TECHNICAL REPORT STANDARD PAGE

1. Report No. FHWA/LA-88/223	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Heat-Straightening Techniques for Repair of Damaged Structural Steel in Bridges		5. Report Date December 1988
		6. Performing Organization Code
7. Author(s) R. Richard Avent George M. Fadous		8. Performing Organization Report No. 223
9. Performing Organization Name and Address Department of Civil Engineering Louisiana State University Baton Rouge, LA 70803		10. Work Unit No.
		11. Contract or Grant No. LA. HPR Study No. 85-3ST
12. Sponsoring Agency Name and Address Louisiana Transportation Research Center P.O. Box 94245 Baton Rouge, LA 70804		13. Type of Report and Period Covered Final Comprehensive Report
		14. Sponsoring Agency Code

15. Supplementary Notes

Conducted in Cooperation with the U.S. Department of Transportation
Federal Highway Administration

16. Abstract

This report summarizes a three-year research effort related to the study of heat-straightening repair for damaged steel bridge girders. Three major areas were emphasized: Laboratory behavior of heat-straightened plates and rolled shapes, experimental behavior of prototype damaged bridge girders during heat straightening, and the development of analytical models to predict the response of heat-straightened members. In addition, a comprehensive literature review is presented in the format of current facts and fables about heat straightening.

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 were vee angle, temperature, and jacking force. After documentation of the experimental behavior of plates, an analytical model was derived. This model was reduced to a simple equation which, for the first time, included the effects of jacking forces along with the other parameters. In a similar fashion, a laboratory study of rolled sections was conducted. This study showed that the heat straightening effect was a function of the cross section shape--a factor heretofore unreported in the literature. Because of this discovery, additional testing is

(continued)

17. Key Words Steel Bridges, Damage, Repair, Heat Straightening, Girders	18. Distribution Statement Unrestricted. This document is available to the public through the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 166	22. Price

Form DOT F 1700.7 (8-69)

FIGURE B-1

needed to more fully document this behavior. It appears that rolled shapes can be grouped into three basic modes of behavior depending on the shape and location of the vee. A preliminary analytical model was developed in the form of a simple equation. While the results agreed well with the experimental behavior, additional testing is needed over a wider range of cross sections.

The knowledge gained through this study was used to field straighten damaged prototype girders. Four 20 foot long girders were straightened. Various heating configurations were studied along with the interaction of indeterminate behavior associated with composite girder/deck systems. These field studies showed the importance of understanding and controlling the jacking constraints used to expedite the process. This study has provided a significant increase in the understanding of the behavior of damaged steel during the heat-straightening process. Although additional research is needed, the method can safely be used on moderately damaged girders, even if they have been previously heat straightened.

HEAT-STRAIGHTENING TECHNIQUES FOR REPAIR OF DAMAGED STRUCTURAL STEEL IN BRIDGES

FINAL REPORT

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STATE PROJECT NO. 736-10-46
FEDERAL AID PROJECT NO. HPR-0010(008)
LSU PROJECT NO. 127-15-4141

CONDUCTED FOR

LOUISIANA DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT
LOUISIANA TRANSPORTATION RESEARCH CENTER
in Cooperation with
U.S. Department of Transportation
FEDERAL HIGHWAY ADMINISTRATION

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JUNE, 1988

ACKNOWLEDGMENTS

As with any research project, the cooperation of the sponsoring agencies is essential. The authors wish to thank the Louisiana Transportation Research Center, the Federal Highway Administration, and the Louisiana Department of Transportation and Development for their support of the project. Special thanks are extended to Professor Ara Arman, Director of LTRC, and Mr. Masood Rasoulian, LTRC technical coordinator, for the helpful technical and managerial direction given to the project.

The authors would like to thank employees of the Maintenance Division of the Louisiana Department of Transportation and Development who assisted in the construction of the HEAT facility: Mr. Joseph T. Smith, structures and facilities maintenance engineer; Mr. Gil M. Gautreau, bridge inventory and inspection engineer; Mr. Frank Castjohn, bridge maintenance supervisor--statewide; and the construction crew: Mr. Marvin Cain, Mr. Jerry Cavanaugh, Mr. Terry Brunston, and Mr. Danny Morris.

