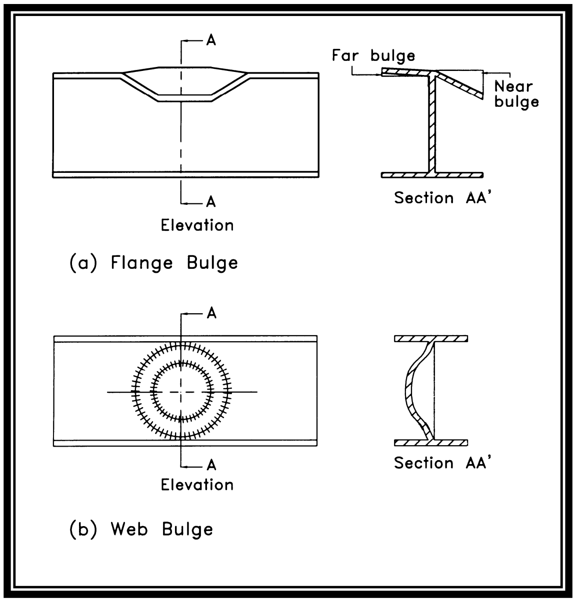
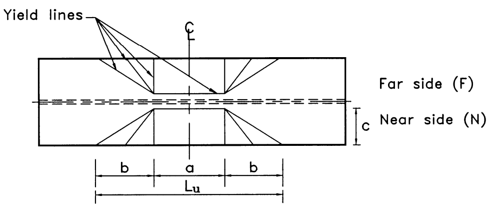


Figure 48. Typical localized damage classified as Category L.

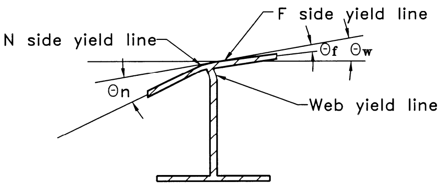
An example of local damage to an unstiffened element is shown in fig. 49. This type of damage was observed during a heat-straightening project executed on the Mississippi River Bridge at Greenville, Mississippi. Three sway struts of the through truss had been damaged by a passing vehicle.

Figure 49. Typical Category L/U damage.

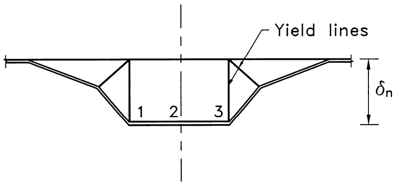
Category L/U local damage is typical in cases with the impact on a plate element with one free edge such as a flange of a beam. Figure 50 shows the typical flange bulge pattern. Often, distinct yield lines form as well as some zones of flexural yielding where curvature is highest. The impacted side of the damaged flange will be referred to as the near side (N). The non-impacted side of the same flange will also typically incur damage. This damage on the far side (F) of the flange has a geometry similar to N, but usually of lower magnitude. The damaged flange typically undergoes rotation about a clearly defined yield-line near the rolled fillet of the web (depth “k” in AISC diagrams). The impacted side (N) of the flange usually deforms in a folded plate pattern, as shown deforming toward the web in Figure 50b. The deformation usually results in strains significantly higher than



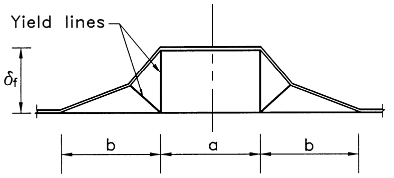
(a) Top view of damaged flange



(b) Section through damaged zone



(c) Edge view of flange on Side N



(d) Edge view of flange on Side F

Figure 50. Heat straightening local flange damage (Category L/U).

yield lines which define the edges of the folded plate (Figure 50c). In some cases, particularly in regions of high curvature, the deformation pattern may be one of a flexural yield surfaces rather than a series of yield lines. These surfaces 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 pattern, fig. 50d, 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 50b illustrates this behavior. The tee section at the flange/web juncture remains close to a 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 resist 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.

