Heat-Straightening of Damaged Structural Steel in Bridges

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A 3-year research effort related to the study of heat-straightening repair for damaged steel bridge girders is summarized. Two major areas are emphasized: laboratory behavior of heat-straightened plates and rolled shapes. During the laboratory investigation of flat plates, a number of parameters were studied, including vee angle, depth of vee, heating temperature, plate thickness, and jacking forces. The most important parameters influencing the amount of straightening per heating cycle were vee angle, temperature, and jacking force. The patterns of behavior during the straightening process are plotted to illustrate the effects of each of these parameters. In a similar fashion, a laboratory study of rolled sections was conducted. In addition to the same parameters as those affecting plate behavior, this study showed that cross-section shape affects heat-straightening behavior—a factor heretofore unreported in the literature. It appears that rolled shapes can be grouped into three basic modes of behavior depending on the shape and location of the vee. Results of these tests are plotted showing how the shape of the member can affect the straightening process. Recommendations are given for factors to consider in the heat-straightening repair of bridge girders.

Although instances of heat straightening to repair damaged steel can be traced back nearly 50 years, the method has been more of an art than a science. As a result, highway officials have been hesitant to utilize the procedures. Principal concerns have been related to a vagueness as to the principles behind the procedure, strength reductions both during and after the repair, and limits as to degree of damage that can be repaired. The purpose of this paper is to address these concerns by describing the results of a comprehensive research project on heat-straightening repair of steel bridge girders.

Heat straightening can be used to repair structural steel bridge elements in place, often without shoring. It is an expedient procedure, usually necessitating minor disruptions in traffic. Up to tenfold cost savings are possible as compared with member replacement methods. However, because heat straightening is not well understood by the engineering profession, most repair work of this type is not engineered, but left to a specialized contractor. Because of this lack of knowledge, some engineers have tended to avoid the use of heat-straightening repair. Although engineering research on the subject has progressed in recent years, there has not been a significant amount of information readily available to the profession. This lack of information, combined with a lack of synthesis of available information, had led to speculation and contradictory statements as to various effects associated with the heat-straightening process. It is therefore pertinent to first describe that process.

A number of papers have been written that primarily describe basic techniques and successful field applications (*1–9*). The concept is based on use of carefully controlled and applied heat without an active force (although passive restraining forces are often used). The basic element of steel construction is the flat plate. Rolled or built-up members consist of plate elements assembled to obtain an advantageous shape. Thus, vee heat can be considered the fundamental heat pattern associated with heat straightening.

As shown in Figure 1, the heat is applied with a torch to a vee-shaped area, starting at the apex and progressing across the vee in a serpentine motion. The series of sketches in Figure 1 was generated from a comprehensive elastoplastic, thermal, and finite-element analysis (*10*). The amplitudes of movement have been magnified for illustrative purposes and a full-depth vee heat is used. As the apex of the vee is heated, expansion occurs, producing the hump at the apex and a slight downward movement at the free end (Figure 1a). As heating continues, this expansion increases to produce a larger hump and more downward deflection. The cool portion ahead of the torch impedes the longitudinal expansion and also results in a plastic thickening of the material in the heated region. As the torch moves into the lower half of the plate, the hump begins to protrude from both top and bottom, and the downward deflection trend is reversed (Figure 1b). At some point, the plate will return to its original undeformed position, with only the top and bottom bulges plus plate thickening. As the torch nears the open side of the vee, the deflection becomes upward due to the expansion in the torch area (Figure 1c). This process continues until a short time after the torch has been removed and the deflection has reached its maximum upward point. As cooling proceeds, the contraction on the open side of the vee creates downward movement again, until at some point, the plate is again in its original position with a bulge on the top and bottom. The latter stages of cooling produce a final downward deflection along with a slight bulge (Figure 1d). The angle of the vee thus tends to be less than it originally was, because some plastic flow has taken place during the expansion phase and there is little restraint to longitudinal contraction during cooling. The net result is a small but sharp change in the angle of the vee when the process is complete. The hump at top and bottom is quite small compared with the angle change and can be neglected. In addition, a net shortening of the member occurs.

