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7. Author(s)
R. Richard Avent
Randy Boudreaux

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Department of Civil Engineering
Louisiana State University
Baton Rouge, LA 70803

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16. Abstract

One of the primary reasons that highway departments are hesitant to use heat-straightening techniques to repair damaged steel girders is the lack of experimental verification of the process. A comprehensive experimental program on the subject has been in progress at LSU for two years. Presented in this report are the results of laboratory experiments on plates and rolled shapes, along with an evaluation of material behavior. The current state of knowledge is reviewed as to the effects of heat applications on the metallurgical properties of steel (including residual stresses) as well as the effects of cold working during damage inducement. A discussion of criteria required to make the repair decision is also presented.

Experimentally evaluated are the effects of temperature, vee angle, jacking force, and depth of vee on the behavior of both plates and rolled shapes. Over 100 plates have been measured along with approximately 20 rolled shapes. Residual stress measurements were also taken which show a distinct variation over typical cross sections. While the experimental program is still incomplete, the results presented include more laboratory testing than all projects combined.

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HEAT-STRAIGHTENING EFFECTS ON THE BEHAVIOR OF PLATES AND ROLLED SHAPES

VOLUME 2: SECOND INTERIM REPORT OF PHASE 1

by

R. RICHARD AVENT
PROFESSOR OF CIVIL ENGINEERING

and

RANDY BOUDREAUX
GRADUATE STUDENT

DEPARTMENT OF CIVIL ENGINEERING
LOUISIANA STATE UNIVERSITY
BATON ROUGE, LA 70803

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ABSTRACT

One of the primary reasons that highway departments are hesitant to use heat-straightening techniques to repair damaged steel girders is the lack of experimental verification of the process. A comprehensive experimental program on the subject has been in progress at LSU for two years. Presented in this report are the results of laboratory experiments on plates and rolled shapes, along with an evaluation of material behavior. The current state of knowledge is reviewed as to the effects of heat applications on the metallurgical properties of steel (including residual stresses) as well as the effects of cold working during damage inducement. A discussion of criteria required to make the repair decision is also presented.

Experimentally evaluated are the effects of temperature, vee angle, jacking force, and depth of vee on the behavior of both plates and rolled shapes. Over 100 plates have been measured along with approximately 20 rolled shapes. Residual stress measurements were also taken which show a distinct variation over typical cross sections. While the experimental program is still incomplete, the results presented include more laboratory testing than all projects combined.

IMPLEMENTATION STATEMENT

The results of this report illustrate the practicality of using heat straightening in bridge repair. The methodology described is applicable to the repair of damaged steel girders on overpasses and elements on bridge trusses. Since research is continuing, full implementation is not yet appropriate. However, a technical paper is being planned for submission to a structural engineering journal. Publication of this material will ensure a wide dissemination of these research findings.

METRIC CONVERSION FACTORS

One pound force per square inch (psi) = 6.89 kilopacals (kPa)
One inch (in.) = 25.4 millimeters (mm)
One pound force (lb.) = 4.45 newtons (N)

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1. INTRODUCTION

Background

Prior to the initiation of this research project, the use of heat straightening to repair steel girders could be classified as more of an art than science. As a consequence, very few state highway departments have used the process to repair damaged steel bridges. The reservations concerning the process have centered around two key issues: Do heat-straightening repair procedures exist which do not compromise the structural integrity of the steel? And if so, how can such repairs be engineered to insure adequate safety of the repaired structure? The primary goal of this research project is to answer these two questions by experimentally evaluating all aspects of heat-straightening techniques and developing engineering analysis and design procedures for general applications.

The project was divided into four phases: (1) laboratory evaluation and initial analytical development; (2) field evaluation and refinement of analytical model; (3) final field evaluation and development of an interactive computer model; and (4) documentation and training. This report describes a portion of the work performed under Phase 1 of the project and is the second interim report of this phase. A companion volume (2) on Phase 1 is also available which provides a current, state-of-the-art survey on heat straightening. Concurrently, Phase 2 has been initiated and the results to date are described in a third companion volume (4). Phase 3 is now just beginning and results are not yet available. Phase 4 is not yet scheduled to begin.

Objectives

The purpose of this report is to describe the research to date as it relates to Phase 1 of the project. The specific objectives are:

(1) To evaluate the basic material characteristics of steel as they relate to inelastic damage and exposure to elevated temperatures.

(2) To evaluate the factors affecting the behavior of plate elements during the heat-straightening process.

(3) To evaluate the factors affecting the behavior of rolled shapes during the heat-straightening process.

(4) To report the preliminary results of the effects of heat-straightening on residual stresses and material properties.

(5) To describe the progress of the analytical modelling and computer programming to date.

Each of these objectives will be addressed in separate chapters of this report.

2. BASIC MATERIAL CHARACTERISTICS RELATED TO DAMAGE AND HEATING

An important aspect of heat-straightening repair relates to the basic characteristics associated with large material strains and the influence of applying heat to the steel. There is relatively little documented information on the behavior of steel at temperatures below the phase transition temperature (approximately 1300°F). Likewise, the material properties effects of large displacements due to damage (which produces large material strains) are not documented as to whether heat applications have a mitigating effect. Finally, there is little discussion in the existing literature concerning how to decide whether damage should be repaired (either because of relatively small or large damage). Many of these fundamental aspects, of particular concern to the engineer supervising repairs, are addressed in the following sections.

Metallurgy of Steel at Elevated Temperatures

It is almost an article of faith among many engineers that the application of heat to steel will harm the material. However, properly controlled heat applications have been shown to have no harmful side effects. An understanding of the composition of steel will provide guidance on how to control heat applications.

By definition, steel is an alloy of iron and carbon, but other elements are often added. Some of these additional elements help remove impurities, some enhance properties such as corrosion resistance, and some are used to obtain higher strength steels. Since the vast majority of structural steels in the United States fall into the category of carbon steels (less than 2% carbon) and low-alloy steels (alloys added but material not heat treated), an understanding of their composition and behavior is of primary interest. The addition of small amounts of carbon to iron at molten temperatures produces steel with the twin attributes of high strength and ductility. At normal temperatures, steel is made up of three major constituents: ferrite, cementite, and pearlite. The carbon combines chemically with some of the iron atoms to form the strong but brittle compound iron carbide, Fe_3C, which is often referred to as cementite. This compound exists as a distinct substance or "phase" within the iron, in particles whose size and shape vary depending on the steel's history of heat treatments. Ferrite is essentially iron molecules with no carbon attached. Pearlite is a mixture of 12% cementite and 88% ferrite. The presence of cementite as a part of the pearlite compound is fundamental to the strengthening of steels because it inhibits microscopic deformations. Steel is made up of many crystals called grains, each made up of ordered arrays of iron atoms. Permanent deformation under stress occurs through microscopic deformations call slip, in which layers of atoms within a grain slide past each other. If the stress is high enough, slip is extensive, and macroscopic yielding occurs. Cementite acts as an obstruction within the slippage planes, the effect of which depends upon the cementite's size, shape, and distribution. If the cementite is in the form of large spheres spaced far apart, the steel will be weak and ductile, since the cementite is not effectively reinforcing the weak and ductile iron. Conversely, if the cementite is in the form of small spheres close together, slip can take place only over very small distances, resulting in stronger steel.

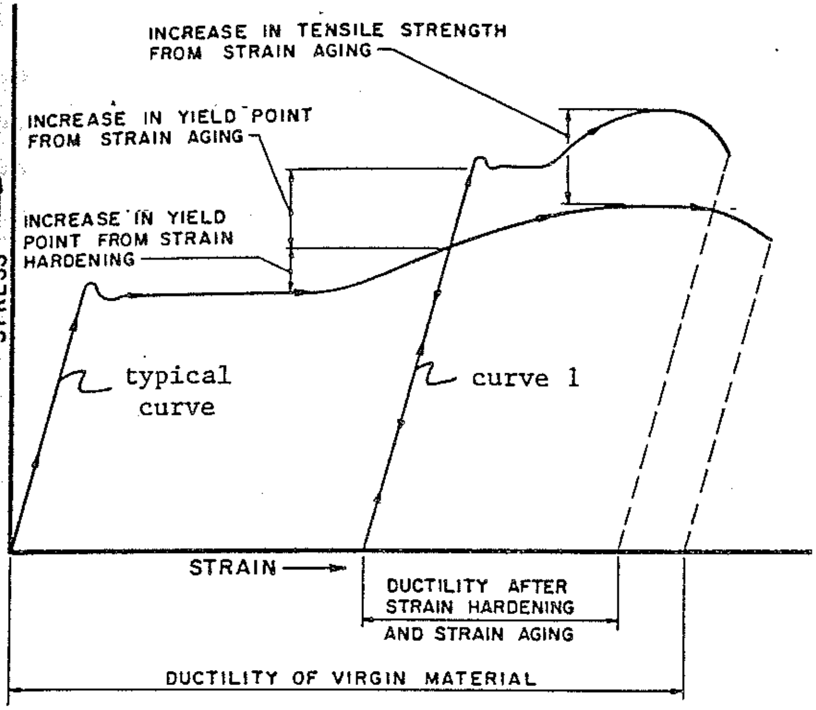
Low-carbon steels (less than 0.8% carbon) do not have enough carbon to develop a 100% pearlite compound, thus some free ferrite molecules exist. High-carbon steels (carbon greater than 0.8% but less than 2%) have more carbon than is needed to form pure pearlite, and therefore consists of pearlite and cementite. Since ferrite is soft and very ductile, while cementite is hard and brittle, low-carbon steels tend to be softer and more ductile than high-carbon steels. The strength of carbon steels increases with increasing carbon content until the condition of full pearlite compound is reached at a carbon content of 0.8%. Beyond the 8% carbon level, the strength of steels levels off because the additional cementite, free of the pearlite compound, adds little effective reinforcement to the ferrite. To obtain higher strength steels, two procedures are used. One is to apply heat treatments such as quenching, which produces a stronger (but more brittle) exterior while retaining the ductile characteristics within the interior. The second is to add additional alloys which combine with iron and carbon to produce new carbides which strengthen the steel in a process similar to that used for pearlite.

The effect of elevated temperature on the molecular composition of carbon steel is negligible below approximately 1330°F. However, above this temperature a phase change occurs in the crystalline nature of the iron atoms. If the steel is cooled slowly, the original compounds can reform, returning the steel to its normal molecular structure and original material properties. However, rapid cooling may not permit this reformation to occur completely, and a very hard, strong and brittle phase called martensite might occur. The potential for creating a brittle material has been one of the major factors in causing engineers to shy away from the use of heat-straightening procedures for repairing steel structures, especially in fatigue sensitive structures such as bridges. However, as long as the temperature does not exceed the phase transition temperature of 1330°F, no permanent degradation would be expected to occur in the steel.

A second factor that has discouraged the use of heat straightening is the loss of strength during heating that is directly proportional to the temperature. This aspect has been addressed in a companion volume (4). Summarizing that discussion, at heating temperatures below the phase transition temperature, the strength reduction in the vicinity of the heat application is approximately 50%. Since design live loads are usually larger than 50%, the reduction in strength can be accounted for by removing or controlling the live loads. As a result many applications of heat straightening can be safely completed without shoring. However, the engineer familiar with the live and dead load stress distributions should evaluate whether shoring should be used.

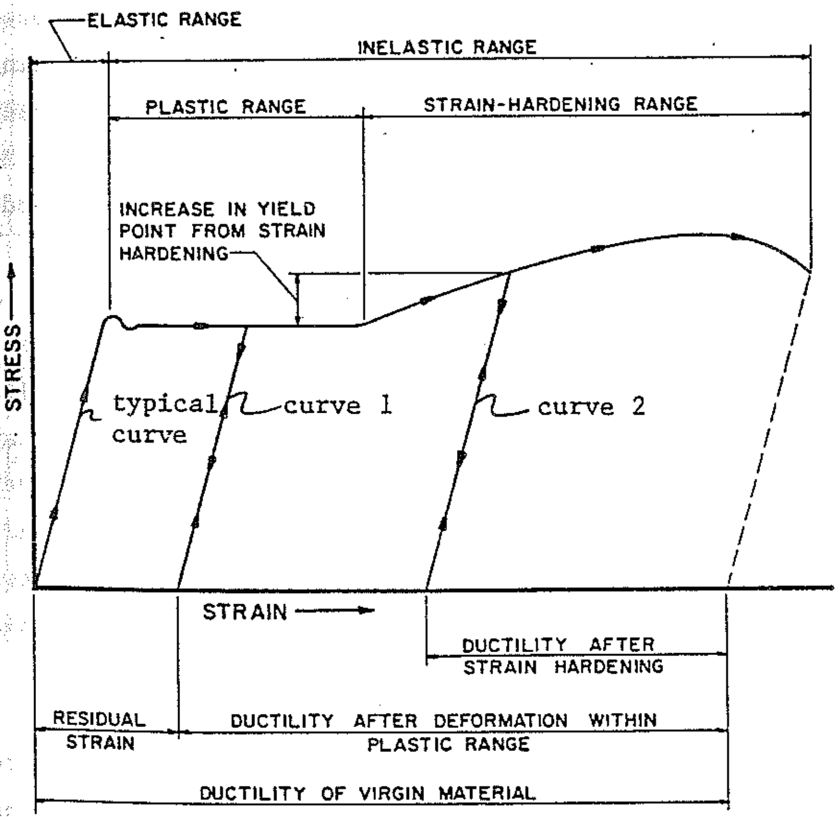
Cold-Working During Damage Inducement

A major concern of engineers is the effect of the damage inducement process on the material characteristics of the steel. The process of deforming steel into the inelastic range without heating is called cold-working. The immediate effect of cold-working is shown in Figure 1. When a steel specimen is unloaded after being stressed into either the plastic or strain hardening range, the unloading curve will follow a path parallel to the elastic portion of the stress-strain curve, producing a residual strain or permanent set after the load is removed. Upon reloading, the unloading curve will be retraced. If the material was initially loaded into the plastic range, the yield stress will be approximately the same as the original (unstrained) material, the tensile strength will remain unchanged, and ductility, as measured from



NOTE: DIAGRAM IS SCHEMATIC AND NOT TO SCALE

Figure 1. Typical Steel Stress-Strain Curves Before and After Immediate Loading



NOTE: DIAGRAM IS SCHEMATIC AND NOT TO SCALE

Figure 2. Typical Steel Stress-Strain Curves When reloading after Several Days

the point of reloading, will be decreased (Curve 1). Steel behaves in a similar fashion when the material is loaded into the strain hardening range prior to unloading. A permanent set remains after unloading (Curve 2), and this curve will be followed if immediate reloading occurs. In this case, the yield stress is increased above that of the virgin material, the tensile strength remains unchanged, and the ductility, as measured from the reloading curve, will be decreased.