ABSTRACT

This report summarizes a three-year research effort related to the study of heat-straightening repair for damaged steel bridge girders. Three major areas were emphasized: laboratory behavior of heat-straightened plates and rolled shapes, experimental behavior of prototype damaged bridge girders during heat straightening, and the development of analytical models to predict the response of heat-straightened members. In addition, a comprehensive literature review is presented in the format of current facts and fables about heat straightening.

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 were vee angle, temperature, and jacking force. After documentation of the experimental behavior of plates, an analytical model was derived. This model was reduced to a simple equation which for the first time included the effects of jacking forces along with the other parameters. In a similar fashion, a laboratory study of rolled sections was conducted. This study showed that the heat-straightening effect was a function of the cross section shape--a factor heretofore unreported in the literature. Because of this discovery, additional testing is needed to more fully document this behavior. It appears that rolled shapes can be grouped into three basic modes of behavior depending on the shape and location of the vee. A preliminary analytical model was developed in the form of a simple equation. While the results agreed well with the experimental behavior, additional testing is needed over a wider range of cross sections.

The knowledge gained through this study was used to field straighten damaged prototype girders. Four 20-foot long girders were straightened. Various heating configurations were studied along with the interaction of indeterminate behavior associated with composite girder/deck systems. These field studies showed the importance of understanding and controlling the jacking constraints used to expedite the process. This study has provided a significant increase in the understanding of the behavior of damaged steel during the heat-straightening process. Although additional research is needed, the method can safely be used on moderately damaged girders, even if they have been previously heat straightened.

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.

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1. INTRODUCTION

BACKGROUND

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

The ability to repair bent structural steel members in place, often without even the need for temporary shoring, has generated interest in heat straightening from the engineering profession. In recent years, engineers have begun to study the effects of heat applications on steel. However, much of the available research data is obscure, with contradictory remarks found in different publications. As a result, engineers faced with the dilemma of choosing the appropriate and most efficient method to repair a damaged steel structure have little organized and reliable data or information upon which to base their decisions. These engineers must rely primarily on their own judgment and the advice of experienced technicians. Two key issues must be addressed: 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 ensure adequate safety of the repaired structure both during and after repair? The primary goal of this research project is to answer these two questions by experimentally evaluating the aspects of heat-straightening techniques and developing engineering analysis an design peocedures for general applications. The project was initiated on June 10, 1985, with the sponsorship of the Louisiana Transportation Research Center (LTRC), the Louisiana Department of Transportation and Development (LADOTD), and the Federal Highway Administration (FHWA). The project was divided into four phases: (1) laboratory evaluation and initial analytical development; (2) field evaluation and refinement of the analytical model; (3) final field evaluation and development of an interactive computer model; and (4) documentation and training. This report is the final project report for the three-year study. In addition to summarizing research findings which have been submitted in several interim reports (6,7,8), new data from both the experimental and analytical phases is included. Through a synthesis of both previous and current research, this report provides a guide for the design of heat-straightening repairs.

OBJECTIVES

The specific objectives of this study can be summarized as follows:

1. Through a comprehensive literature review, define the state of the art as it relates to engineering applications of heat straightening.
2. Conduct an experimental program of heat-straightening plates and rolled shapes so that all important engineering parameters are defined and quantified.

3. Extend the experimental investigation to include field testing of the behavior of bridge girders during heat straightening.
4. Develop analytical models which can be used by the engineering profession to predict the behavior of damaged bridge elements during heat straightening.
5. Develop an engineering guide for heat-straightening repair of bridges.

SCOPE OF THE INVESTIGATION

The nature of research is exploratory, which means that direction and emphasis can change as new discoveries or patterns of behavior are uncovered. During the course of this project, that has certainly been the case. For example, after a cursory literature review, it would appear that the state of the art could be summarized as follows:

1. The basic mechanisms of heat straightening were well understood.
2. Fundamental parameters had been identified.
3. Vee heat behavior was fairly well-documented for simple plate elements.
4. The effect of heat straightening on material properties had been verified for a wide range of steels.
5. Actual field studies had verified basic behavior.
6. Practical applications depended primarily on the skill and knowledge of the practitioner as opposed to rigorous engineering analysis.