Of course, if the member is already bent, the distortion can be removed by applying the vee heat to oppose the initial deformation, hence the idea of heat straightening. By judi-

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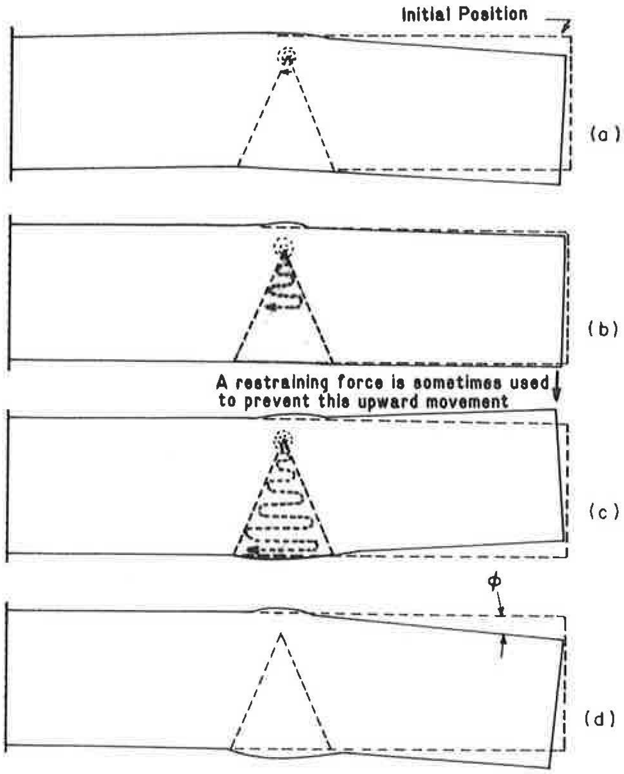

FIGURE 1. Stages of plate deformation as a vee heat is applied to an initially straight plate (deformations are magnified for illustration purposes).

ciously applying vee heat to members, damage to curvature can be removed. Because the net change in curvature after one heating sequence is small, cycles of heating and cooling are often required to correct serious damage. A similar approach can be used on various rolled shapes or built-up members. For large or irregular initial bends, the heating can be done at a number of locations successively along the length of the member. Although simple in principle, the wide variety of structural shapes, damage, and structural configurations likely to be encountered in practice makes it difficult to establish guidelines. In addition, the varied methods of heating and restraining during the repair process complicate the picture even further.

A comprehensive survey of heat-straightening literature has been conducted by Avent (*11*).

In summary, the literature review reveals that additional research is needed to better define the process. Two aspects are of particular importance. First, the basic mechanism of heat straightening is not well understood in that the effects of both external restraints (jacking) and internal restraints (redundancy) have been considered to be of minor concern rather than fundamental to the broad application of the process. Second, because the importance of this parameter has not been identified, there has been little documentation on the behavior of vee-heated plates subjected to varying degrees of constraint and even less on rolled shapes. Third, although a fair amount of research has indicated that most material properties are unaffected by heat straightening, two important aspects have been overlooked: the influence of strain aging on ductility and residual stress distribution. Finally, the research information available has been 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 future research. Because of these gaps in heat-straightening research, it was indeed true that the artisan practicing the trade was much more important than the engineer. The goal of this paper is to provide a more detailed knowledge base to enable the engineer to assess the need for and direct the application of heat-straightening repairs.

BEHAVIOR OF PLATES SUBJECTED TO HEAT STRAIGHTENING

Although the heat-straightening repair process is relatively simple, it has not been widely used. Two main factors are responsible. First, those who currently use heat straightening practice it as an art form as much as a technique based on engineering principles. These practitioners rely on their experience to guide them through a heat-straightening repair. Second, many engineers believe that any application of heat to steel will permanently weaken it. Because there are no engineering design criteria for using heat straightening, engineers are often hesitant to use it. In recent years, research studies have led to greater understanding of this phenomenon. The purpose in this section is to describe the experimental study of heat straightening as applied to plates.

Vee heats produce small but sharp curves at the vee location. By varying the spacing of the vee heats, a smooth curve of changing radius can be produced. Because damage is usually of varying curvatures, vee heats are the most suitable for structural repairs.

Several detailed studies by Weerth and Nicholson (*13*), Weerth (*12*), and Roeder (*18*) have been conducted on the application of vee heats to plates. These studies have attempted to identify parameters that influence vee heats and to develop predictive models based on these data. The specific findings of these studies will be evaluated in connection with the results of the current investigation.