An important question is whether this loss of ductility still exists after the completion of the heat-straightening process, since heat is known to mitigate this effect. If so, the possibility exists that an area of potential brittle failure could be created. A few tests to date (3) indicate that the loss of ductility is relatively small. However, more research is needed on this important topic.

Another area of concern is whether the heat-straightening process should be applied a second time if a previously repaired beam is redamaged. A steel specimen that has been strained into the strain hardening range, unloaded, and allowed to age for several days at room temperature (or for a much shorter time at a moderately elevated temperature) will tend to follow the path indicated in Figure 2 upon reloading (curve 1). This phenomenon is known as strain aging and has the effect of increasing yield and tensile strength while decreasing ductility. No studies of this effect have been conducted. However, part of the research plan in the current investigation includes a study into this behavior.

Geometric Considerations in Decisions to Repair

An engineer faced with a damaged steel girder must first make a decision as to whether the damage is serious enough to require repair before deciding on a repair technique. 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.

The primary variable in evaluating the level of damage for a bending member is the section modulus. Typically, the most serious

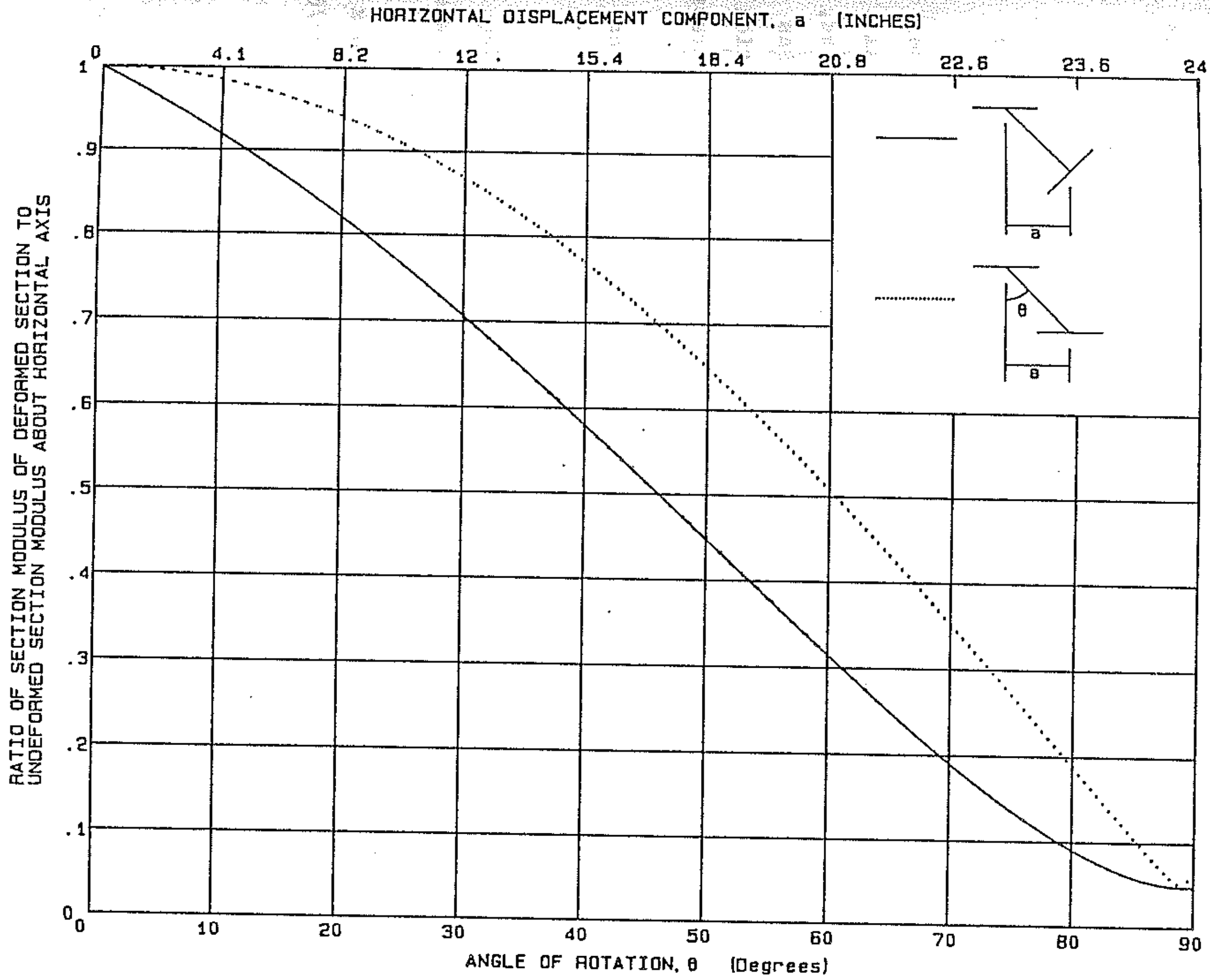


Figure 3. Reduction in Effective Section Modulus for a W24 x 76 Beam Subjected to Varying Degrees of Idealized Damage.

strength reduction is due to deformations resulting from twisting of the cross section. A good example is the impact on the bottom flange of a bridge girder by an over-height vehicle. Two ideal cases are evaluated here for two wide-flange sections. As shown in Figures 3 and 4, the damage is assumed to produce a rotation of the web about the juncture of the web and top flange. The bottom flange is modelled in two ways: either it remains parallel to the top flange, or it remains perpendicular to the web. Other combinations of damage often fall between these two conditions. Plotted in Figures 3 and 4 are the variations in the section modulus (bending about the strong axis) associated with different levels of damage for two beams: a W24 x 76 and W10 x 39. Both of these beams have been damaged and heat-straightened as a part of this research project (4). The case of the bottom flange remaining perpendicular to the web is the more critical case for the comparison of section modulus values. As can be observed, the section modulus drops fairly rapidly with an increase in the cross section rotation. A 10 degree rotation results in a strength reduction within the range of 8-15%, depending on the section, while at 20 degrees, the strength reduction is between 18 and 29%. Although an engineer should evaluate the specific conditions and configuration of each case, a good general guideline is to repair the member if the damage is greater than 10%. This level of damage typically corresponds to a rotation of approximately 10 degrees. In reference to the field tests conducted on the W10 x 39 and W24 x 76 beams (4), the damage induced was considered to be moderate. In both cases the flange remained almost perpendicular to the web. The bending strength reduction for the W10 x 39 beam was therefore approximately 25%. The reduction for the W24 x 76 beam was approximately 9%.

For compression members, the square of the minimum radius of gyration is the section property associated with the strength of the member. The effect of the two idealized cases of damage previously described are plotted in Figures 5 and 6. In this case, the configuration in which the bottom flange remains parallel to the top flange is the more critical. The curves are very similar for both wide-flange sections. The reduction in strength, as measured by the square of the radius of gyration, is not quite as large as the corresponding case for

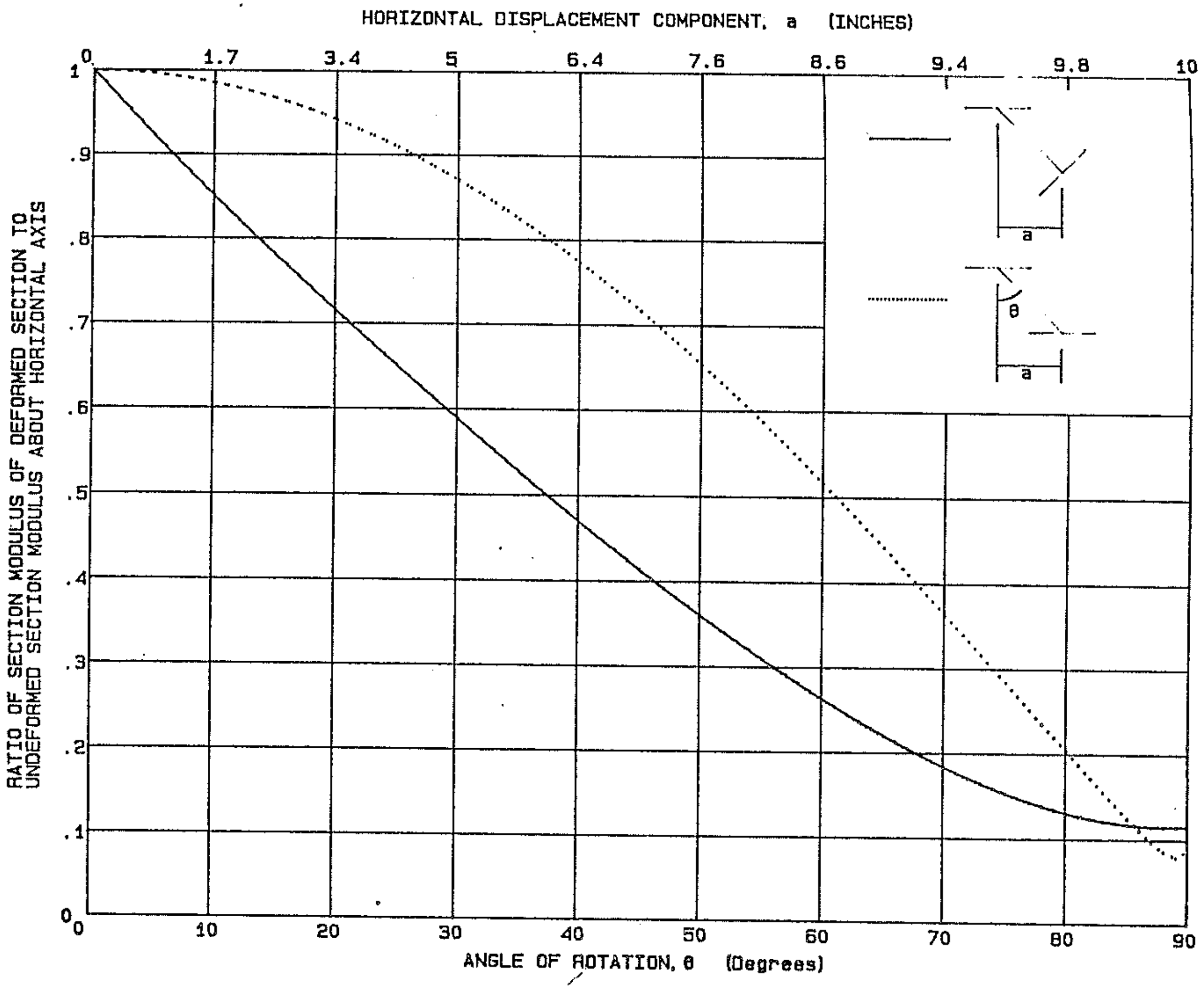


Figure 4. Reduction in Effective Section Modulus for a W10 x 39 Beam Subjected to Varying Degrees of Idealized Damage

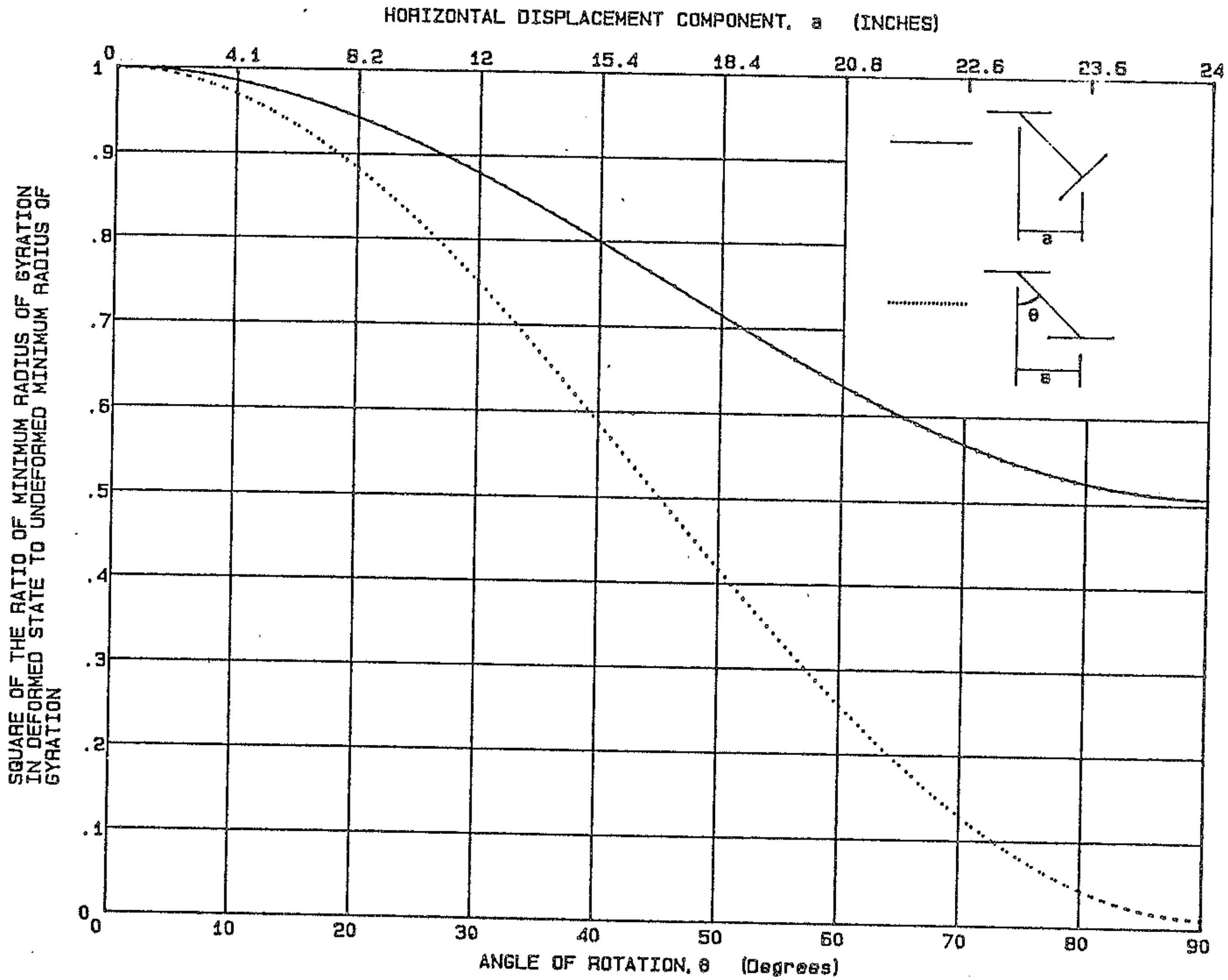


Figure 5. Reduction in the Square of the Effective Minimum radius of Gyration for a W24 x 76 Beam Subjected to Varying Degrees of Idealized Damage.