The original research plan was based on these premises with the goal of supplementing laboratory studies and developing engineered procedures for field applications. However, as the research progressed, it became apparent that these original assumptions were too broad. First, the basic mechanism of heat straightening was not well-understood in that the effects of both external restraints (jacking) and internal restraints (redundancy) were considered to be of minor concern rather than fundamental to the broad application of the process. Second, as a result of not identifying the importance of 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. Third, while a fair amount of research 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 was predicated almost entirely on laboratory studies of simple elements. The reported field investigations were qualitative rather than quantitative and thus could not serve as a building block for this research. Because of these voids 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 project was to develop guidelines to enable the engineer to assess the need for and direct the application of heat-straightening repairs.

This report is organized into chapters addressing the basic objectives. Chapter 2 forms a comprehensive literature review which compares misconceptions about heat straightening to documented facts. Since the basic cross section element of most steel structures is the flat plate, Chapter 3 addresses the behavior of plates subjected to heat straightening. An experimental evaluation of factors influencing heat straightening is given, along with an analytical model for describing this behavior. The behavior of rolled shapes, including experimental and analytical findings, is covered in Chapter 4. Chapter 5 describes the results of field tests on simulated prototype bridge girders. Chapter 6 provides a preliminary guide to engineers for implementing heat-straightening repairs. Chapter 7 presents conclusions and recommendations from the investigation.

2. SEPARATING FACT AND FABLE

INTRODUCTION

The structural behavior of steel systems repaired by heat straightening is not well understood by the engineering profession. As a consequence, most repair work of this type is not engineered, but rather left in the hands of a specialized contractor. Because of this lack of information, some engineers have tended to avoid the use of heat-straightening repair. While engineering research on the subject has progressed in recent years, a significant amount of information has not been readily available to the profession. This fact, combined with a lack of synthesis of available information, has led to speculation an contradictory statements as to various effects associated with the heat straightening process. The purpose of this chapter is to synthesize available knowledge into a state-of-the-art report on heat straightenin The format used will be to give some of the more common fables that hav arisen and then provide the documented facts related to each one. One of the most basic fables relates to the concept itself.

Fable.--Heat straightening of steel is a myth. The only way to straighten damaged steel is by cold or hot mechanical straightening.

Fact.--Heat straightening of steel can be traced in the literature to 1938, when Holt (31) wrote what appears to be the first paper describing heat-straightening procedures. A number of papers have followe that primarily describe basic techniques and successful field applications (20,22,30,32,33,37,44,46,55). The concept is based on using carefully controlled and applied heat without the use of 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. Expertise in heat straightening therefore requires a thorough understanding of the behavior of plates during the heating and cooling process. There are two basic types of distortion generally associated with plates: bends about the strong axis, which are usually straightened with vee heats, and bends or bulges about the weak axis, which are usually straightened with line or spot heats. The large majority of damage encountered in practice consists of plate elements in structures bent about their strong axis. Thus, the 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 shape 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 elasto-plastic, thermal and finite element analysis (24). 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,