The actual method of heat straightening is easily learned; however, the handful of practitioners currently using the method rely extensively on their many years of experience to guide them through a repair. An engineer lacking this wealth of experience needs a set of analytical procedures to determine how best to apply the heat-straightening process to a particular repair. These analytical tools, for reasons of economy, should be relatively fast and easy to apply and should allow for such considerations as different vee geometries, temperature ranges, external loadings, and support restraints. At present there are, at one extreme, overly simplistic models (*1,5,15*) that cannot take into account the effect of either temperature variations or internal and external restraint and, at the other extreme, comprehensive computer models (*10,16,14,17,18,12*) based on elastoplastic finite-element or finite strip stress analysis combined with a similar thermal analysis. However, there is not yet an analytical model that offers both practicality and a comprehensive inclusion of all important variables to accurately predict behavior.

This portion of the study is devoted to the development of simple yet efficient procedures for predicting the response of deformed steel plates during the heat-straightening process. In this section, all parameters are identified and quantified that have an important influence on the heat-straightening process. This phase was accomplished by studying the experimental data available from previous research as well as by conducting an extensive experimental program to provide additional data.

The tests conducted in the experimental program consisted of applying vee heats to straight specimens and measuring the resulting change in geometry. By using straight specimens as opposed to deformed ones, a larger variety and number of tests could be conducted in the least possible time. A total of 255 individual heating cycles were performed during this study. Several supporting frames were used during the course of this study. The specimens were mounted as either cantilevers or simply supported members. All plates were hot-rolled A36 grade steel, and the majority were 1/4 in. × 4 in. × 24 in. The only exceptions to these dimensions were associated with tests on variations in plate thickness and geometry. Plate deformation measurements consisted of measuring the offsets between the plate edge and a reference frame to the nearest 0.001 in.

It has been shown (*18*) that the plastic deformation developed by a vee heat occurs primarily within the vee area. Thus, the acute angle formed between the tangents to the straight portions outside the vee is the angle of plastic rotation, ϕ.

Practically all the existing experimental data on vee-heated plate behavior are found in two studies (*12–14,18*). The basic parameters studied were angle of the vee, ratio of the vee depth to the plate depth, level of external constraining force, and heating temperature. The number of data points was in general relatively small and the variation fairly large. As a result, only general conclusions could be drawn and unanswered questions remained. Therefore, additional experimental data related to these basic parameters were obtained in the current study. In addition, several other variables were evaluated, including plate thickness, plate depth, and heating technique.

The available data on plate behavior include the present study and those of Nicholls and Weerth (*13*), Roeder (*18*). Indicated on plots presented here is the type or source of the data. The data type "current" indicates that only the results of the current study were used, and reference numbers are given for other data. Each parameter is evaluated separately in the following sections.

Vee Angle

Researchers agree that the vee angle is one of the fundamental parameters influencing the plastic rotation of a plate. The data show a fairly linear relationship between plastic rotation and vee angle. For this reason, all data will be plotted with the vee angle as the ordinate and plastic rotation, ϕ, as the abscissa. A first-order least-squares curve fit will also be shown. Plots in succeeding sections show a consistent proportional relationship between these variables.

Of particular interest is the scatter of the experimental results. In both the current study involving 255 plate tests and in Roeder's research (*18*) involving 99 plate tests, a similar level of scatter was observed. In both cases, special efforts were made to control the heating temperature using not only temperature-sensing crayons, but also thermocouples or calibrated contact pyrometers. In spite of such efforts, a significant amount of variation occurred in identical repetitive tests. Surprisingly, the smaller-scale study by Nicholls and Weerth (*13*), which included 21 tests, showed no evidence of random scatter. The consistency of data points was such that smooth curves were produced with no curve fitting necessary. This pattern is even more remarkable when apparently the only temperature control was temperature-sensing crayons. The writers therefore view these data points with some suspicion and have omitted them from most of the comparative studies.

Because a significant level of scatter does exist, the data samples were evaluated. The coefficients of variation for typical cases were on the order of 50 percent. Because the coefficient of variation is quite high, possible causes must be addressed. The most obvious source of the scatter would be the relative degree of control exerted over the parameters of the heating process, in particular, the restraining force and heating temperature. For the available equipment of the current study, the accuracy of measurements could vary by 10 to 15 percent. Similarly, the control of the heating temperature could introduce an error of 10 to 15 percent. A third possible cause is the development of residual stresses. Both Holt (*4*) and Roeder (*18*) suggest that residual stress is not significant in the heat-straightening process. However, a small number of tests conducted as part of this study indicate that very large residual stresses are possible as a result of the heating process. Thus, because of the difficulty in controlling the restraining forces and heating temperatures and the possible development of large residual stresses, a relatively large scatter in the data is not surprising.