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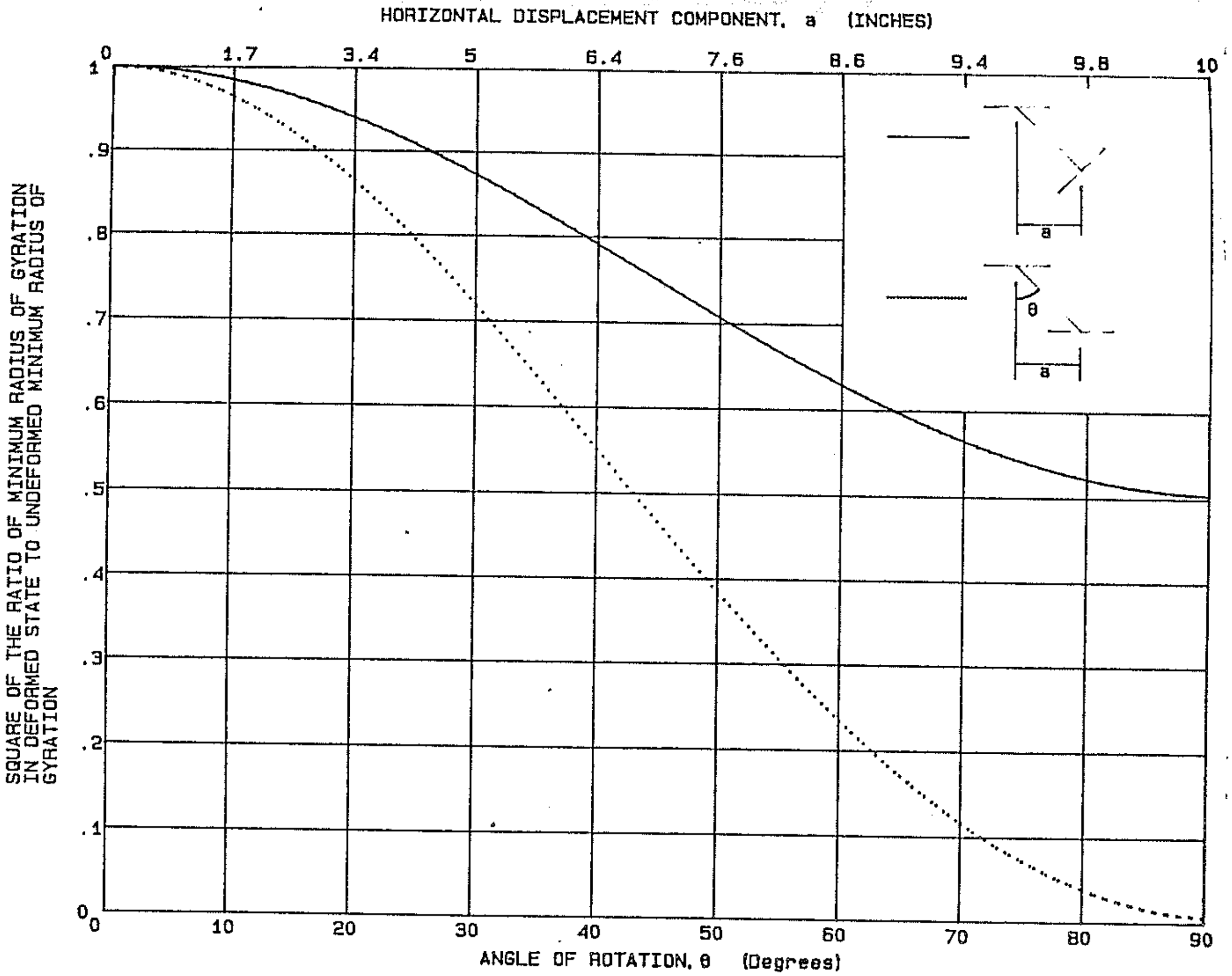

Figure 6. Reduction in the Square of the Effective Minimum Radius of Gyration for a W10 x 39 Beam Subjected to Varying Degrees of Idealized Damage.

section modulus. The reduction is only about 5% for the 10 degree rotation and about 14% at 20 degree rotation. However, another aspect that must be considered when evaluating compression members is the strength reduction due to the P-delta effect. If a simply supported column has an initial midpoint deflection, y_o, due to impact damage, then the deflection (and bending moment) is amplified according to the amplification factor

$$A.F. = \frac{y_o}{1 - P/P_{euler}} \tag{1}$$

This factor is taken into account in design codes by an adjustment in the safety factor for columns. Consider the AISC code (1), for example. The long column formula (Eq. 1.5-2) is the classical Euler buckling formula, divided by a safety factor of 23/12. Conversely, the safety factor for tension members is given as 5/3. The reason for the higher safety factor for compression members is to account for the P-delta magnification effect. A plot of the amplification factor is given in Figure 7. As the load approaches the critical buckling load, the deflection (and consequently the moment) approaches infinity. Failure must therefore be defined as the point where the deflection (and consequently the moment) remains finite but becomes excessively large. The safety factor for column buckling was therefore increased by 0.25 above that used in tension members. As can be seen from Figure 7, this extra safety factor accounts for 0.08 of the total load ratio reduction to allowable values. In deciding upon this value, it was assumed that relatively small initial values of lateral deflections would exist due tc lateral loads or fabrication imperfections, e.g., within the elastic range. When a compression member has larger permanent deformations well into the plastic or strain-hardening range due to damage, then the effective strength of the member is reduced by a larger factor than expressed by even the column safety factor.

In light of these considerations, even relatively small permanent deformations should be repaired for compression members unless a stability analysis is performed to justify that the strength reduction is small.

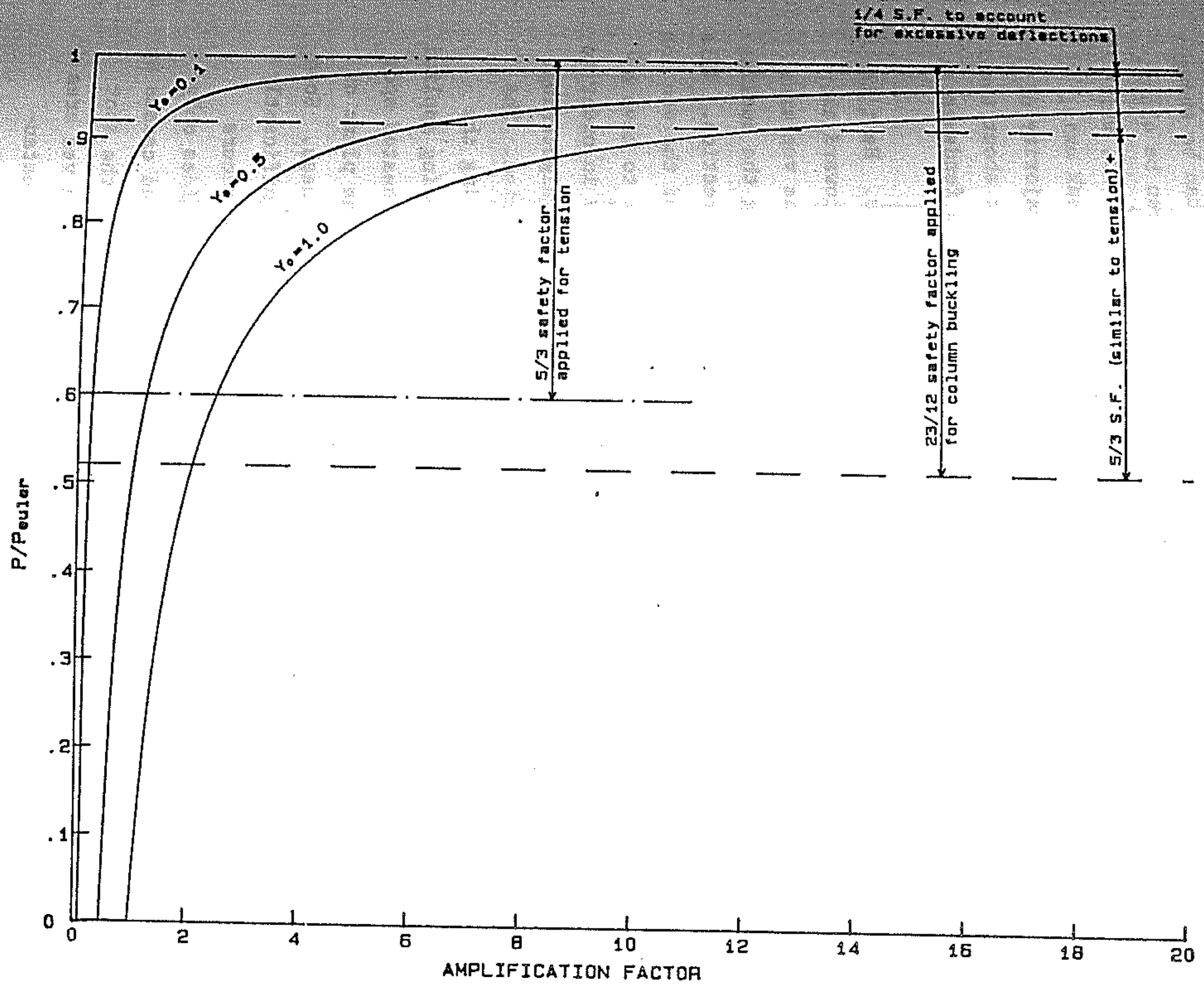

Figure 7. Effect of Amplification Factor for Lateral Deflections on Compression Members

3. FACTORS AFFECTING THE BEHAVIOR OF HEAT-STRAIGHTENED MEMBERS

Bending of Undeformed Plates

Before an engineer can develop a predictive procedure for the heat-straightening process, he must thoroughly understand the behavior of all the parameters involved. Flat plates are used in the initial investigation construction. Rolled and built-up sections can be thought of as an assemblage of plate elements. Damage to plates can be classified into two general categories: bends about the strong axis, which are usually repaired with vee heats, and bends about the weak axis, which are usually repaired with line or spot heats. The majority of damage encountered in practice involves plate elements bent about their strong axis. Therefore, the vee heat can be viewed as the fundamental heat pattern in heat straightening.

The basic concept of the vee heat is relatively simple. Heat is applied in a progressive fashion from the apex of the vee toward the open end using an acetylene torch. During this heating, the vee area experiences a permanent increase in thickness, while during the cooling phase, a permanent shrinkage occurs in the longitudinal direction. This "reshaping" process creates a small decrease in the angle of the vee and produces a curvature in the plate. It is helpful, however, to have a more detailed understanding of the mechanism just described in order to better evaluate the influence of the parameters of heat straightening. Figure 8a-d shows a plate to which a vee heat has been applied. The figures indicate the plates response at different times during the heating and cooling process. Figure 8a shows a spot heat being applied to the apex of the vee. The cold material surrounding the heated spot provides a partial restraint to thermal expansion within the plane of the plate, while increasing the expansion through the thickness. Soon the in-plane compressive stresses reach yield (which is significantly lowered due to the elevated temperature), and plastic flow occurs through the thickness. Since the surrounding material provides only partial restraint, some longitudinal expansion does occur and causes an initial downward deflection in the plate (Figure 8a). Once the spot heat temperature reaches 1200°F, the torch is moved over the vee area in a serpentine fashion. The same process of yielding occurs instantaneously at each point under the torch. When the torch reaches a

AIGHTENED MEMBERS

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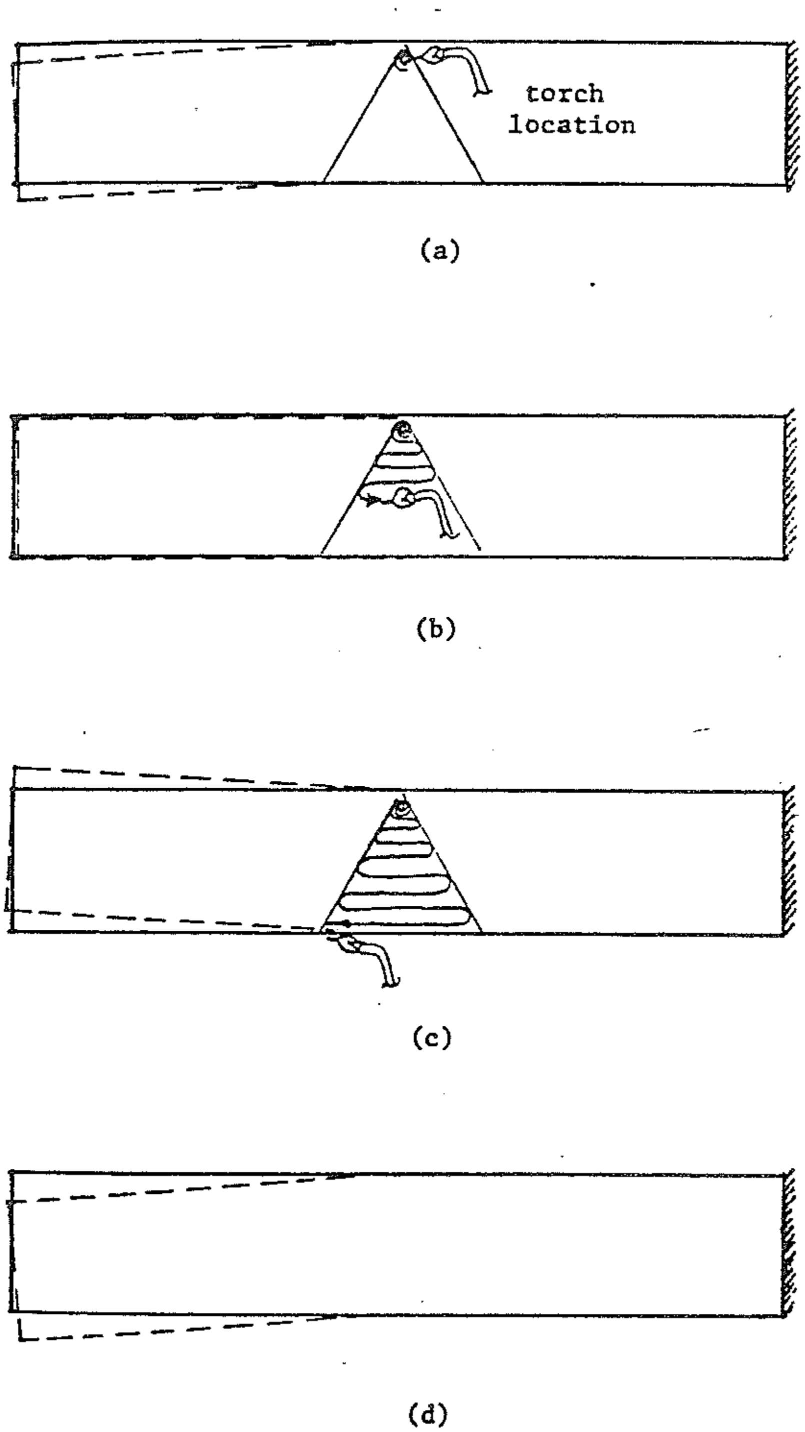