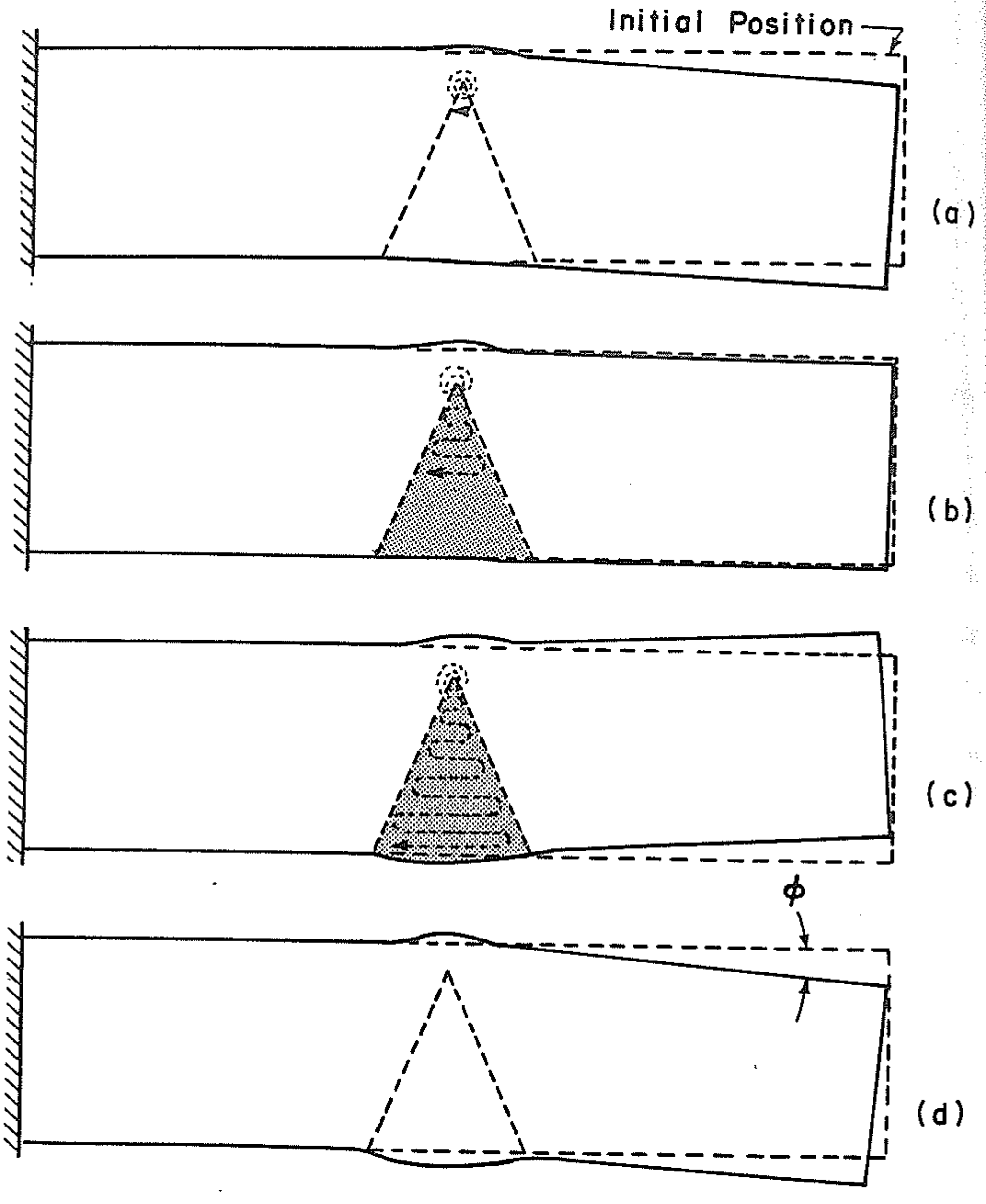

Figure 1. Stages of plate deformation as a vee heat applied to an initially straight plate (deformations are magnified for illustration purposes.

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 is removed and the deflection reaches 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 will thus tend to close more than it originally opened, since 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 to the angle change and can be neglected. In addition, a net shortening of the member will occur, although this effect can be minimized by using a vee heat pattern which is less than the full depth of the member (55). 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 judiciously applying vee heats to damaged members, curvature due to damage 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 successively at a number of locations along the length of the member. While simple in principle, the wide variety of structural shapes, damage, and structural configurations likely to be encountered in practice mak difficult to establish guidelines. In addition, the varied methods heating and restraining during the repair process complicate the pi even further.

STRESS-STRAIN CHARACTERISTICS

Fable.--Since the coefficient of thermal expansion for steel increases with temperature, the hotter the better when applying a ve heat.