Depth of Vee

Past research (*18,12*) has been inconclusive as to the effect of vee depth on plastic rotation. These studies suggest that the relationship is inverse for vee depths greater than two-thirds the plate depth. However, the trend of the experimental data indicates relatively small variations. Indeed, the plate rotations are all approximately the same when using a least-squares curve fit. Therefore, even though it may seem intuitive that increasing the vee depth increases the plastic rotation, there appears to be little justification for such a general statement. Additional research is needed with a larger data base before a conclusive evaluation can be made.

Plate Thickness and Depth

From the results of tests involving different plate thicknesses, it is concluded that plate thickness will not have an important influence on heat straightening. In the current study, the influence of plate depth was investigated in a series of tests with plates of equal thicknesses, vee angles, and zero load ratios. These results showed similar rotation for each case; thus, plate depth under these conditions is not deemed an important factor.

Temperature

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 of the torch orifice, intensity of the flame, speed of torch movement, and thickness of the plate.

Assuming that adequate control is maintained over the applied temperature, the question arises as to what temperature produces the best results in heat straightening without altering the material properties. Previous investigators differ on the answer. For example, Shanafelt and Horn (*9*) stated that heats above 1200°F on carbon and low-alloy steels will not increase plastic rotation. Rothman and Monroe (*19*) concluded that reheating areas where previous spot heats had been performed will not produce any useful movements. However, the comprehensive testing program by Roeder (*18*) showed that the resulting plastic rotation is directly proportional to the heating temperature up to at least 1600°F. These results were verified in the current research. Plots of vee angle versus angle of plastic rotation for the data from the current study are shown in Figure 2, which indicates that the plastic rotation generally increases linearly with increasing temperature.

The maximum temperature recommended by most researchers is 1200°F for all but the heat-treated high-strength steels. Higher temperatures may result in greater rotation; however, out-of-plane distortion becomes likely and surface damage such as pitting (*18*) will occur at 1400° to 1600°F. Also, temperatures in excess of 1300°F may cause changes in molecular composition (*19*), which could result in changes in material properties after cooling. The limiting temperature of 1200°F allows for several hundred degrees of temperature variation, which was common among experienced practitioners. For the heat-treated constructional alloy steels (F_y = 100 ksi), the heat-straightening process can be used, but temperatures should be limited to 1050°F to ensure that no metallurgical transformations occur (*19*). The conclusion that heat-treated constructional alloy steels can be heat-straightened is contrary to that of Shanafelt and Horn (*9*); however, Roeder (*18*) concurs with this recommendation.

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 maintained at the appropriate level, the contraction effect will be similar. This conclusion was verified by two test series on plates in which the intensity of the torch was varied. In one series, a low-intensity torch was moved slowly to maintain a 1200°F temperature, whereas in the other series a high-intensity torch was moved more quickly while the same temperature was maintained. The rotations in either case were similar.

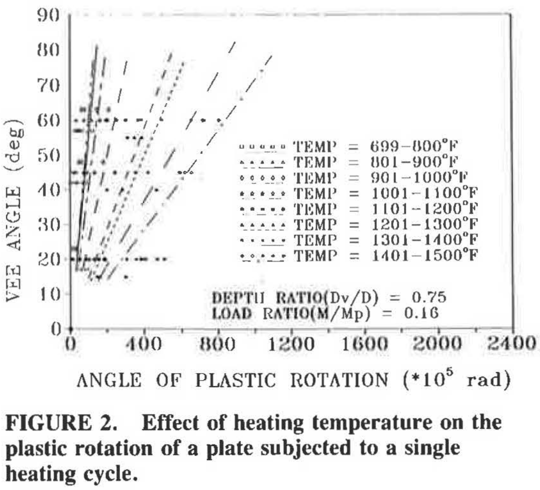

FIGURE 2. Effect of heating temperature on the plastic rotation of a plate subjected to a single heating cycle.

Restraining Forces

The term "restraining forces" can refer to either externally applied forces or internal redundancy. These forces, when properly utilized, can expedite the straightening process. However, if improperly understood, 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 1. 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 1b and 1c, some longitudinal expansion occurs because the surrounding cool material does not offer perfect confinement. After cooling, the degree of damage 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 plate movements associated with longitudinal expansion during the heating phase. For example, if a restraining force is applied as shown in Figure 1c, the upsetting effect will be increased through the flexural constriction of free longitudinal expansion at the open end of the vee. A restraining force is usually applied externally, but sometimes the structure itself provides restraint through internal redundancy.