7.2 Heat Straightening Procedures for Unstiffened Local Damage

The specific heating pattern depends on the details of the damage geometry. The typical damaged cross section is shown in Figure 50a. There are three components of rotation: (1) the web/flange juncture, which remains at right angles, and has a rotation θ_w resulting from rotation about the web yield line; (2) the near side flange, N, which has a maximum rotation θ_n, resulting from additional rotation about the flange yield line; and (3) the far side flange, which has a reduced rotation, $\theta_w - \theta_f$, resulting from the resistance of flange F to rotation caused by forces applied to flange N. The heating/jacking pattern to straighten this damage will depend on how the geometry changes as heat straightening progresses. The following steps outline a typical procedure. However, because there are so many possible damage shapes, exact procedures cannot be established.

7.2.1 Phase I. –Initial Heating Patterns and Jacking Locations

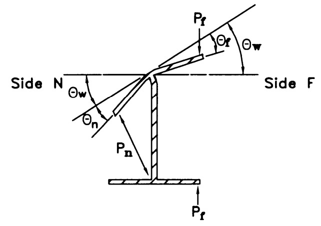
This phase is most effective with jacking forces on both the near and far sides of the flange. However, it can be conducted with jacking only on the near (impacted) side. The specific steps are:

7.2.1.1 Restraining forces

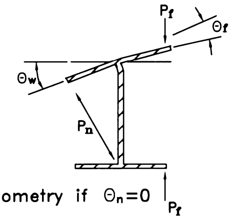
Place jacking forces on both the near and far sides of the damaged flange in the direction tending to restore the flange to its original condition. As shown in Figure 51a, a convenient arrangement on the near side is to place a jack, P_n, between the top and bottom flange. The far side jack, P_f, requires 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 51d, 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. In certain cases, P_f should be reversed (see following sections).

7.2.1.2 Vee heats

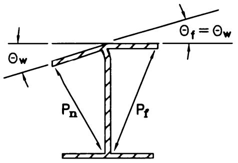
Although vee heats may not be necessary, a limited number may be used to assist in the flange shortening effort. The vees should be approximately half depth and applied to both the near and far sides of the flange to eliminate global curving of the member. The vee should be narrow with an angle of 20° 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 52b.



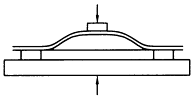
(a) Initial geometry after damage



(b) Geometry if Θ_n=0



(c) Geometery if $\Theta_f = \Theta_w$



(d) Spreader beam arrangement for applying clamping force to far side bulge

Figure 51. Arrangement of restraining forces during various stages of repair.

7.2.1.3 Line heats

All flange yield lines should be heated (on the convex surface (if practical) after any vee heats used. A typical pattern is shown in Figure 52a. In yield surfaces of continuous plastic strain such as often occurs in regions such as ABC in Figure 52a, 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.

7.2.1.4 Web line heat

The web yield line should be heated last. It is typically located at the fillet as shown in Figure 52c.

7.2.2 Phase II. Heating/Jacking Pattern if $\theta_n = 0$ or $\theta_f = 0$

These four steps complete the cycle. The cycle should be repeated until the flange is straightened within specific tolerances. Quite often phase I 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 on either side of the flange. If the flange movement progresses too quickly, then θ_n or θ_f may become zero prior to θ_w. This situation is shown in Figure 51b. Should this behavior occur, a modification in the phase I pattern should be made in Step 3 for line heats. Rather than heating all seven lines (Figure 52a), line 4 should not be heated.

7.2.3 Phase III. Heating Pattern if $\theta_f = \theta_w$.

If straightening progresses to the point that $\theta_f = \theta_w$, then the far flange may over-straighten with the continuation of Phase I heating. The pattern should be changed.