Fact.--One of the most fundamental aspects of heat straightenin the thermal expansion behavior of steel. The coefficient of thermal expansion (CTE) is a measure of the rate of strain per degree tempera ture. This coefficient varies directly with temperature such that th rate of expansion increases as temperature increases (10,19,45,50,52, 60). Plots showing the variation of the CTE are given in Figure 2. Most curves of this type do not exceed a temperature of 1200° to 1400 because research has shown (23) that the CTE varies in an irregular manner over the range of temperatures between 1300° to 1600°F. If onl the CTE were considered, "the hotter the better" might be acceptable. However, a number of other factors addressed here negate this assumption.

Fable.--The modulus of elasticity for steel is permanently altere after heat straightening.

Fact.--The modulus of elasticity does decrease with increasing temperature. At 1400°F the modulus for steel typically decreases

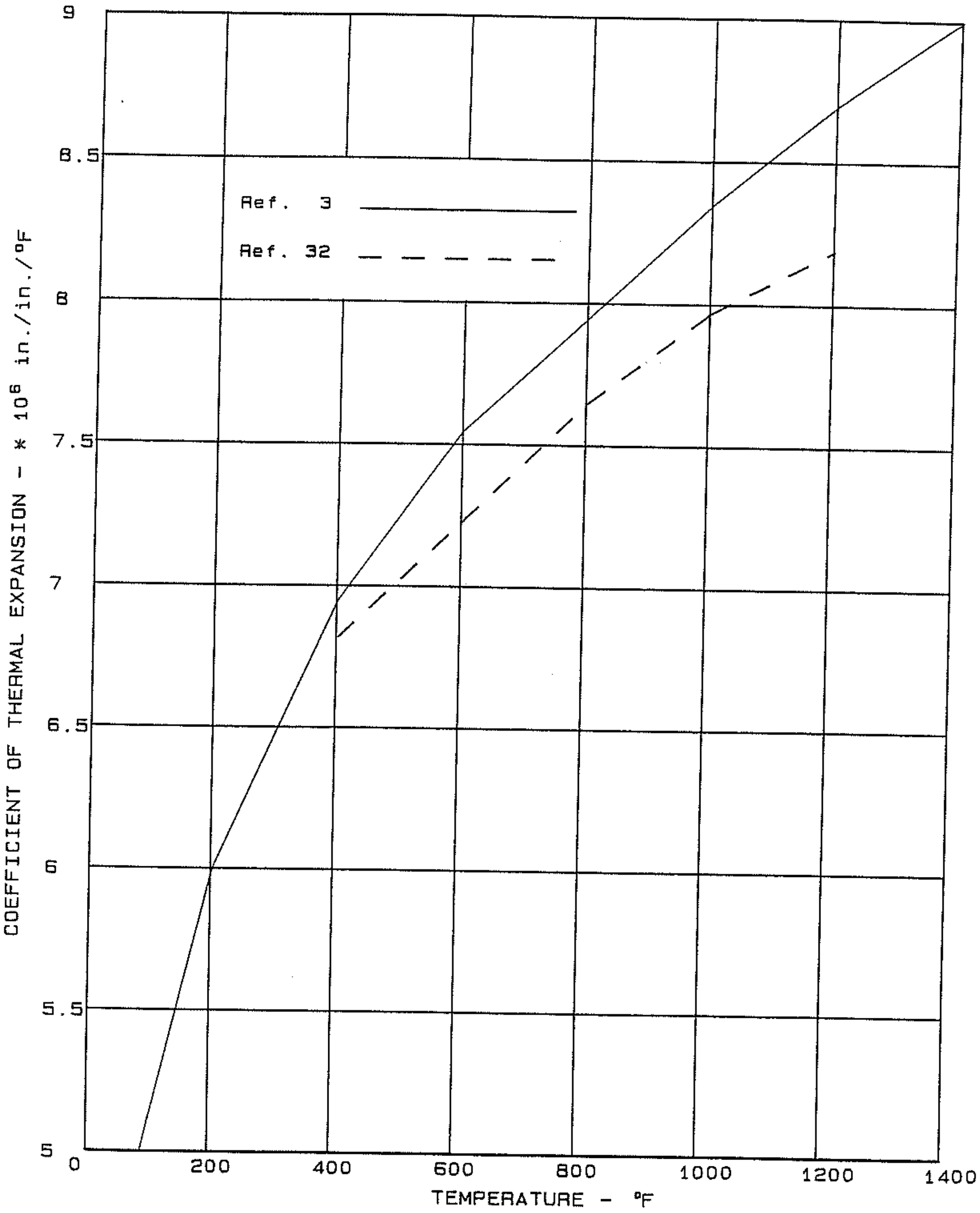

Figure 2. Coefficient of thermal expansion vs. temperature.