In essence, a restraining force acts in an identical manner to that of the vee heat concept itself. The material behavior can be viewed as shown in Figure 3. A small element from a plate, when constrained in the *x*-direction and heated, will expand and flow plastically primarily through the thickness (Figure 3c). 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 3d). The material itself cannot distinguish the cause of the constraint: either cooler adjacent material in the case of the vee heat or an external force in the case of a jacking force. In either case the plastic flow occurs in an identical manner.

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

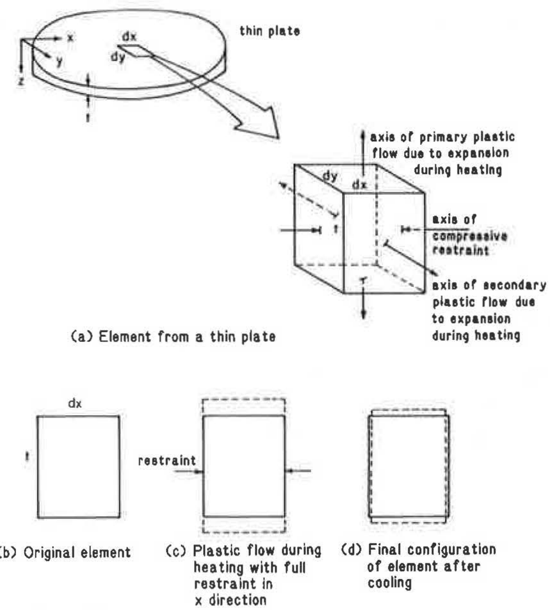

FIGURE 3. Characteristics of plastic flow and restraint during heating straightening.

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 prohibit contraction during the cooling phase.
3. Constraints should not produce 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 heat phase.

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

Although practitioners have long recognized the importance of the application of jacking forces during the heat-straightening process, little research has been conducted to quantify its effect. A series of tests designed to evaluate this parameter involved applying a jacking force to a plate such that a moment was created about the strong axis in a direction tending to close the vee. This moment is nondimensionalized for comparison purposes by forming a ratio of the applied moment at the vee to the plastic moment of the cross section, M/M_p. This term is referred to as the load ratio. The tests included load ratios of 0, 0.16, 0.25, and 0.50, with four different vee angles and vees extending over three-fourths the depth of the plate. The results are shown in Figure 4. Roeder (*18*) also studied the effect of load ratio variation, and his results indicated similar behavior. The plots indicate that the variation is generally proportional to the load ratios and that using external loads can greatly expedite the heat-straightening process.

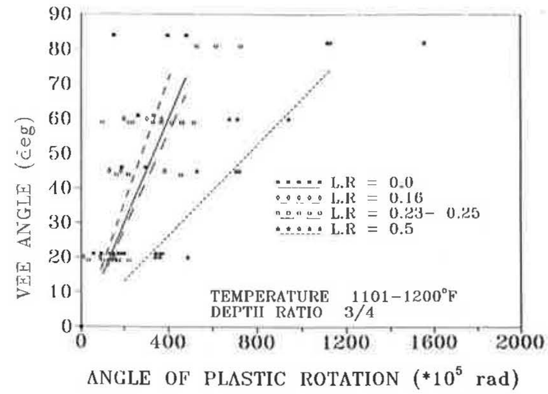

FIGURE 4. Effect of the ratio of bending moment at the vee heat due to restraining force and the plastic moment capacity (L.R.) on the plastic rotation of a plate subjected to a single heating cycle.

A second type of constraint that may exert external forces on a member is axial restraint. A series of tests were conducted using a superimposed axial load on plates for various vee angles. The load created a 20-ksi axial stress or a ratio of actual stress to yield stress of 56 percent. These results are shown in Figure 5 in comparison with the results from the bending load ratios of 0 and 50 percent. The axial load does increase the plastic rotation, but to a lesser extent than the 50 percent bending load ratio.

In summary, the parameters found to have an important influence on the plastic rotations produced by vee heats are vee angle, heating temperature, and external restraining force. The depth of the vee appears to have a small influence in the practical range of greater than 50 percent of the plate width. Likewise, plate thickness and geometry are not important in the range of practicality.