Figure 8. Progression of a Vee heat

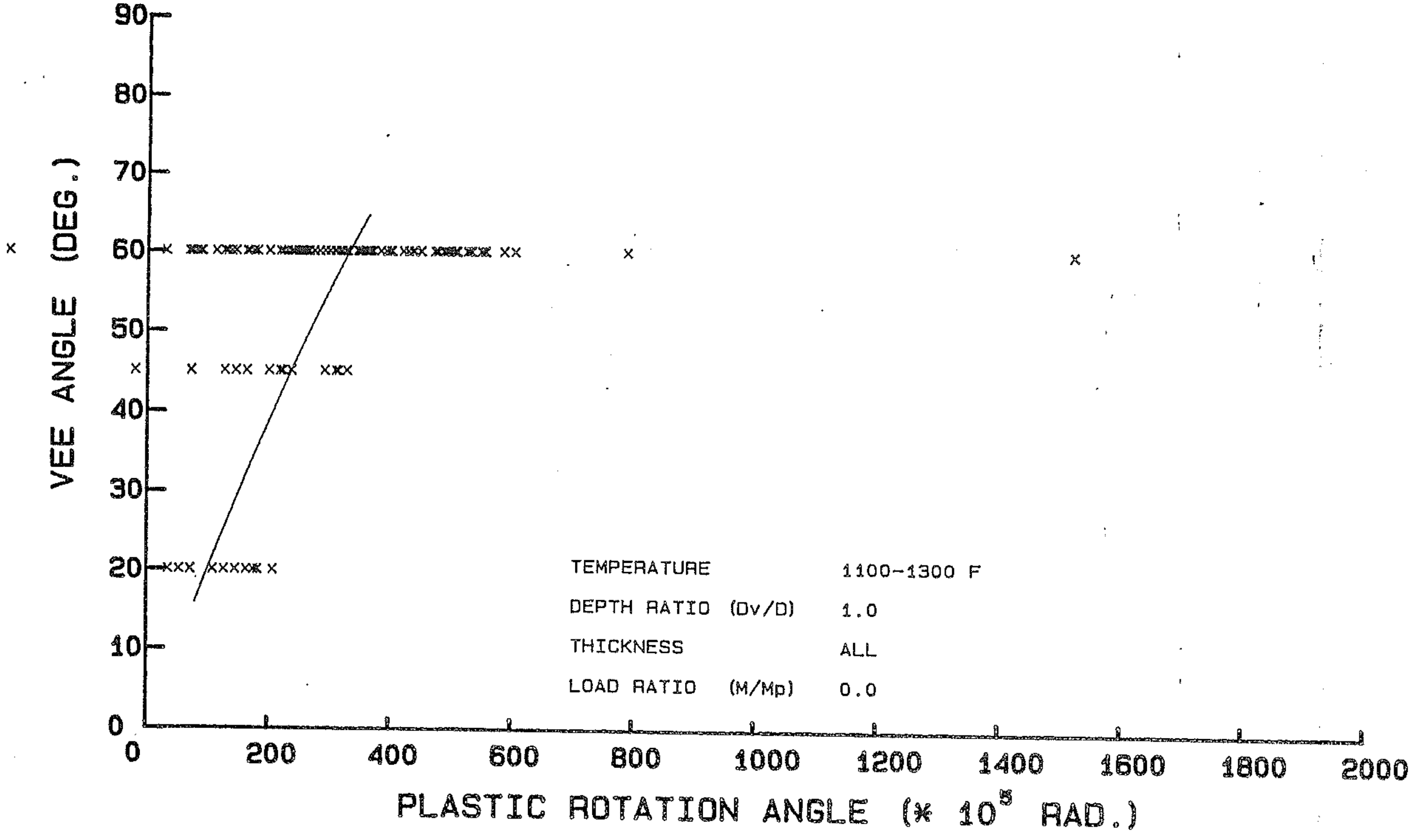

Figure 11. Plot of Vee Heat Angle vs. Plastic Rotation for Plates.

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recommended that the vee base width not exceed 10 inches to reduce the chances of buckling at the elevated temperatures.

Constraining Forces

Practitioners have recognized the importance of applying jacking forces during the heat-straightening process. The principle involved is that applying a jacking force in the direction of the desired contraction reduces the longitudinal expansion which occurs during the heating phase, increasing the plastic strain through the thickness and thus producing more plastic rotation during the cooling phase. A series of tests designed to evaluate this parameter involve applying jacking force to a plate such that a moment is created about the strong axis in a direction tending to close the vee. This moment is non-dimensionalized 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 include load ratios of 0, 16%, 25% and 50% and four different vee angles extending over 3/4 the depth of the plate. Nicholls and Weerth (10) and Roeder (11) also studied the behavior of load ratio variation, and their results, along with those of this project, are plotted in Figure 12. A straight line is shown fitted to each of the groups of data. This plot indicates that the variation appears to be linear with respect to the 25% and 50% load ratios (i.e., doubling the load approximately doubles the increase in rotation). The 16% load ratio appears to violate this trend; however, close examination of the data reveals that a relatively small number of data points were available at the 82 degree vee angle. If only the data for the other three vee angles is considered, then the linear variation is noticed. Thus, it can be seen from these results that using external loads can expedite the heat-straightening process.

The level of the jacking force for a given application has not been addressed in the literature. Most practitioners do not have pressure gages on their jacks and apply the force by "feel." The primary concern in limiting the applied force is the buckling capacity of the vee area during the heating phase, since the yield strength is reduced. Some difficulties have been encountered in the current study when using combinations of the largest vee angles and largest load ratios. A force to a plate such that a moment is created about the strong axis in a direction tending to close the vee. This moment is non-dimensionalize 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 include load ratios of 0, 16%, 25% and 50% and four different vee angles extending over 3/4 the depth of the plate. Nicholls and Weerth (10) and Roeder (11) also studied the behavior of load ratio variation, and their results along with those of this project are plotted in Figure 12. A straight line is shown fitted to each of the groups of data. This plot indicates that the variation appears to be linear with respect to the 25% and 50% load ratios (i.e., doubling the load approximately doubles the increase in rotation). The 16% load ratio appears to violate this trend; however, close examination of the data reveals that a relatively small number of data points were available at the 82 degree vee angle. If only the data for the other three vee angles are considered, then the linear variation is noticed. Thus, it can be seen from these results that using external loads can expedite the heat-straightening process.

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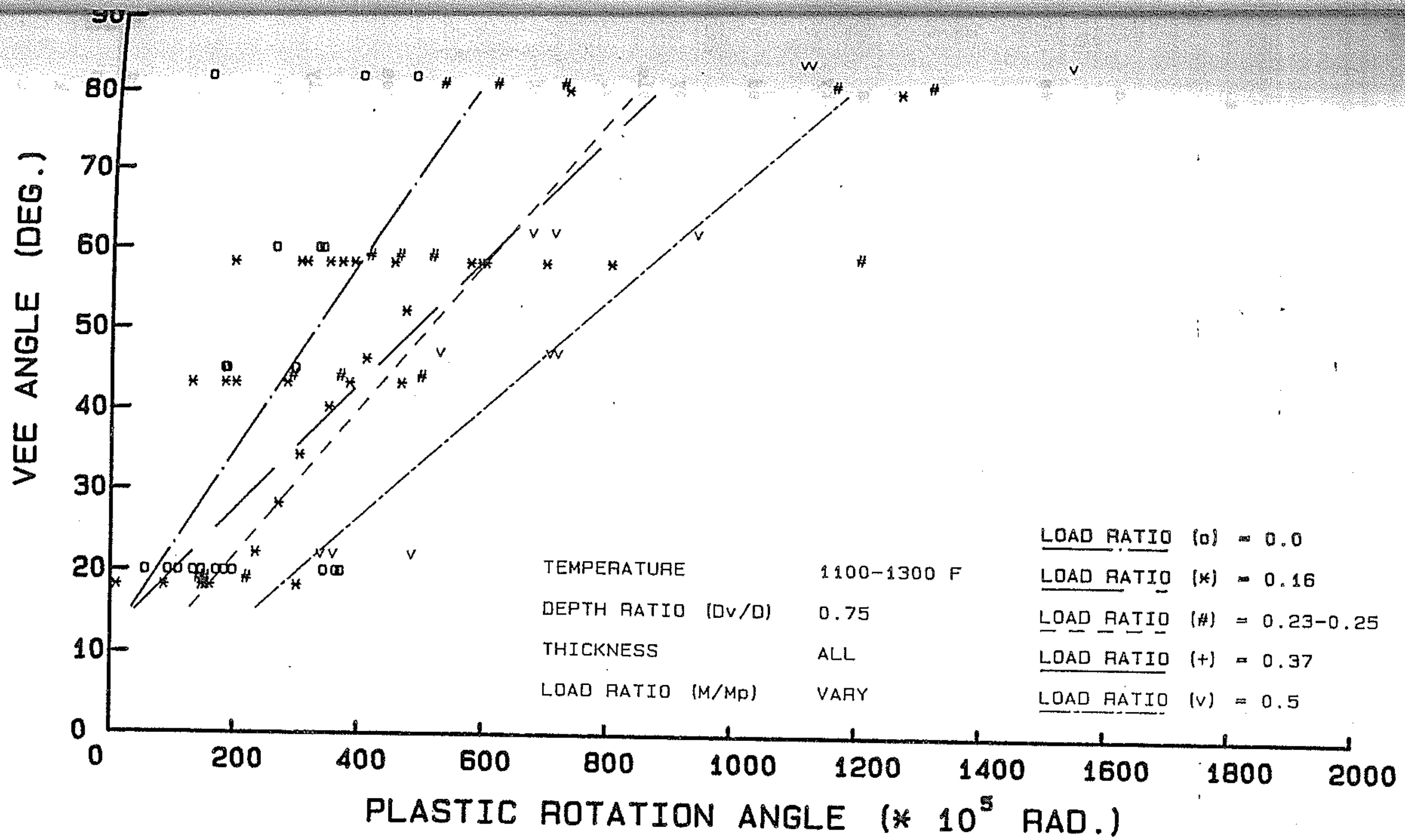

Figure 12. Plot of Vee Heat Angle vs. Plastic Rotation for Vee Heated Plates with Variation in the Load ratio (11, 14).

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A second type of constraint which 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 an actual load to ultimate load ratio of 56%. These results are shown in Figure 13 in comparison to the result from the bending load ratios of 0% and 50%. The axial load does increase the plastic rotation but to a lesser extent than the 50% bending load ratio.

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 torch orifice and intensity of the flame, speed of torch movement, and thickness of the plate. Roeder (11) made careful temperature measurements of the heats produced by experienced practitioners in his experiments. He found that these practitioners, when judging temperature by color, commonly misjudged by 100°F and, in some cases, as much as 200°F. Thus there are considerable variations in temperature control, even with experienced practitioners.

Several methods are available for monitoring temperature during heat straightening. The most common method is by watching the color of the steel lying just beneath the tip of the torch. The level of background lighting will have an influence on this method. In normal daylight or interior lighting conditions, a 1200°F temperature will produce a bright satiny silver color near the torch tip. A more precise method, such as temperature indicating crayons, should be used to calibrate the steel color for different lighting conditions. A properly heated vee will produce a gray color over the entire vee once the plate has cooled. A cherry red color during heating or a black color after cooling indicates the temperature was too hot. Temperature indicating crayons, which melt and become fluid at the indicated temperature, can be applied to the vee surface prior to heating or applied during heating by removing the torch momentarily and striking the surface. Experiments by the writers revealed that applying a flame directly to a crayon mark produce a very bright glow, making it impossible to determine the point