one-third of its value at room temperature. The variation in modulus is plotted in Figure 3 for typical carbon steels. Only two investigators have reported the results of measuring the modulus of elasticity after the heat-straightening process has been completed. Neither Horton (35) nor Nicholls and Weerth (45,60) indicated the number of tensile specimens tested and only average values were given. As indicated in Table 1, these tests showed that no appreciable change occurs in the modulus of elasticity after completing the heat-straightening process where the material had cooled to room temperature. Even during heat straightening, the effect of change in modulus is relatively small because the yield stress is also reduced. Thus at 1200°F the strain at initial yield is only 25 percent greater than the yield strain at room temperature.

Fable.--Heat straightening should never be used without temporary shoring since the heating effect may weaken the steel and produce a collapse.

Fact.--It is common knowledge that high heat reduces the yield stress of steel to very low values. A plot of the yield stress versus temperature is shown in Figure 4 for various steels. It can be seen that the yield stress may be on the order of one-half its original value when the temperature reaches 1200° to 1400°F. Yield stresses are rarely plotted for temperatures above 1400°F because the values become so low. For example, at temperatures in the range of 1600° to 1800°F, the yield stress is between 5 and 15 percent of its value at room temperature (19). This behavior is one important reason why the metal temperature during heat straightening should not exceed 1200° to 1400°F. When temperatures are limited to this range, the yield stress will be on the