BEHAVIOR OF ROLLED SHAPES SUBJECTED TO HEAT STRAIGHTENING

The basic characteristics of plate behavior have been quantified experimentally. The purpose in this section is to similarly quantify the behavior of rolled shapes subjected to heat

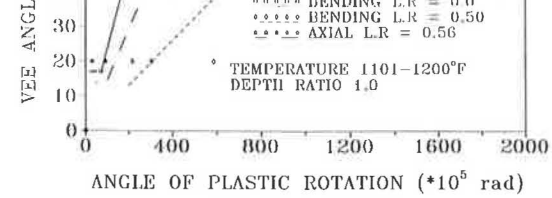

FIGURE 5. Effect of axial restraining forces on the plastic rotation of a plate subjected to a single heating cycle.

straightening. Because rolled shapes are an assemblage of rectangular plate elements, the basic question is how the pattern of assemblage modifies the basic plate behavior during heat straightening. The primary factors to be considered are cross-section configuration, restraining forces, and angle of vee. It is believed that the influence of other factors such as temperature, element thickness, and vee depth is either similar to that of individual plates or has been previously studied and does not warrant additional consideration here.

Very little experimental data are available that provide measurements of the plastic rotation in rolled shapes. Horton (*16*) measured the plastic rotation for a series of 18 wide-flange beams subjected to bending-type restraining forces. In the only other similar study, Roeder (*18*) measured the plastic rotation for eight wide-flange beams subjected to axial restraining forces. This small pool of experimental data was inadequate by itself for the formulation of conclusions on all aspects of behavior. In order to expand this data base, several series of comprehensive experiments were conducted. The laboratory experiments on A36 steel rolled shapes were conducted in a manner quite similar to those for plates. Members were mounted in frames and initial measurements were taken before heating. The primary variables were vee angle and level of restraining force. All specimens were heated at 1200°F. After cooling, the specimens were remeasured. The degree of plastic rotation was computed by comparing the two sets of measurements. Presented here is an evaluation of the significance of these test results. Plots referred to in this discussion will generally include all related data points along with a first-order least-squares curve fit.

Heating Sequence and Pattern

For cross sections consisting of multiple elements, the usual practice is to heat the elements consecutively, although simultaneous heatings are sometimes conducted. Heating sequence refers to the order in which each element is heated. Rolled shapes generally require a vee heat in combination with a rectangular heat. The rectangular heats are necessary because of the perpendicular orientation of plate elements forming the cross section. Thus a pattern of vee and rectangular heats is used for many types of rolled shapes. A set of typical heating patterns for wide flanges, channels, and angles is shown in Figure 6. By using the proper pattern, sweep, camber, and twisting-type movements can be generated. These movements will be referred to as Mode I, II, and III bends, respectively. Through these combinations, a wide variety of damage conditions can be repaired. Although there is general agreement on the use of vee heats, there has been little information on how to optimize heating sequences and patterns combining vee and rectangular heats. Horton is the only researcher to have addressed this subject in even a limited manner. His conclusion was that an effective approach is to perform the vee heat (or heats) first and then the rectanglar heats. This approach was used in all experiments discussed here.

Water-Mist Versus Air Cooling

Another aspect of Horton's study deserves mention here. In most cases he conducted identical experiments, but in one case the beam was allowed to cool by convection to room temperature, and in the another case a water mist was applied. The water-mist application had no significant effect on the amount of plastic rotation that occurred.

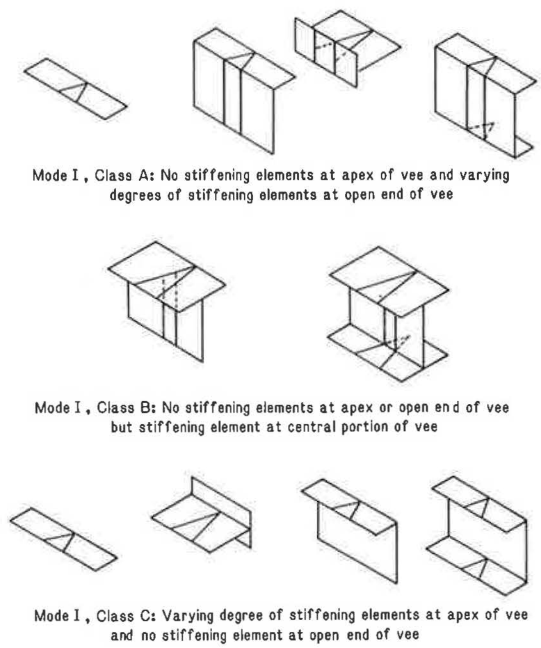

FIGURE 6. Classification of Mode I heating configurations.