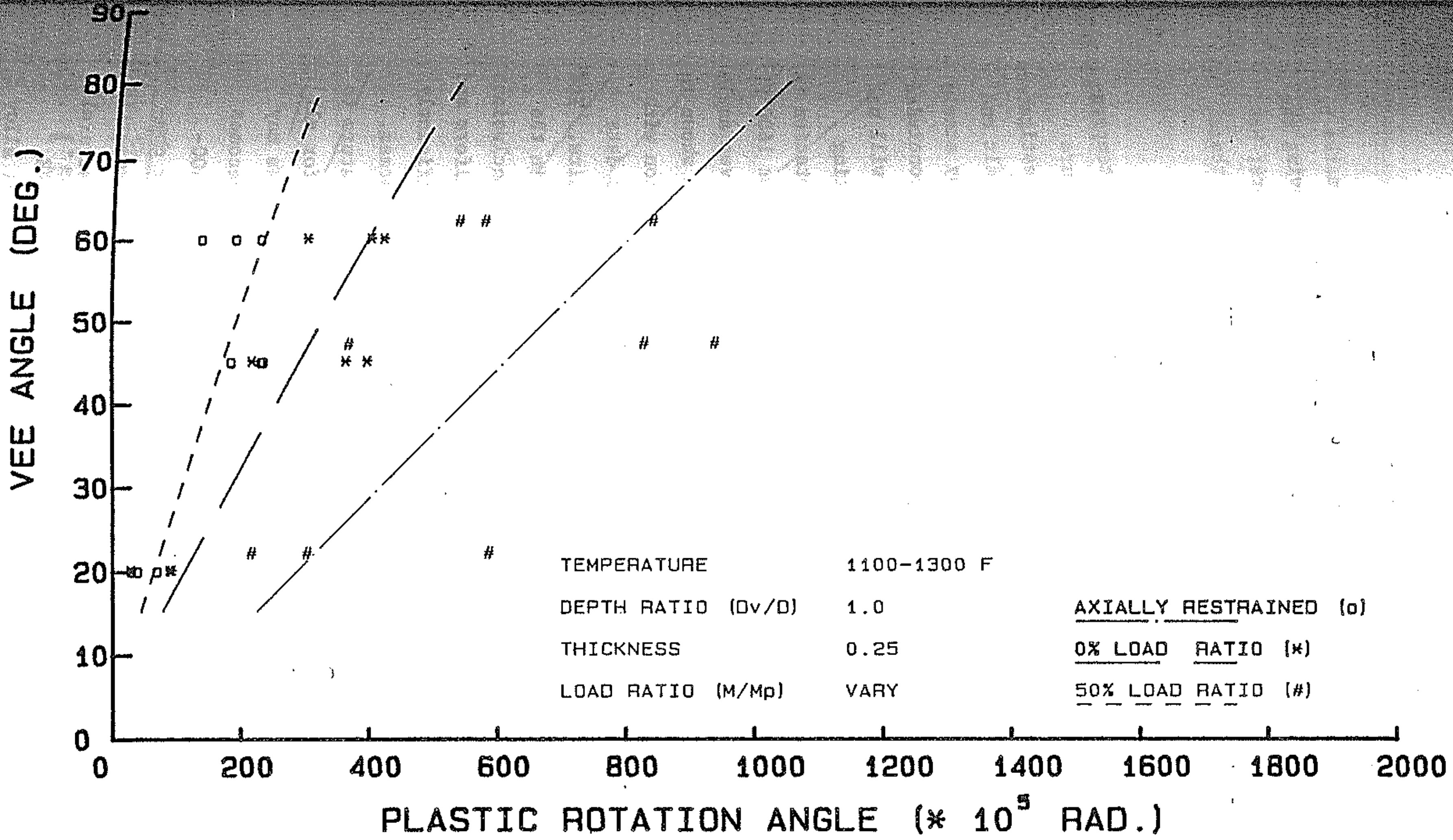


Figure 13. Plot of Vee Heat Angle vs. Plastic Rotation for Vee Heated Plates with Axial Restraints

of melting. Therefore, it is recommended that either crayon marks be placed on the back side of the vee or that the method of removing the torch be used. A third method is the use of contact pyrometers; however, experiments by Graham (7) and the writers indicate that these temperature readings are approximately 200°F below the actual temperature.

Assuming adequate control is maintained over the applied temperature, the question which must now be answered is what temperature produces the best results in heat-straightening? Previous investigators have differed in answering this question. For example, Shanafelt and Horn (13) state that heats above 1200°F on carbon and low alloy steels will not increase plastic rotation. Rothman and Monroe (12) concluded that reheating areas where previous spot heats were performed will not produce any useful movements. However, the comprehensive testing program by Roeder (11) has shown 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. Plot of vee angle versus plastic rotation for Roeder's and the writer's data are shown in Figures 14 and 15. Both figures indicate the increased rotation with increased temperature. The only variation between the sets of data concerns the 900-999°F and 1100-1199°F ranges in Roeder's results. It is the writers' opinion that this deviation could be an error in the data. It is likely that earlier researchers made erroneous conclusions from very limited temperature data or that the effects of a uniform and slow heating used by some investigators produced results significantly different from the rapid heating in the heat-straightening process.

In light of the research to date, what is the best temperature to use for a vee heat? The recommendation here is to use 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 (11) will occur at 1400-1600°F. Also, temperatures in excess of 1600°F cause molecular composition changes (6) which may 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

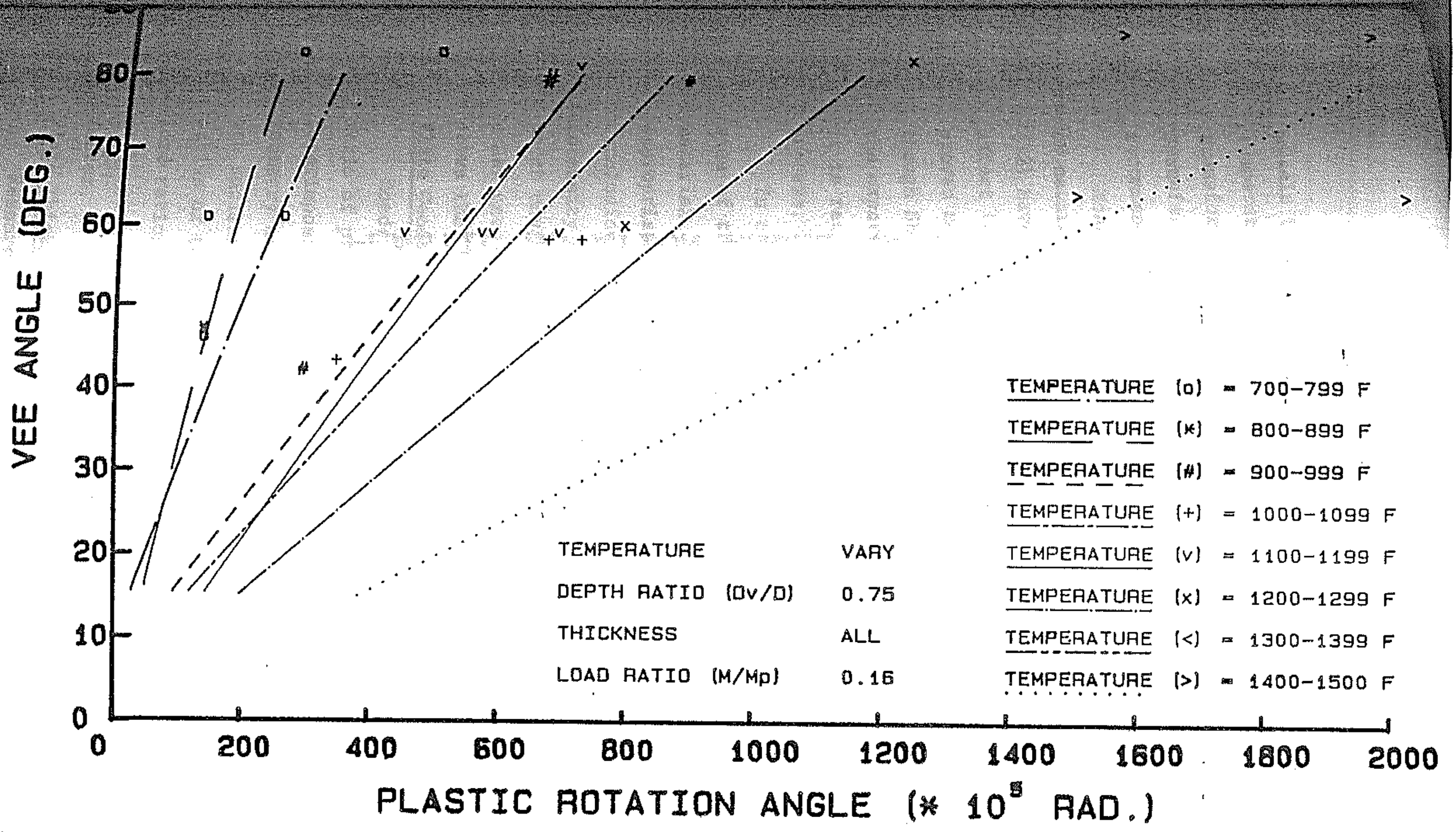


Figure 14. Plot of Vee Heat Angle vs. Plastic Rotation for Plates with Various Heating Temperatures (11).

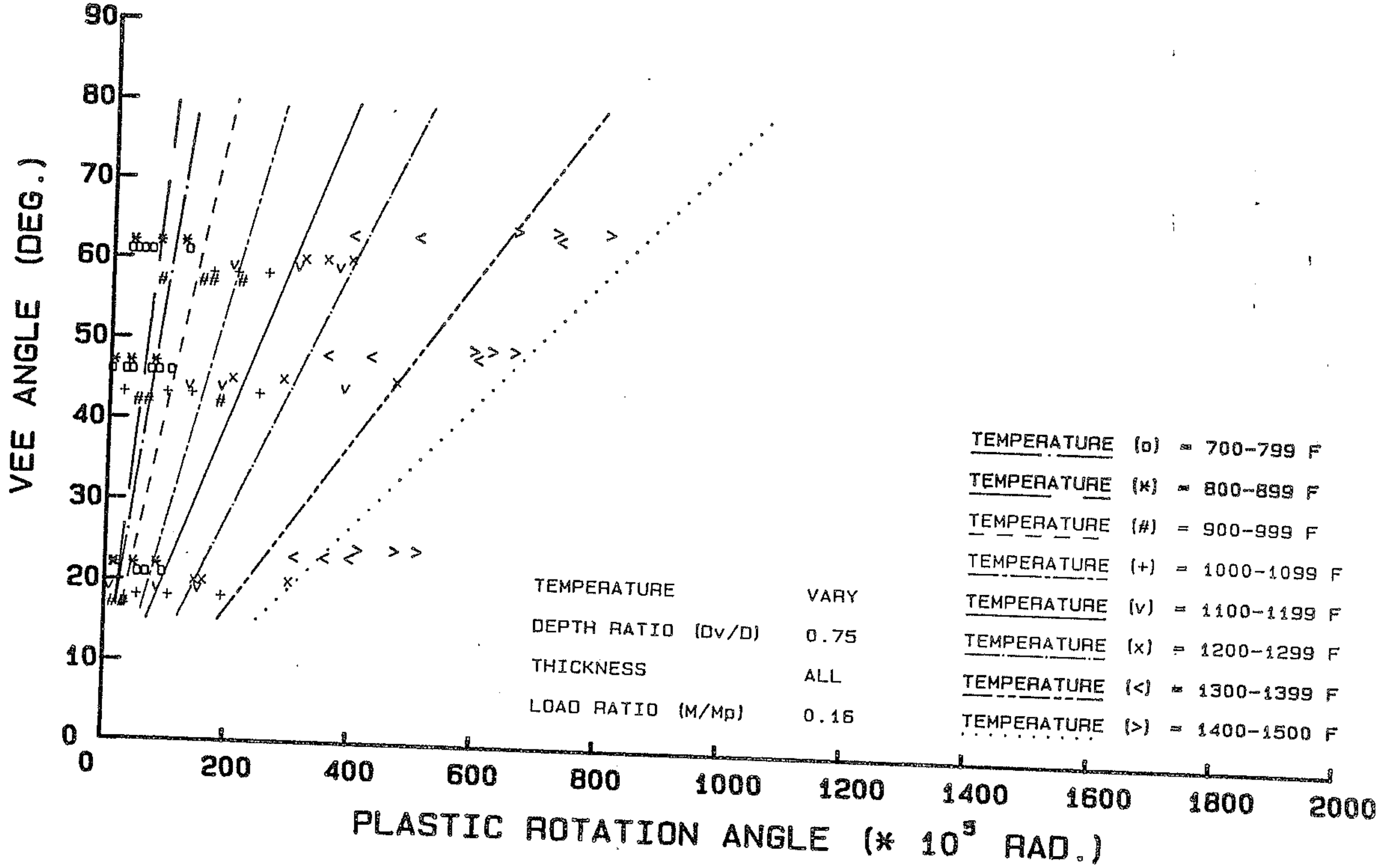


Figure 15. Plot of Vee Heat Angle vs. Plastic Rotation for Plates with Various Heating Temperatures.

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 (12). This conclusion is contrary to that of Shanafelt and Horn (13); however, Roeder (11) concurs with this recommendation.

Most researchers have only considered cooling of vee heats by way of natural air cooling. However, Roeder (11) and Rothman and Monroe (12) have shown that quenching not only is effective, but also does not affect the steel properties after cooling. In fact, quenching has proven more effective than air cooling in some applications (12). Even though Shanafelt and Horn (13) specifically recommend against quenching, the experimental evidence does not support this conclusion; therefore, it is recommended that quenching be considered as an acceptable cooling process.

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. One set used a low-intensity torch which moved more slowly to maintain a 1200°F temperature, while the other used a high-intensity torch which moved more quickly. Figure 16 shows that the rotations in either case were similar.

Plate Geometry

Roeder (11) considered the effect of plate geometry by varying the ratio of plate depth to thickness in a group of experiments while superimposing various load ratios. His findings suggested that the geometry as defined had some influence on rotation, but the exact nature was unclear. In the current study, the influence of plate depth for a series of tests in plates with equal thicknesses, vee angles, and zero load ratios was investigated. These results show similar rotation for each case. Thus, plate depth under these conditions is not an important factor.