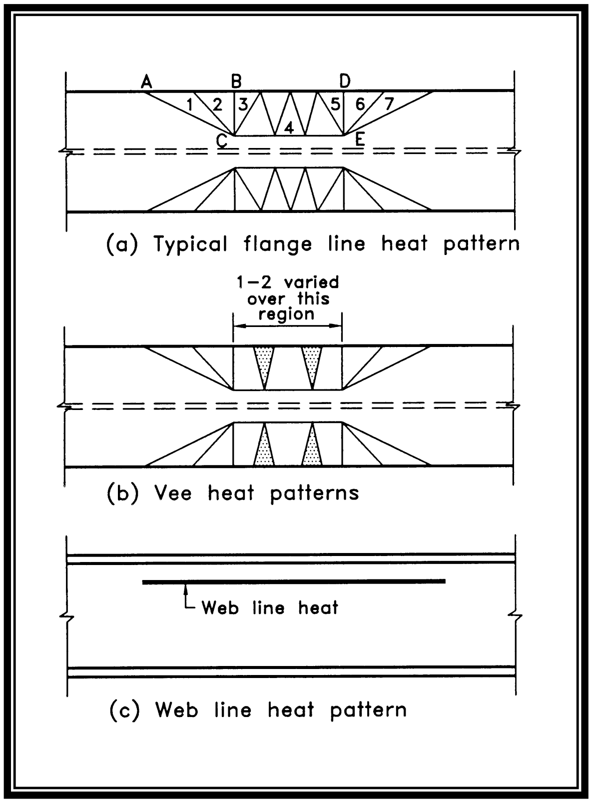


Figure 52. Arrangement of vee and line heats.

The situation is depicted in Figure 51c. The modification is to reverse the direction of the far side jacking force while continuing the phase I patterns including lines. The force P_f will prevent over-straightening while allowing the near flange and web to continue corrective movement.

7.2.4 Flange Damage in Opposite Direction

If the damage is reversed, **i.e.**, side N is pushed away from the opposite flange instead of toward it, the direction of the restraining forces should be reversed. The heating patterns are similar to those previously described.

Localized damage to unstiffened elements can have a wide variety of geometries, so the cases shown establish both the pattern and principals upon which heat straightening can be based. Judgment is needed to apply this methodology for specific cases.

7.3. Heat straightening Procedures for Stiffened Elements

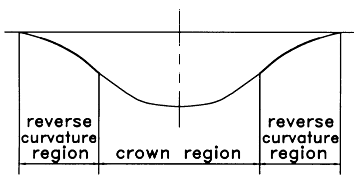
Select the heating patterns for damaged stiffened elements based on an evaluation of the total situation. Treating the regions of sharpest curvature with combinations of lines and/or narrow vees is the most effective approach, heating only in the regions with plastic curvature. As straightening progresses, regions should become smaller. The following line heat methodology is recommended for bulges in stiffened elements. A star vee pattern is sometimes used but has been found to be less effective.

7.3.1 Initial Heating Pattern

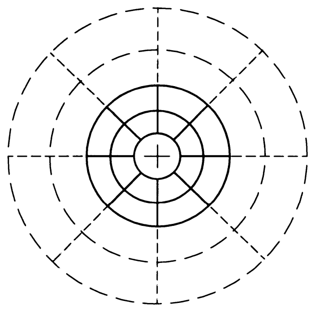
The typical bulge will have reverse curvature bending as shown in Figure 53. The crown region should be heated first with the torch on the convex side. As movement progresses, the heating patterns can be expanded into the reverse curvature region again with the torch on the convex side. The initial heating patterns should consist of radial and ring line heats as illustrated by solid lines in Figure 53. The exact number of ring heats will depend on the size of this region. The diameter of the smallest ring should be no less 50 mm (2 in) with spacing between rings of at least 50 mm (2 in). For large bulges the ring spacing should be larger than 50 mm (2 in). For cases where the curvature is relatively uniform, equally spaced rings may be used, but a ring heat should be centered at each location where sharp changes in curvature occur.

Heat the outer ring of the crown region (solid lines) on the convex side first and work inward. After the rings are heated, the radial lines in the crown region 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.

Jacks are typically placed at the crown tending to straighten the bulge. Heating patterns must be adjusted to work around jacks and to avoid heat transfer to the jacks which may damage them.



(a) Reverse curvature regions of a bulge



(b) Ring and line heating patterns

Figure 53. Curvature and line heating patterns for category L/S damage

7.3.2 Final Heating Pattern

As the crown section flattens, the heating pattern should be expanded into the reverse curvature regions as shown by the dashed lines. The ring heats should be spaced as described in 7.3.1 and the radial heats extended as shown by dashed lines in Figure 53b. 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.