Vee Depth

A final aspect of Horton's study was the effect of the vee depth on the Mode I bends. The plastic rotation produced by half-depth vees was significantly smaller than that produced by the full-depth vees, particularly for the most effective heating patterns. The data here are much more conclusive than those discussed previously for partial-depth vee heats in plates. The average value of plastic rotation for 50-degree vee heats for the Mode I case (a) and (d) sequences is 0.00387 rad as compared with the half-depth vee pattern, which produced an average plastic rotation of 0.00253 rad.

Vee Angle

Horton's study indicated that the relationship between plastic rotation and vee angle was fairly linear. The same trend was found in all tests conducted for this study. This behavior will be illustrated in subsequent sections. The accumulation of data suggests that the behavior of rolled shapes is similar to that of plates with respect to vee angle effect.

Restraining Forces

One of the primary factors evaluated in this study was the effect of restraining forces on plastic rotation. This factor has been shown to be of primary importance for plate behavior, but little data are available for rolled shapes. For example, Horton used a single load ratio, M/M_p, of 16 percent for all cases. To expand the data base, a series of tests were conducted on W 6 × 9 beams for three load ratios: 0, 25, and 50 percent. The results for Mode I bends on wide flange shapes are shown in Figure 7. Also shown for comparison purposes are similar curves for rectangular plates and Horton's results. The plastic rotation is proportional to the load ratio although it does not appear linear. Note, however, that two data points for the 30-degree vee angle and zero load ratio distort that curve. Even though the trend is present, additional data points are needed to more precisely define the relationship between load ratios.

Geometric Effect of Size

A comparison of Horton's data with those of the current study (Figure 7) indicates that the specimen size may be a significant factor. Comparison of Horton's beams (load ratio, 16 percent) with those of the current study (load ratio, 25 percent) indicates that the plastic rotation is inversely proportional to the beam weight (which for these cases roughly translates to wall thicknesses). Three factors may account for this behavior. First, Horton used a different measuring technique for determining plastic rotation. His measurements were limited to a region across the vee of only 8.375 in. The full length of 60 in. was used in this study for measurements. It may be that the short length used by Horton did not capture the full degree of plastic rotation. However, even Horton's data alone (which were obtained in a consistent fashion) indicate the same trend. Second, there is a longer time frame during the heating process in comparison with plates. This time lag to heat separate elements would be proportional to size, allowing previously heated elements more time to cool. Smaller plastic rotations could result from such a scenario. Third, the thicker elements may not have been heated to 1200°F. Horton provides little information on his level of temperature control. As a result, the writers are hesitant to draw firm conclusions from these data. Additional tests are needed to verify this observed trend.

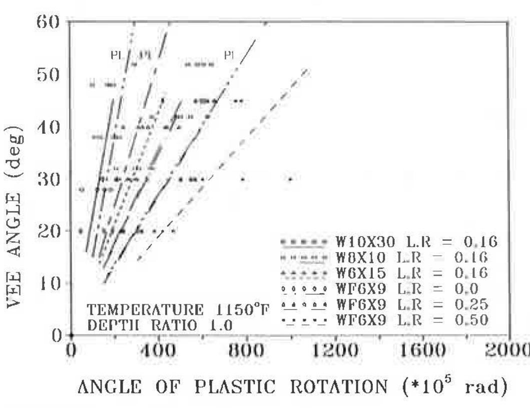

FIGURE 7. Effect of the ratio of bending moment at the vee heat due to restraining force and the plastic moment capacity (load ratio) on the plastic rotation of Mode I wide-flange sections subjected to a single heating cycle.

Geometric Effects of Shape Configuration

This study is the first to determine the plastic rotation for angles and channels in addition to wide flange shapes. As a consequence, the influence of shape factors can be evaluated. Three categories will be considered: Mode I bends (sweep), Mode II bends (chamber), and Mode III bends (twist).