Plate Thickness

Researchers have generally considered plate thickness to have a negligible affect on plastic rotation. The only reservation expressed

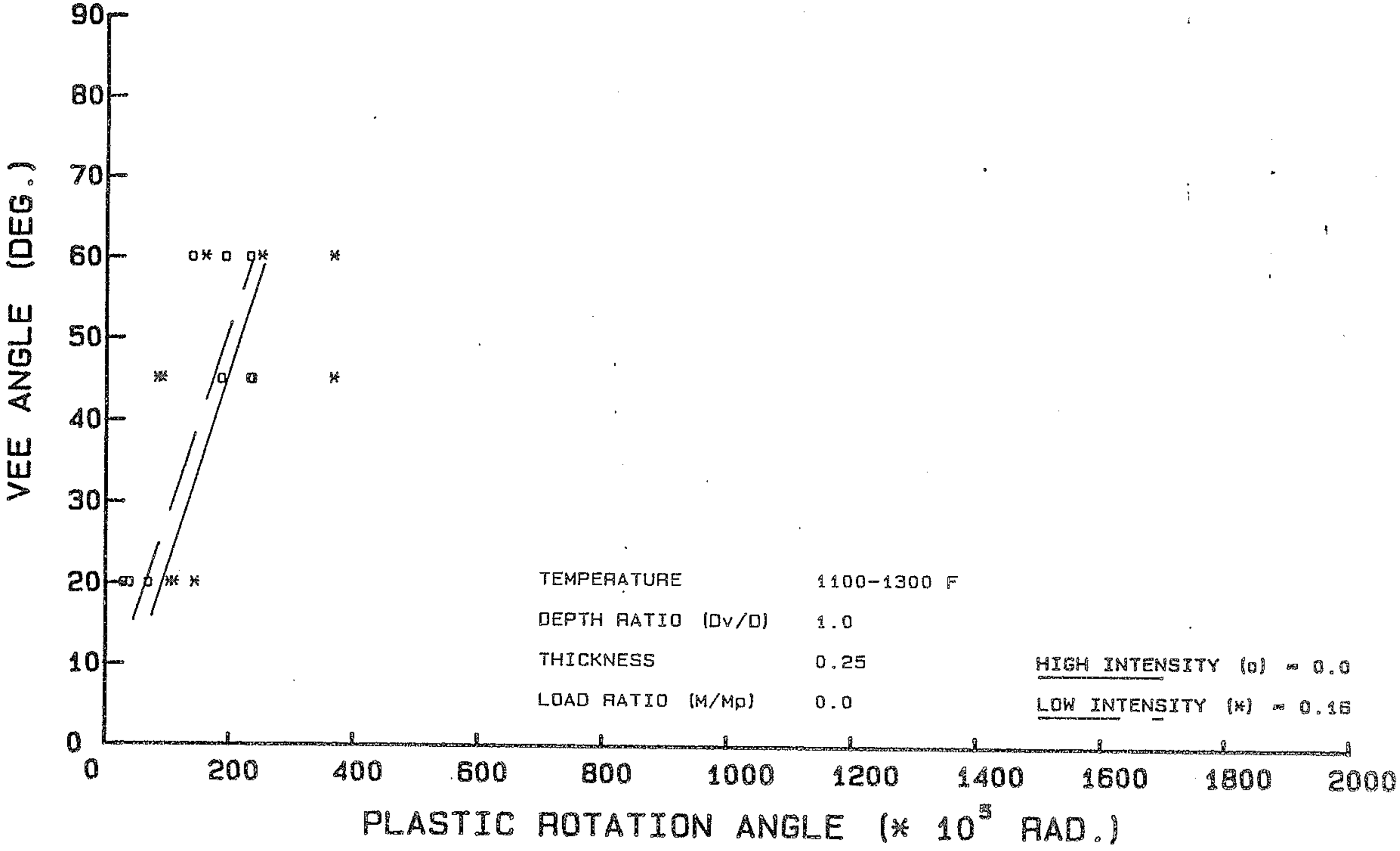


Figure 16. Plot of Vee Heat Angle vs. Plastic Rotation for Variations in Flame Intensity

was that the plate should be thin enough to allow a relatively uniform penetration of the heat through the thickness. The practical limiting value is on the order of 3/4 to 1 inch. Thicker plates can be heated on both sides simultaneously to ensure a uniform distribution through the thickness. The results from tests involving different plate thicknesses are plotted in Figure 17, and each group has a second order, least squares curve fit also plotted. The variations in rotation appear random, indicating that thickness is not a factor.

Depth of Vee

The depth of the vee in comparison to the depth of the plate also influences the plastic rotation. The available data was relatively sparse. In the current study, a series of tests to produce additional data was conducted; however, some inconsistencies existed in the data. Further experiments are required before a conclusion can be reached on the influence of vee depth.

Heat-Straightening Bent Plates

To date, two series of tests have been conducted in the current study to straighten plates bent about their strong axis. In the first series, three 24 inch long plates were simply supported and deformed plastically with a midpoint loading. The permanent deformation at midpoint was approximately one-half inch. Each of the specimens was then supported as a cantilever and a sequence of full-depth 60-degree vee heats was applied to remove the distortion. No external force was used during the straightening process. The results of the straightening process are shown in Figures 18 and 19. The original deformed shape indicates that the zone of plastic deformation occurred in a small, 4-inch long region at the point of load application. A single vee heat was applied during each cycle and the curvature was measured after cooling. The process required slightly over 20 heating cycles to remove the distortion. The irregularities associated with the progression of heats shown in Figure 18 stem from the fact that the measuring blocks were modified and replaced between heats. The excessive gaps reflect a rigid body movement of the measuring device. To clarify the heating process, the location of each vee heat is shown in Figures 19 and 20. All vees were located within a two-inch zone at the point of maximum plastic rotation. It can be seen that each heating cycle produced a

Figure 16. Plot of Vee Heat Angle vs. Plastic Rotation for Variations in Flame Intensity.

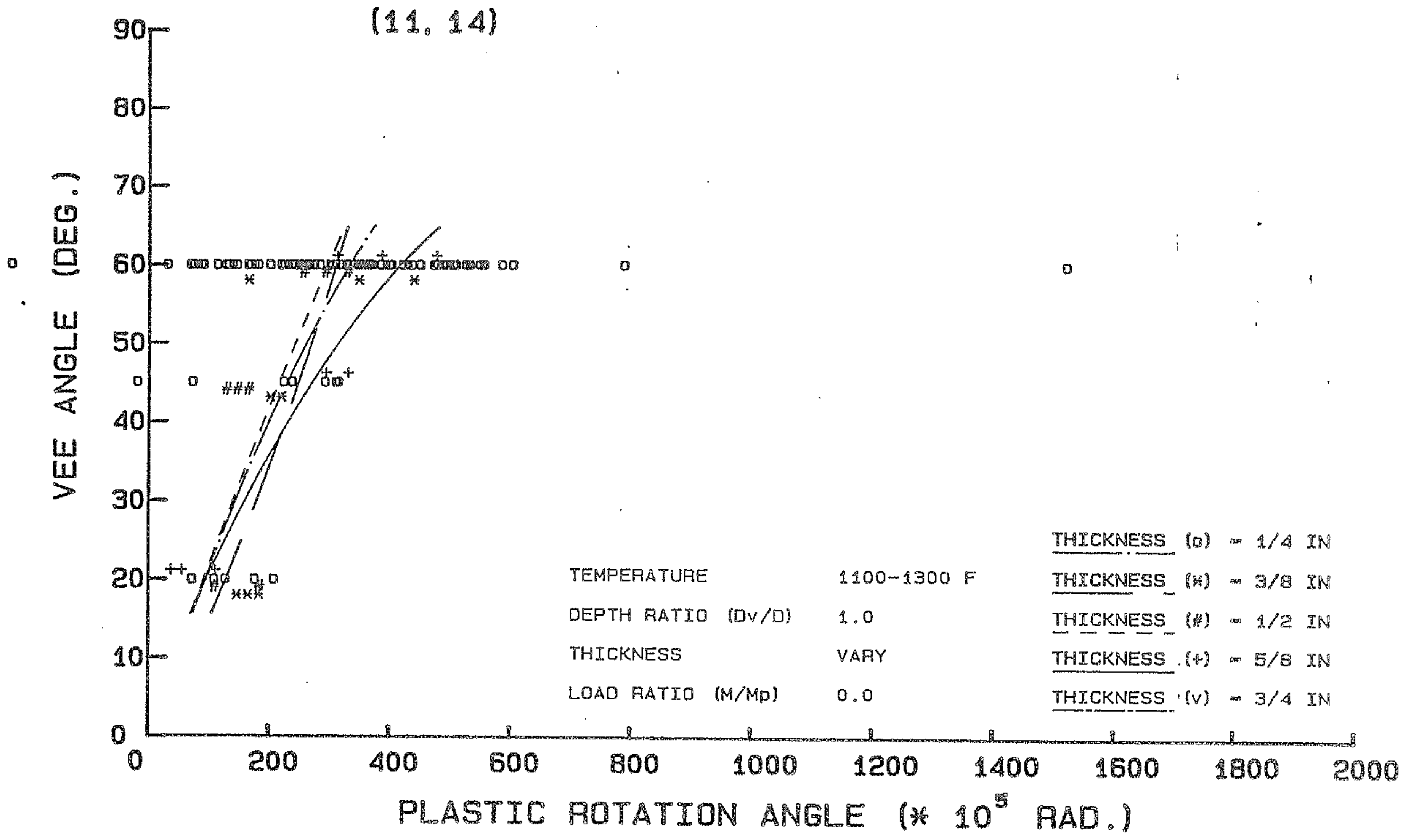
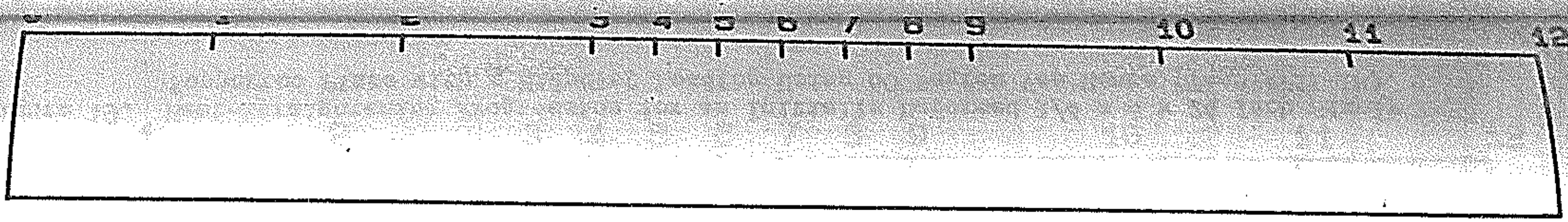


Figure 17. Plot of Vee Heat Angle vs. Plastic Rotation to Evaluae the *Effect* of Thickness Variation (11, 14).

Figure 17. Plot of Vee Heat Angle vs. Plastic Rotation to Evaluae the Effect of Thickness Variation (11, 14).



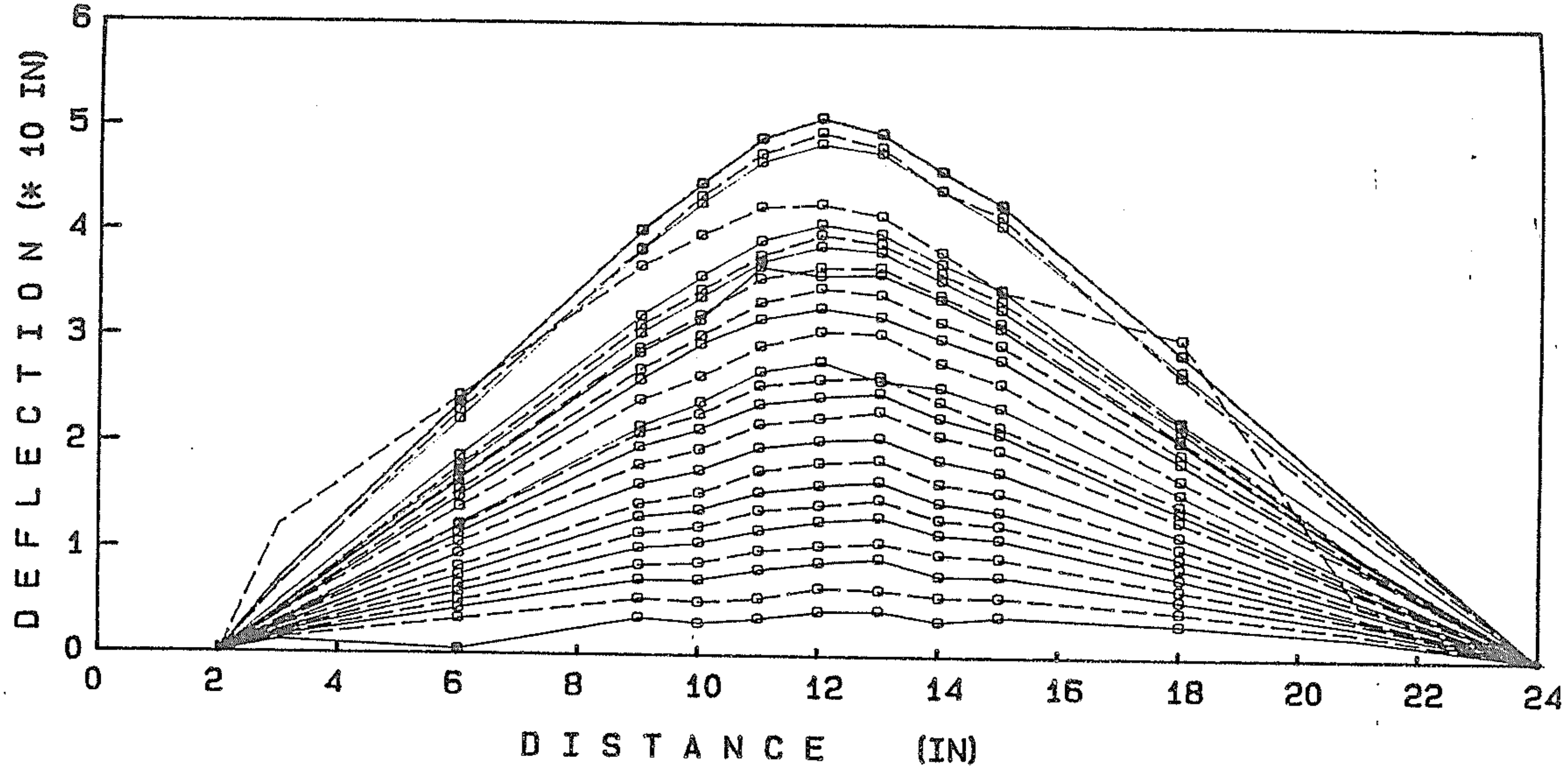


Figure 18. Heat-Straightening Progression for an Initially Deformed 1/4 x 4 x 24 Inch Simply Supported Plate with a Midpoint Loading Using 60 Degree Vee Heats (Test #VII-1A).

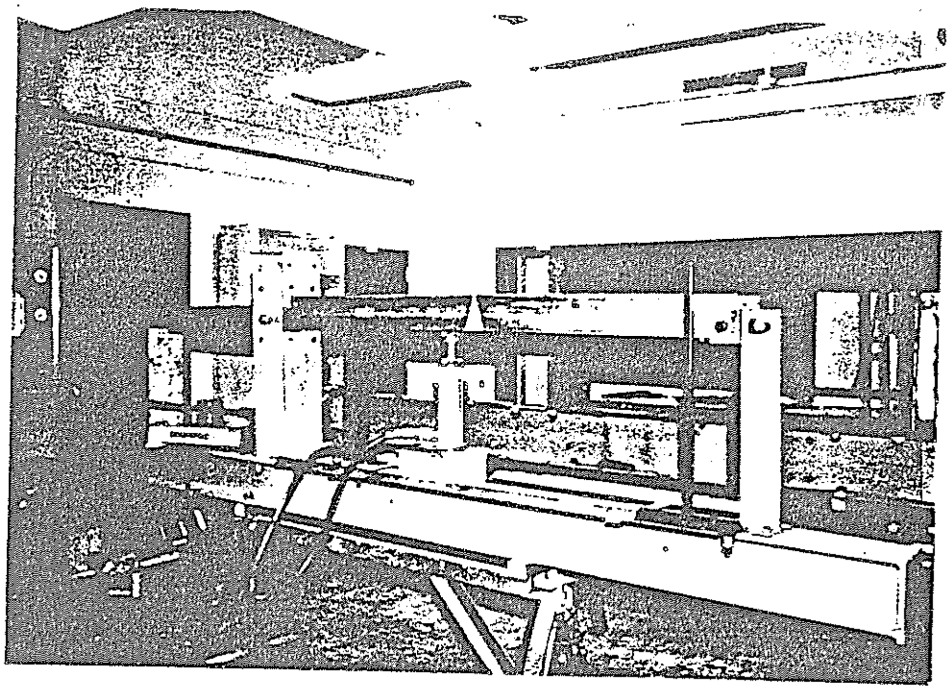


Figure 24. Typical Test Set-Up for Rolled Shapes

results are shown in Figures 25 and 26, respectively. As with plates, the angle of plastic rotation is used as a convenient measure of the curvature from a vee heat. These plots show that increasing the vee angle increases the plastic rotation and that load ratios increase the rotation in a fairly linear fashion for camber heats, but in a more undefined manner for the sweep heat. A more careful examination of the data is required.