7.4 Determination of Jacking Forces

Since there is no direct equivalent to plastic moment for this type of plate element, Capacity should be taken as the load at initial yielding. Jacking forces should not produce stresses greater than 50% of yield. However, the determination of these stresses for local damage is quite difficult to determine analytically. One way to determine the jacking force that produces yield is experimentally. One approach is to select an area of low stress due to live loading and jack in this area until small permanent deformations are observed. This procedure will define the yield jacking force without significant damage to the member. One-half of this value should be the maximum jacking force used in the damaged zone. Otherwise, jacking forces must be estimated and judged by the amount of movement after each cycle. It is recommended that movement not exceed 4 mm (1/8 in.) per cycle.

7.5 Conclusions

Local damage to can be heat straightened by using jacking forces and a relatively small number of line heats rather than a large number of vee heats. Straightening local damage is usually done in stages in which both jacking forces and heating patterns are varied in response to the progression of movements. As a general rule, apply heat to the convex side of the surface. For shallow configurations without sharp changes in slope, the jacking force may be greatly relieved during the cooling cycle. To increase effective movement, the jacking force may be maintained at the original, pre-heated level during cooling but, never increased above that value. If jack pressure is maintained, take care not to exceed the desired movement.

Local damage often has highly irregular patterns requiring a variety of heating patterns based on the damage and member configuration. The principles discussed in this chapter provide a guide but judgment is needed for individual applications.

A second area requiring judgment relates to degree of damage. For plate elements bent about their weak axis, the strain ratio ($\varepsilon/\varepsilon_y$) may well exceed 100, often considered the upper limit for heat straightening repairs. However, local damage often occurs at locations where design live and dead load stresses are not large, such as secondary bracing members. In such cases, the repair of large strain cases might be undertaken for Category L damage which would not be considered for Categories S, W, or T. In all cases engineering judgment is required.

APPENDIX I

SPECIFICATIONS FOR THE SELECTION OF CONTRACTORS AND THE CONDUCT OF HEAT-STRAIGHTENING REPAIRS

This Appendix contains suggested specifications for contractor selection and the conduct of heat-straightening repairs. The criteria presented here are guidelines only. The Engineer should select the criteria appropriate for the structure's anticipated use, the complexity of the project and to ensure contractor competency..

A1 Selection of Contractor (or the Contractor's field supervisor)

The selection of a contractor shall be based on one or more of the following criteria: experience, training, certification, and educational background. If there is neither a certification nor established training program currently available, experience and educational background shall be the primary criteria for selecting a heat-straightening contractor. Typical experience criteria are:

The contractor's organization shall have at least _____ years of experience in conducting heat-straightening repairs for damaged steel structures. During the preceding three year period, the contractor shall have conducted an average of at least _____ heat-straightening projects per year. Experience documentation shall include: date of project, location, bridge owner, number and type of members straightened, and duration of project.

The years of experience and number of projects conducted can be varied at the Engineer's discretion. Factors which may influence this decision include: criticality of damaged members, urgency of repairs, traffic volume and need to maintain traffic, complexity of damage, degree of damage, accessibility, climatic conditions, and scale of the project.

Educational background and specific training may be considered by the Engineer if the preceding criteria are not satisfied. Licensing as a professional engineer in such fields as metallurgical, structural, mechanical, or welding engineering may also be considered. Typical educational background criteria are:

The contractor (or the contractor's field supervisor) shall have a baccalaureate degree from an accredited program in one of the following engineering disciplines and be a licensed professional engineer qualified to practice in one of the following disciplines: structural, metallurgical, mechanical, or welding engineering.

The Engineer may require evidence of qualifications for the technicians involved in the conduct of the heat applications. These qualifications may include evidence of similar, prior work on equivalent structures, documented training in heat straightening, and the ability to explain performance of their duties.

For additional quality control, the following technical specifications apply to the conduct of the project.