The Mode I bends in general can be classified into several subcategories according to the distribution of material with respect to the vee. This classification is shown in Figure 6. Obviously, the location and size of the stiffening element will influence the member behavior. The magnitude of this influence is shown in Figures 7 and 8 for Mode I, Classes B and A, respectively. Three characteristics are apparent:

1. As the stiffening element to the vee-heated flange varies from the open end toward the apex of the vee, the plastic rotation decreases.
2. For Mode I, Class A, the plastic rotation is proportional to the area of the stiffening element. At this stage only the trends can be noted. Note that no Mode I, Class C tests were conducted.
3. Both Modes I-A and I-B suggest that plastic rotation is larger for these shapes than for similar plates. It appears that the plastic rotation may be proportional to the location of the stiffening element from the vee apex.

The results for Mode II bends of both the channel and wide-flange types are compared in Figure 9. The plastic rotation is significantly smaller for this case in comparison with Mode I. It appears that the stiffening element at the apex offers little significant internal restraint against rotation. The resulting curve fits compare favorably with that those plates.

Mode III bends were also induced by heat straightening. However, only two beams were heated in this fashion, so data are sparse. Enough heating cycles were conducted to obtain a good average value of plastic rotation. For 48 cycles the average plastic rotation of the heated flange alone was 0.00625 rad. Comparing Modes I and III indicates that the behavior is quite similar. Although additional data are needed, it appears that for noncomposite cases, Mode III can be modeled similarly to Mode I. The use of these heating procedures on

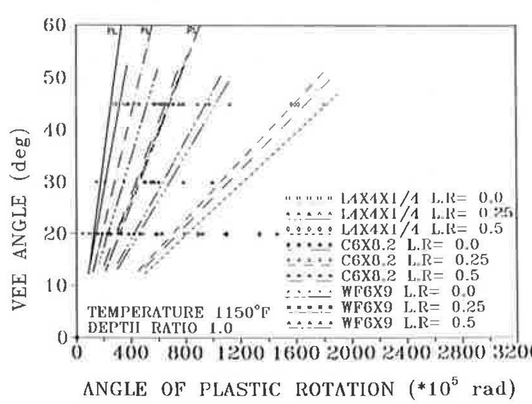

FIGURE 8. Effect of load ratio and cross-section type on the plastic rotation of Mode I, Class A rolled shapes subjected to a single heating cycle.

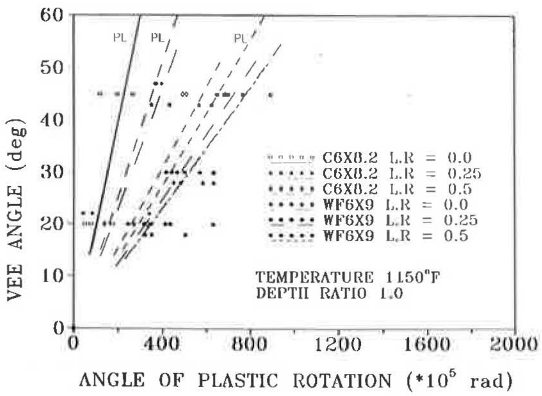

FIGURE 9. Effect of load ratio and cross-section type on the plastic rotation of Mode II rolled shapes subjected to a single heating cycle.

simulated full-scale bridge girders has been reported elsewhere by Avent and Fadous (*20*).

The behavior of rolled shapes was found to be quite complex. In addition to the same factors influencing plate behavior, rolled shapes are influenced by geometric patterns. Additional experimental data are needed to further quantify this behavior.

CONCLUSIONS

Heat straightening as applied to plates and rolled shapes has been studied in detail. The results are summarized as follows:

1. Plates and rolled shapes behave in predictable patterns under cyclic heat straightening. Even though significant scatter exists for specific data points, the average values for a large number of cycles are generally consistent.
2. The primary factors influencing heat straightening are vee angle, temperature, restraining force, and cross-section shape.
3. Movement is proportional to vee angle. However, a vee angle of greater than 45 degrees often leads to bulging of the flange or plate element about its weak axis.
4. Heating temperature should be limited to 1200°F for carbon steel and 1050°F for heat-treated steels.
5. Restraining forces expedite the straightening process without damaging the steel. However, the magnitude of these forces should be known and controlled so as to prevent drifting into the realm of hot mechanical straightening or to cause overstressing under heat.
6. Rolled shapes can be straightened, with the movement per cycle depending on the cross-section shape.

Experimental data suggest that heat straightening of plates and rolled shapes can be quantified for general applications. More research is needed to determine these analytical relationships.

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