Summary

The heat-straightening behavior of plates is now well documented and understood. It has become apparent that the external constraints, which have heretofore been undocumented, play an integral role in the process. A fundamental key to understanding the behavior of rolled sections is to control the restraining forces. The emphasis of future testing will be related primarily to documenting restraint effect.

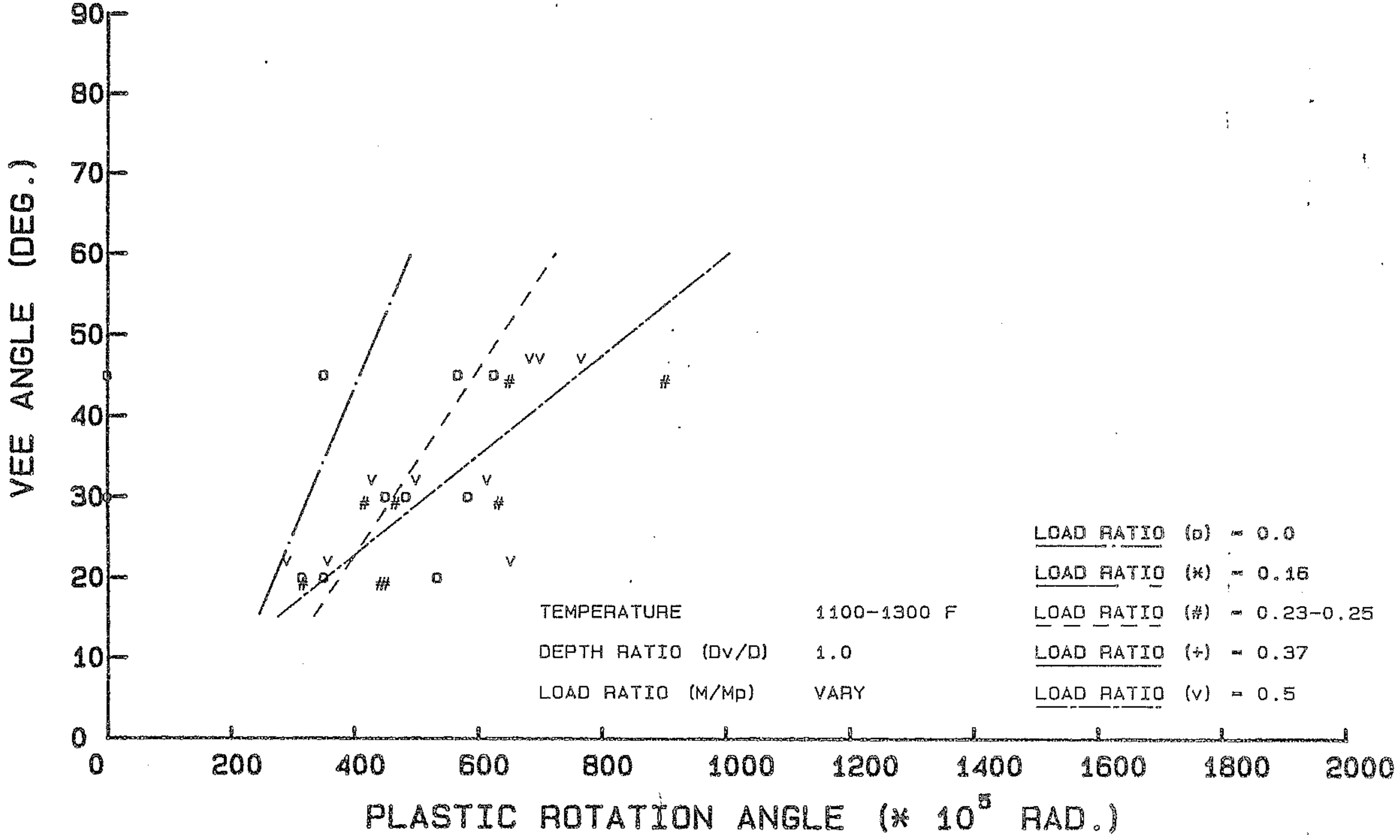


Figure 25. Plot of Vee heat Angle vs. Plastic Rotation for W6 x 9 Beams for Camber Under Various Load ratios.

PLASTIC ROTATION ANGLE (* 10 RAD.)

Figure 25. Plot of Vee heat Angle vs. Plastic Rotation for *W6 x 9 Beams* for Camber Under *Various Load ratios.*

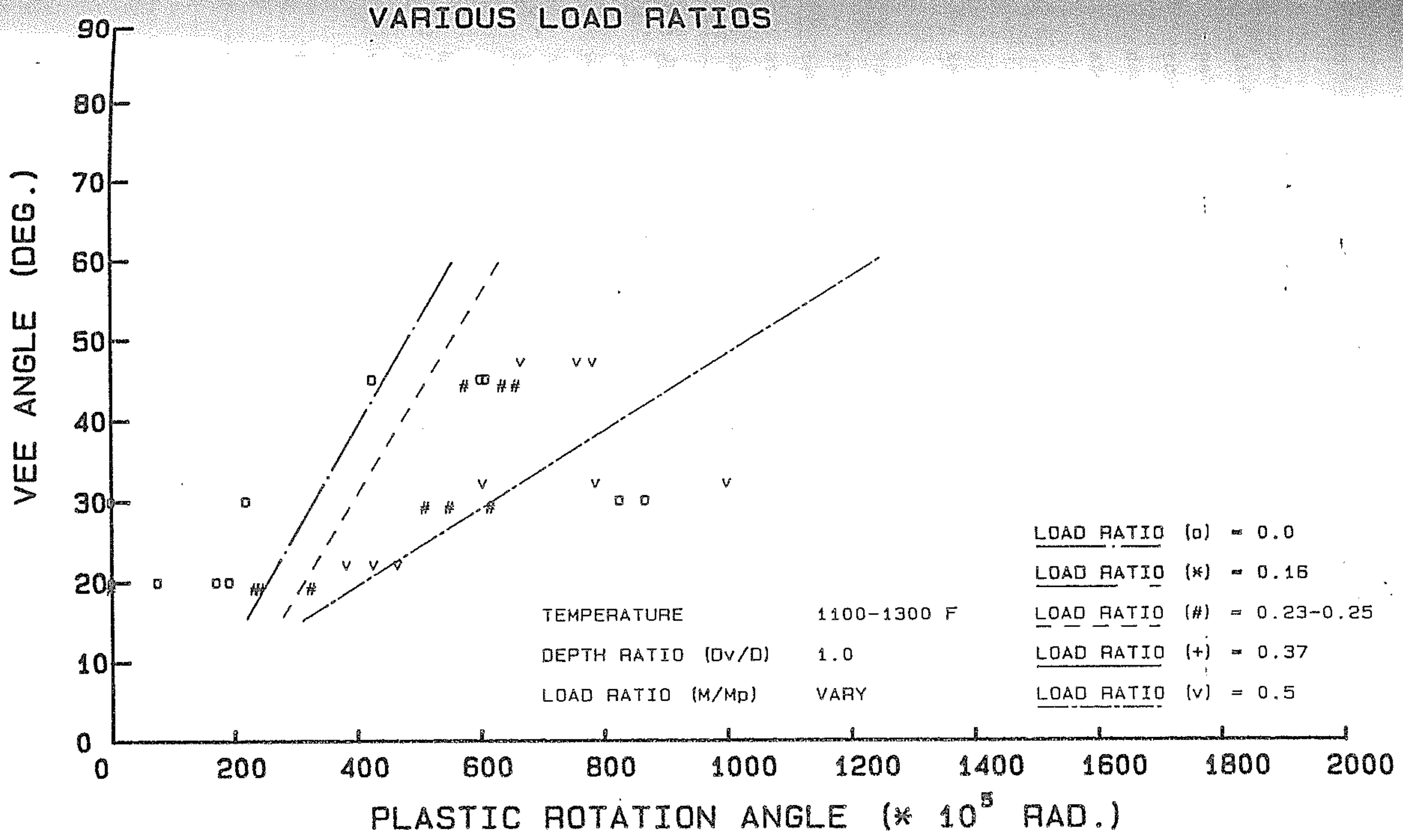


Figure 26. Plot of Vee Heat Angle vs. Plastic Rotation for W6 x 9 Beams Under Various Load Ratios.

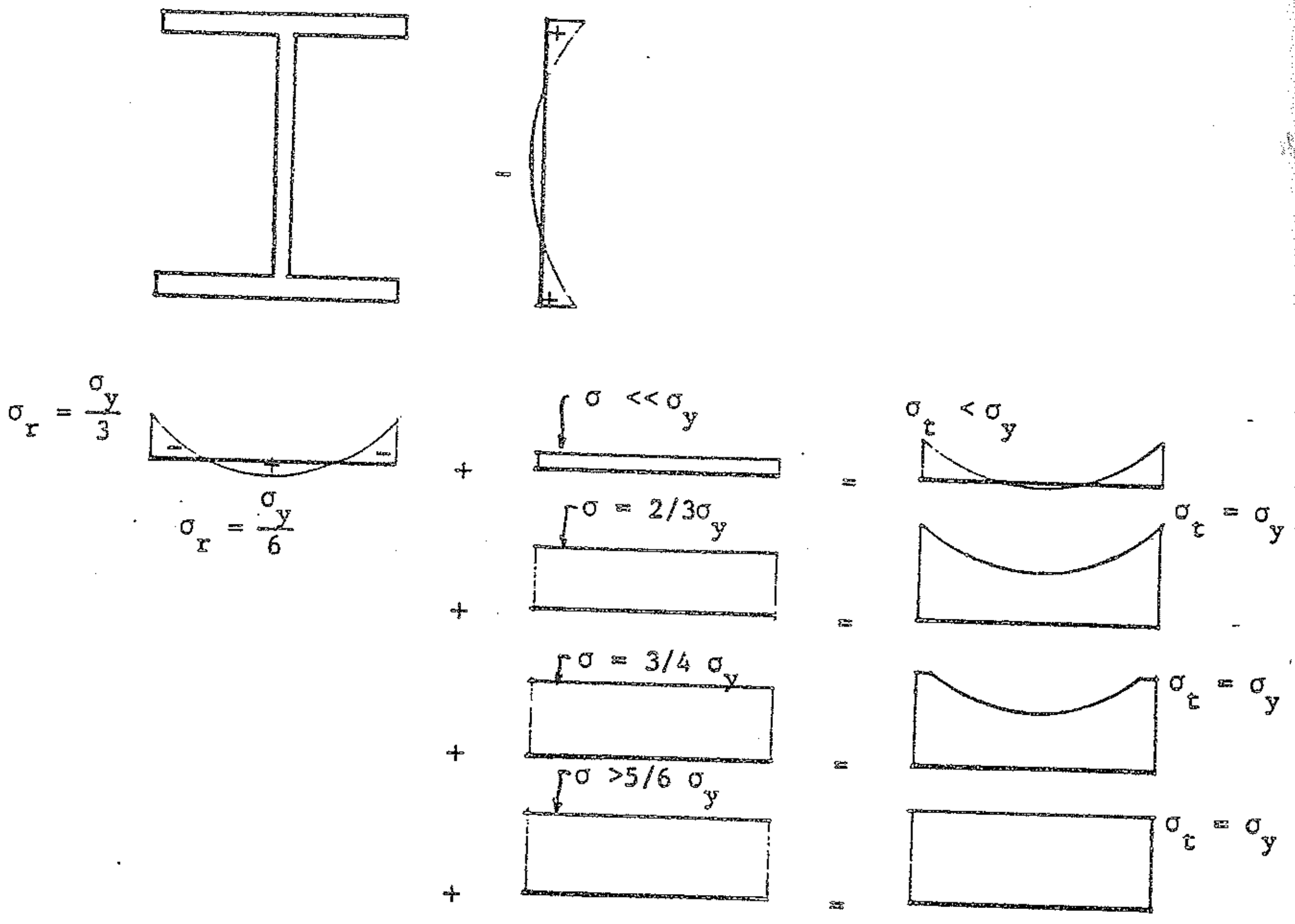


Figure 27. Effect of Residual Stresses on Column Behavior

Code formulas for lateral buckling of beams in bending are based on elastic considerations and do not take into account the residual stress patterns. Consequently, it can be concluded that residual stresses due to heat straightening will have a significant degrading effect on the design strength of a member only when both of the following conditions are met:

1. The member must be loaded in axial compression.
2. The maximum compressive residual stress due to the heat straightening must exceed one-half the yield stress.

Residual Stresses in Heat-Straightened Members

A study has been initiated to evaluate the magnitude and distribution of residual stresses due to heat straightening. The basic procedure is to take representative samples from heat-straightened members during the course of this project and measure the residual stresses. At this point, only a relatively small portion of the eventual data is available.

The procedure used here to measure residual stresses is the sectioning method (5). Initial extensometer readings are taken in the zone of heating. Then the section is cut into thin longitudinal strips, which relieves the residual stresses. Finally, the extensometer measurements are repeated and both residual strains and stresses are calculated. A typical strip layout for a plate is shown in Figure 28.

Eight plates have been tested to date. A summary of the plate heating characteristics is given in Table 1 and the maximum residual stresses in Table 2. A plot of the residual stress distribution for each plate is shown in Figures 29-36. The trend of the results is that the edges are in tension, with compression near the midsection. More tests are needed to establish a clear pattern of the residual stress characteristics.