A2 Technical Specifications for the Conduct of Heat-Straightening Repairs

The following technical specifications are suggested for incorporation into repair contracts. The Engineer should use judgment in selecting the criteria that best fits the specific damage situation. These are only partial guide specifications focusing on the heat straightening aspects of bridge repair. Specifications on general areas of bridge repair such as traffic control, worker/public safety, permitted hours of operation, documentation of final geometry, etc., should be included by the owner

1. Equipment

1.1 *Heating shall be with an oxygen-fuel combination. The fuel may be propane, acetylene or other similar fuel as may be selected by the contractor, subjected to the Engineer's approval.*

1.2 *Heat application shall be by single or multiple orifice tips only. The size of the tip shall be proportional to the thickness of the heated material. As a guide, the tip sizes shown in table A2 are recommended. No cutting torch heads are permitted.*

1.3 *Jacks, come-alongs or other force application devices shall be gauged and calibrated so that the force exerted by the device may be controlled and measured. No external force shall be applied to the structure by the contractor unless it is measured.*

2. Damage Assessment

2.1 *Suspected areas of cracking shall be called to the attention of the Engineer and shall be inspected by one or more of the following methods as applicable.*

2.1.1 *Visual Inspection*

2.1.2 *Liquid penetrant examination as described in ASTM E165 (1994 or latest edition).*

2.1.3 *Magnetic-Particle testing as described in ASTM E709 (1994 or latest edition).*

Table A1. Recommended Tolerances for Heat Straightening Repair.

Member Type	Recommended Minimum Tolerance[1,2]	
	English (in)	SI (mm)
Beams, Truss members, or Columns		
overall	½ in over 20 ft	13 mm over 6 meters
at impact point	¾ in over 20 ft	19 mm over 6 meters
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

Table A2. Recommended torch tips for various material thicknesses.

Steel Thickness (in)	Orifice Type	Size
< ¼	Single	3
3/8	Single	4
½	Single	5
5/8	Single	7
¾	Single	8
1	Single Rosebud	8 3
2	Single Rosebud	8 4
3	Rosebud	5
> 4	Rosebud	5

2.1.4 *Ultrasonic examination as described in section 6, part C of the ANSI/AASHTO/AWS Bridge Welding Code D1.5, American Welding Society (1996 or latest edition).*

2.1.5 *Radiographic examination as described in section 6, part B of the ANSI/AASHTO/AWS Bridge Welding Code D1.5, American Welding Society (1996 or latest edition).*

2.2 *The cost of the inspections under 2.1 shall be additional to other testing required and costs shall be negotiated between the Engineer and contractor.*

2.3 *Contractor shall identify and document all yield zones, yield lines and associated damage and provide this information to the Engineer prior to initiation of heat straightening by either visual inspection or measurements.*

2.4 *Steel with strains up to 100 times the yield strain may be repaired by heat straightening. For strains greater than this limit, the Engineer shall determine if heat straightening may be used.*

2.5 *Cracks and/or strains exceeding 100 times the yield strain, or other serious defects may require changes in the scope of the contract which shall be negotiated between the Engineer and the contractor.*

3. Heat Application

3.1 *The temperature of the steel during heat straightening shall not exceed the following:*

3.1.1 *650°C (1,200°F) for Carbon Steels.*

3.1.2 *620°C (1,100°F) for A514 and A709 (grades 100 and 100W) steels.*

3.1.3 *565°C (1,050°F) for A709 grade 70W steel.*

3.2 *The Contractor shall use one or more of the following methods for routine,* *ongoing, documented temperature verification during heat straightening:*

3.2.1 *Temperature sensitive crayons*

3.2.2 *Pyrometer*

3.2.3 *Infrared non-contact thermometer*

3.3 *Material should be heated in a single pass following the specified pattern and allowed to cool to below 120°C (250°F) prior to re-heating.*

3.4 *Heating patterns and sequences shall be selected to match the type of damage and cross section shape.*

3.5 *Vee heats shall be shifted over the yield zone on successive heating cycles.*

3.6 *Simultaneous vee heats may be used provided that the clear spacing between vees is greater than the width of the plate element*

3.7 *Repair of previously heat-straightened members in the same region of damage may be conducted once. Further repairs are not recommended unless approved by the Engineer.*

4. Application of Jacking forces

4.1 *Jacks shall be placed so that forces are relieved as straightening occurs during cooling.*

4.2 *Magnitude of Jacking Forces*

4.2.1 *Jacking shall be limited so that the maximum bending moment in the heated zone shall be less than 50 percent of the plastic moment capacity of the member or major bending element. For local damage, the jacking force shall be limited to 50 percent of initial yield of the element.*

4.2.2 *The jacking force shall be adjusted so that the sum of jacking-induced moments and estimated residual moments shall be less than 50 percent of the plastic moment capacity of the member. As an alternative to considering residual moments, the moment due to jacking forces can be limited to 25 percent of the plastic moment capacity of the member during the first two heating cycles. For additional heating cycles, the limit of 50 percent may again be used.*

4.3 *Control of jacking forces*

The contractor shall determine and document the maximum jacking force for each damage location, and the proposed sequence of jacking and heating. Copies of the documentation shall be submitted to the Engineer for acceptance before beginning repairs. Modifications due to changing condition shall be submitted to the Engineer. The maximum jacking force may be controlled by measuring the deflection resulting from the jacking force. The deflection limitation can be computed by one of the following methods.

4.4 *The calibration of jacks and electronic temperature monitoring equipment shall be performed and documented monthly, and load cells used for calibration must be certified within a two year period.*

5. Field Supervision of Repair

5.1 *Jacking forces shall be monitored to insure that limits are not exceeded.*

5.2 *Heating patterns shall be approved by the Engineer.*

5.3 *Heating temperatures shall be routinely monitored to insure compliance with specified limits.*

6. Tolerances

6.1 *The dimensions of heat-straightened structural members shall conform to the tolerances specified in table A1 except as noted* *below.*

6.2 *Tolerance limits may be relaxed at the discretion of the Engineer, based on one or more or the following considerations:*

(a) *Type and location of damage in the member.*

(b) *Time considerations resulting from the nature of traffic congestion during the repair operation.*

(c) *Cost of repair.*

(d) *Degree of restoration required to restore structural integrity.*

APPENDIX II. NOMENCLATURE

a,b,c = Dimensional constants

b_f = Flange width

b_s = Width of stiffening element

C = Temperature in degrees Celsius

c_d = Chord length across the yield zone of a curved beam

d = Depth of wide flange beam or primary plate element

d_s = Distance between the vee apex edge of the primary plate element and the stiffening element

d_v = Depth of vee in flat plate

E = Modulus of elasticity

f_a = Axial stress in a compression member due to live and dead loads

F_a = Stress factor for calculating plastic rotation in rolled shapes

F_ℓ = Jacking load factor

F_s = Shape factor for calculating plastic rotation in rolled shapes

F_y = Yield stress

ℓ = Span length of flexural member

L, L_r = Lengths between offsets

L_u = Length of free edge of flange before localized damage

M_j = Moment produced by jacking forces

M_p = Plastic moment capacity of a member

M_r = Residual moment

M_y = Moment at initial yield

n = Number of single vee heats required to remove a specified amount of damage

P = Axial load in compression member

P_a = Total jacking force for an axially loaded member

P_{ec} = Additional jacking force required to cancel eccentric moments due to axial loads

P_j = Jacking force

P_n, P_f = Jacking force on near and far side of locally damaged flange

r = Radius of arbitrary circle on flange bulge

R = Actual radius of curvature

R_ℓ = Jacking ratio M_j / M_p

R_y = Radius of curvature at initial yield

S = Section modulus

T = Heating temperature

t_w = Web thickness

V = Width at open end of vee

W = Primary plate element width

y_o = Initial out-of-straightness of compression member

y_r = Measured offsets at point r

y_{max} = Distance from centroid to extreme fiber

Z = Plastic section modulus

α = Coefficient of thermal expansion

δ_f, δ_n = Deflection of locally damaged flange on far and near side, respectively

δ_{max} = Maximum deflection of laterally loaded beam

Δ = Lateral deflection of loaded member

ε = Actual strain

ε_e = Elastic strain at open end of vee

ε_{max} = Actual strain at extreme fiber of member

ε_y = Strain at initial yield of material

γ = Distribution factor for heated composite beam

μ = Ratio of maximum strain to yield strain, $\varepsilon_{max}/\varepsilon_y$

φ_b = Basic plate rotation factor

φ_c = Plastic rotation of composite girder

φ_d = Degree of damage

φ_p = Plastic rotation resulting from a single vee heat on a plate or rolled shape

θ = Vee angle

θ_f = Slope of flange on side away from impact for locally damaged member

θ_n = Slope of flange on impact side of locally damaged flange

θ_w = Slope of web for beam with local flange damage

APPENDIX III. REFERENCES AND OTHER SOURCES OF INFORMATION

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