Material Properties Based on Stress-Strain Curves

Some of the residual stress strips were milled to ASTM standards for tensile testing. The results are summarized in Table 3 and stress-strain curves are plotted in Figures 37-52. In general, the properties were consistently in the expected range. However, the percent elongation was somewhat smaller than usual. Other researchers have also noticed this trend.

Table 1. Experimental Data for Mild Steel Head-Treated Plates

Specimen			Heat			Load Ratio	Angle Plastic Rotation (rad.)	Net Elongation (in.)
Code	Thick. (in.)	Depth (in.)	Depth (in.)	Temp. (°F)	Angle (deg)			
I-1A	.250	4.000	1.00	1200	20	0.00	0.00073	———
I-1B	.250	4.000	1.00	1200	20	0.00	0.00073	———
I-1C	.250	4.000	1.00	1200	20	0.00	0.00073	———
I-2A	.250	4.000	1.00	1200	43	0.00	.00238	-.06
I-3A	.250	4.000	1.00	1200	60	0.00	.00073	-0.3
LR-4	.250	4.000	0.75	1244	45	0.50	.00746	0.00
LR-10	.250	4.00	0.75	1148	82	0.50	.00927	0.00
LR-12	.250	4.000	0.75	1171	82	0.00	.00385	0.00

Table 2. Results of Residual Stress Analysis

Specimen Code	Maximum Residual Stress (ksi)			
	Tension	@ Strip Number	Compression	@ Strip Number
I-1A	+16.1101	6	-12.2711	5
I-1B	+15.1525	4	-2.9725	6
I-1C	+50.3150	1	-15.0075	6
I-2A	+37.7725	1	-6.4525	4
I-3A	+70.8325	8	-23.2000	3
LR-4*	+11.4840	1	-15.9342	3
LR-10*#	+30.6730	2	-5.8630	7
LR-12	+34.5825	1	-11.3825	4

*The out-of-plane deflection was included in the stress calculation.

#Strips 3, 4 and 5 were rendered unreadable by milling.

5. ANALYTICAL PROCEDURE FOR PREDICTING BEHAVIOR

It is easy to see the wide range of damaged steel structures to which heat-straightening repair could lend itself. And while the actual method is easily learned, 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 predictive procedures to determine how best to apply the heat-straightening process to a particular repair. This predictive tool, for reasons of economy, should be relatively fast and allow for such considerations as different vee geometries, temperature ranges, external loadings, and support restraints. Several researchers have offered analytical models which have met these criteria with varying levels of success.

Holt (8) developed one of the first and simplest methods for predicting plastic rotations from vee heats. His model was derived from the geometry of the vee heat, as shown in Figure 53. Recognizing that heat straightening merely "reshapes" the volume of material being heated, Holt suggests that the plastic flow through the thickness which occurs during heating will be "recovered" along the direction of initial restraint, provided the member is free to contract. The plastic flow or strain is found by subtracting the elastic strain from the total free expansion at a given temperature. The plot of thermal strains versus temperature is shown in Figure 54. Holt defines the upset or shortening of the concave side of a bend as

$$\text{upset} = \frac{DW}{L},$$

and the vee heat width, W_v, required to correct the damage is found as

$$W_v = \frac{\text{upset}}{\text{plastic strain}}$$

This method produces fair results for members with no support restraints and therefore has limited use in practical applications. It also does not realistically account for variations in the vee depth.

Both Horton (9) and Weerth (14) used a Duhamel strip analogy to develop a predictive model. The vee area is divided into a number of longitudinal strips and subjected to temperature distribution steps

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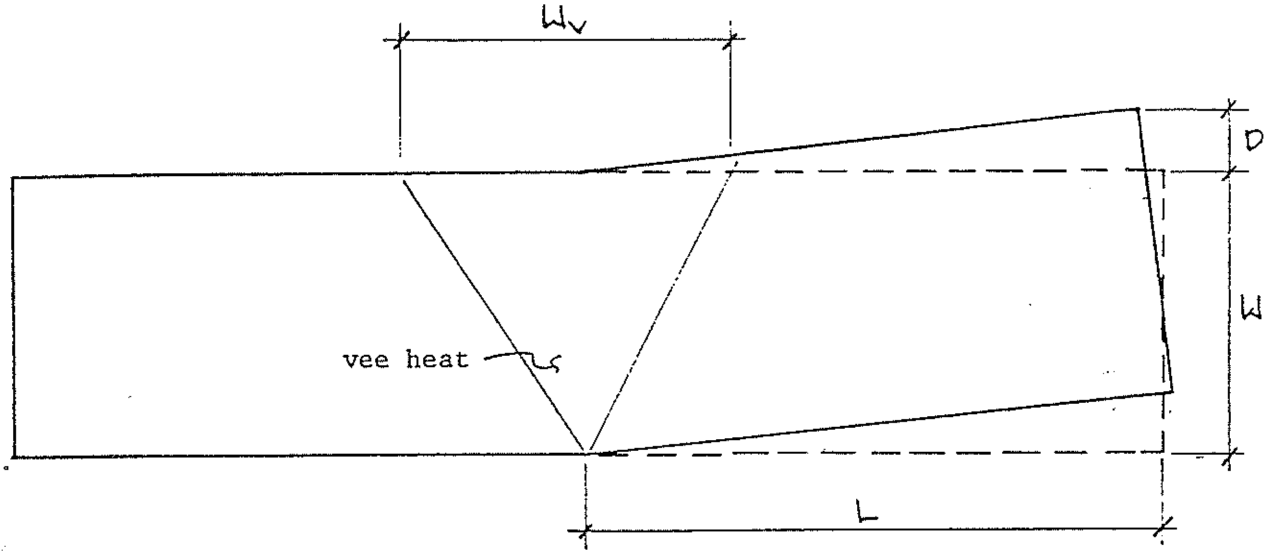

Figure 53. Vee Geometry for Holt Equation

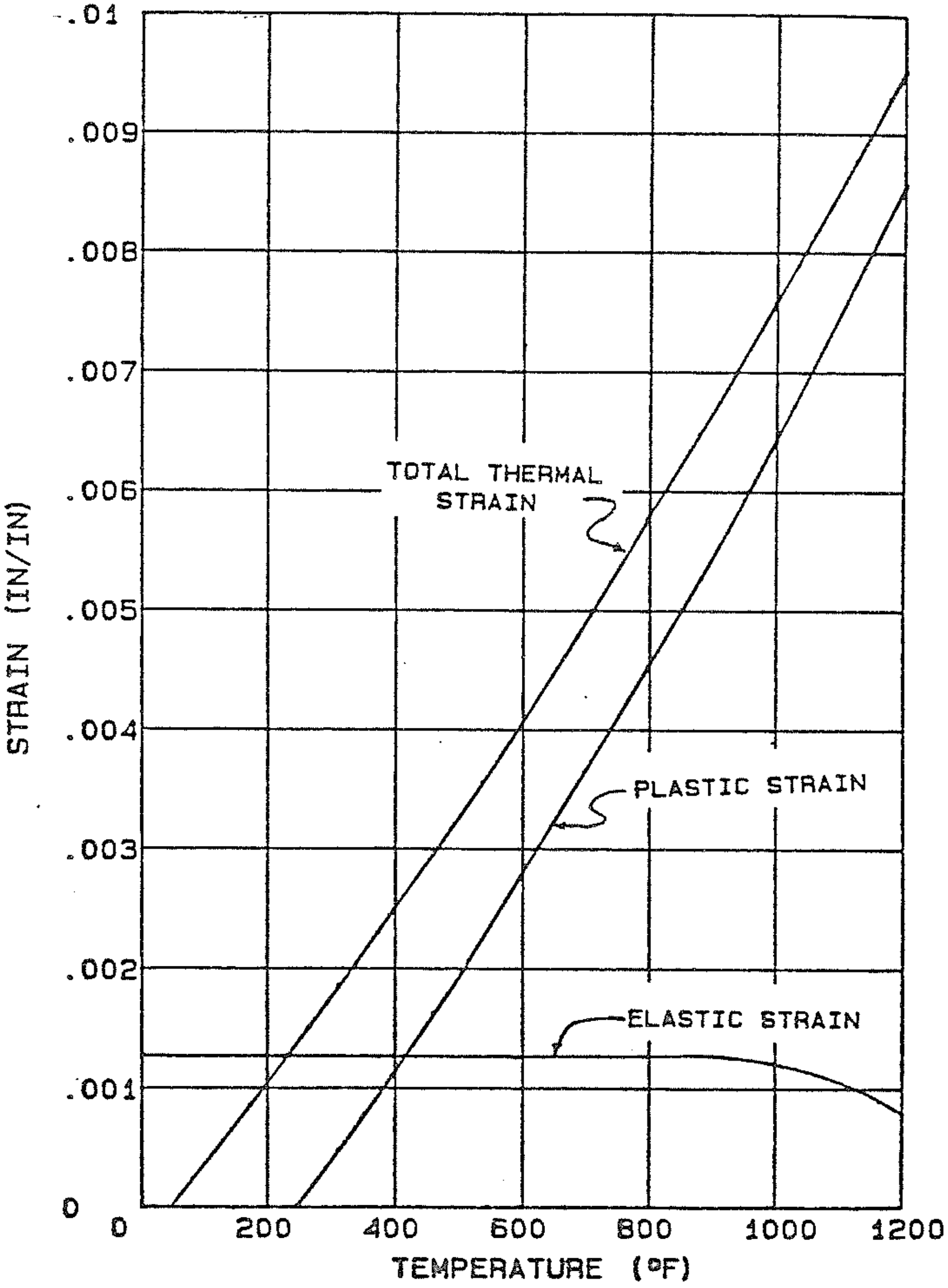

Figure 54. Strain vs. Temperature for a A-36 Steel

representing the heating and cooling phases. Each strip is allowed to expand, and is then compressed back to its original length to induce a restraint to expansion and enforce compatibility between strips. At each step, a strain pattern is assumed and a trial and error solution followed to determine a stress distribution which satisfies equilibrium. The resulting stress distribution becomes a load in the next step. The residual strains from the final step are used to calculate the plastic rotation. This solution produced good results; however, the trial and error solution required a great deal of computer time for the analysis of even one vee heat.

A third approach was used by Roeder (11). He recognized that since the rate of change in the temperature distribution for heat straightening was not critical, the heat flow and elastic deformation problems could be solved independently. Thus, he used a finite difference model to generate time independent temperature distributions which became load steps for a nonlinear finite element analysis. Like the previous model, the results compared well with experimental data, but this model also required large amounts of computer time.

The current research is considering an approach whereby a theoretical maximum plastic rotation is computed for a given vee geometry and number of support restraints and then adjusted for less than ideal conditions. By assuming perfect confinement exists during heating, the resulting curvature should be maximum. A simplified finite element model could be used for the analysis. The "adjusting" process would be based on the wealth of experimental data currently available on the parameters of the vee heat. The key to the success of this approach lies in the correlation of the experimental to the analytical results.

6. SUMMARY AND CONCLUSIONS

The laboratory studies were originally based on supplementing previous work. However, a review of such data showed that experimental documentation was far from complete. Of particular importance was the fact that the basic mechanism 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. As a result of not identifying the importance of this parameter, there has been little documentation on the behavior of vee heated plates subjected to varying degrees of constraint and even less on rolled shapes. In addition, two important aspects of material properties have been overlooked: the influence of strain aging on ductility and residual stress distribution.

The laboratory work accomplished to date, while not complete, has addressed these major areas. The influence of various parameters on plates has been identified and documented experimentally with emphasis on constraint effects. Without this development, engineered heat-straightening repairs would not be possible. More such laboratory tests have been conducted during this project than in all combined previous projects. In addition, the strength characteristics of damaged members subsequently repaired have been shown to be equal to their original strength.

The heat-straightening process offers a potentially economical and safe approach to the repair of steel bridges. The primary need is to develop engineering criteria for controlling and directing the process. The laboratory work to date lays the groundwork for developing that criteria which, when completed during the next year, will bring heat-straightening into the arena of engineering design.

7. REFERENCES

1. Manual of Steel Construction, 3th ed., American Institute of Steel Construction, Chicago, IL, 1980.
2. Avent, R. R., "Use of Heat-Straightening Techniques for Repair of Damaged Steel Structural Elements in Bridges," Interim Report, La. HPR Study No. 85-3ST, Report No. FHWA/LA-86/193, Louisiana Transportation Research Center, Baton Rouge, 1986.
3. Avent, R. R., "Heat-Straightening of Steel: Fact and Fable," Department of Civil Engineering, LSU, Baton Rouge, LA, 1987.
4. Avent, R. R., and Fadous, G. M., "Heat-Straightening Effects on the Behavior of Full-Scale, Simulated Bridge Girders," Department of Civil Engineering, LSU, Baton Rouge, LA, 1987.
5. Avent, R. R., and Wells, S., "Experimental Study of Thin-Web Welded H Columns," Engineering Journal, AISC, July 1982.
6. For Chin, W., "Linear Shrinkage of Steel," M.S. Thesis, University of Washington, 1962.
7. Graham, R., "Investigation of Flame Straightening Methods for Steel Structures," Boeing Co. Manufacturing Development Report, MDR 2-32075, October 30, 1975.
8. Holt, R. E., "Primary Concepts in Flame Bending," Welding Engineer, Vol. 56, No. 6, June 1971, pp. 416-424.
9. Holt, R. E., "Flame Straightening Basics," Welding Engineer, Vol. 50, No. 9, September, 1965, pp. 49-53.
10. Nichols, J. I., and Weerth, D. E., "Investigation of Triangular Heats Applied to Mild Steel Plates," Engineering Journal, AISC, October 1972, pp. 137-141.
11. Roeder, C. W., "Experimental Study of Heat-Induced Deformation," Journal of Structural Engineering, ASCE, Vol. 112, No. 10, October 1986, pp. 2247-2262.
12. Rothan, R. L., "Flame Straightening Quenched and Tempered Steels in Ship Construction," Ship Structures Committee, U.S. Coast Guard, Report No. 247, 1973.
13. Shanafelt, G. O., and Horn, W. G., "Guidelines for Evaluation and Repair of Damaged Steel Bridge Members," NCHRP Report No. 271, Transportation Research Board, National Research Council, Washington, D.C., June 1984.

14. Watanabe, M., and Satoh, K., "On the Correction of Distortion in Welded Thin Plate Structures," Journal of the Japan Welding Society, Vol. 20, 1951, pp. 194-202 (in Japanese).