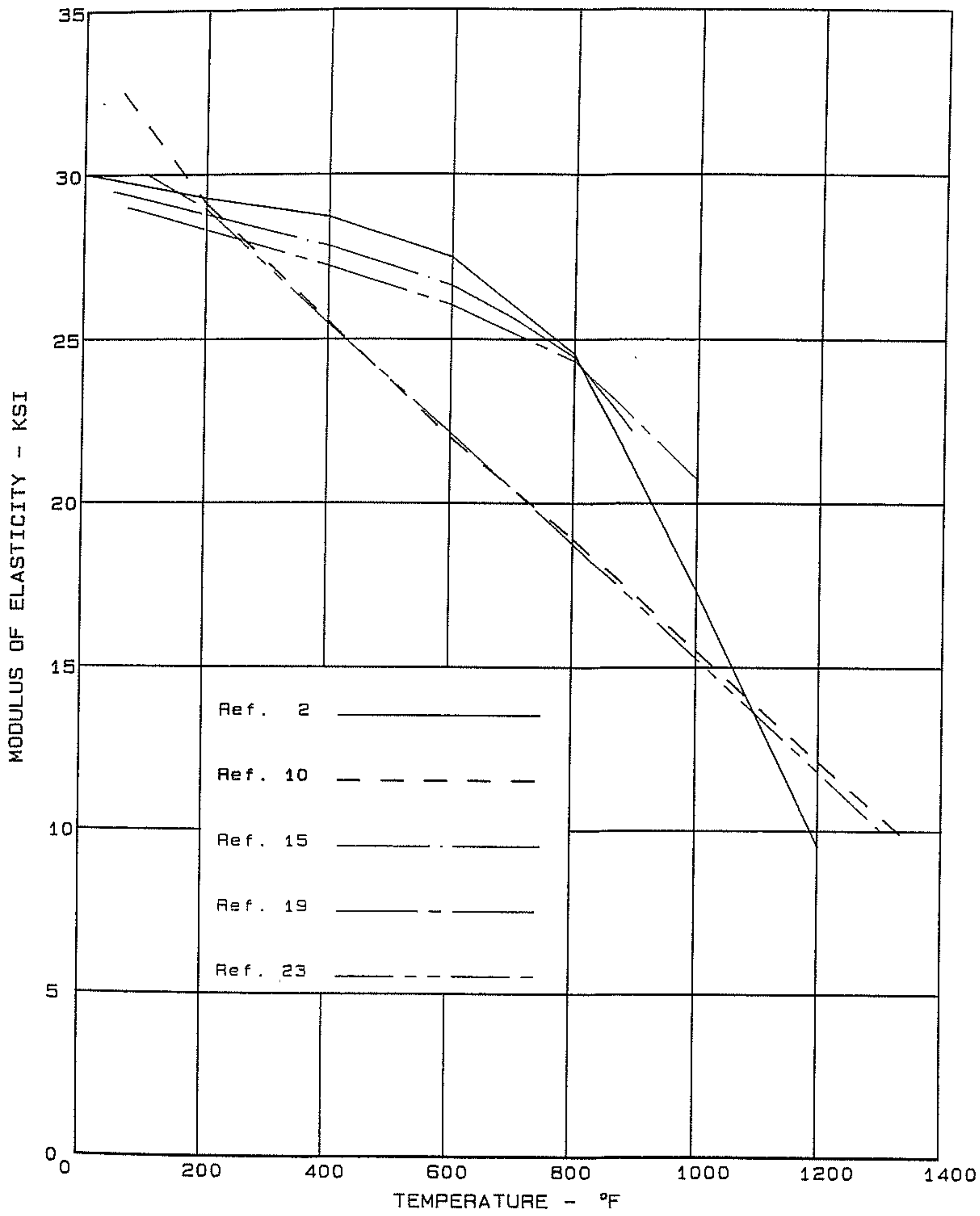

Figure 3. Modulus of elasticity vs. temperature.

Steel		Heat Conditions					Tensile Coupon Results[1]				Charpy Results			
	Design.	σ_y (ksi)	Elev. Temp. °F	Time (min)	Cooling	Applied Strains	Yield Stress $\frac{\sigma_y}{\text{nom. }\sigma_y}$	Elong. in 2" $\frac{\Delta\ell}{\text{nom. }\Delta\ell}$	Tensile Stress $\frac{\sigma_{ult}}{\text{nom. }\sigma_u}$	$\frac{E}{\text{nom. }E}$	Temp.	$\frac{\text{Impact Energy}}{\text{Nom. Impact Energy}}$	T_{50} - Nom.[2] T_{50}	Ref.
on	A-7[4]	33	1100-1200	after five	air	dead + residual	1.13	1.63	1.02		--	--	--	2
				after five & V-heat	air	dead + residual	1.17	0.59	1.00		--	--	--	
				after five & V-heat	air	dead + residual	1.22	0.75	1.00		--	--	--	
				after five & V-heat	air	dead + residual	1.18	0.85	1.01		--	--	--	
				after five & V-heat	air	dead + residual	1.32	0.73	1.00		--	--	--	
				after five & V-heat	air	dead + residual	1.14	0.77	1.00		--	--	--	
				after five & V-heat	air	dead + residual	1.42	0.63	1.04		--	--	--	
	A-36[3]	36	1100-1200	from V-heat	air	residual	1.00	0.87	1.01		--	--	--	3
	A36[5]	36	1000	after line heat	air	residual	1.18	0.96	1.06		--	--	--	4
			1000	after line heat	air	residual	1.08	0.94	1.07		--	--	--	
			1000	after line heat	air	residual	1.06	0.93	1.07		--	--	--	
			1000	after line heat	air	residual	0.90	0.96	1.06		--	--	--	
			1000	after line heat	air	residual	0.97	0.96	1.04		--	--	--	
			1000	after line heat	air	residual	1.05	0.96	1.04		--	--	--	
			1000	after line heat	air	residual	1.01	1.00	1.04		--	--	--	
			1000	after line heat	air	residual	0.97	1.00	1.04		--	--	--	
			1000	after line heat	air	residual	1.00	1.00	1.04		--	--	--	
	A36	36	1200	--	air	25% yield	1.03[3]	0.75[3]	1.05	1.00	--	--	--	5,6
	A36	36	1200	--	air	25% yield	1.00[3]	0.87[3]	1.01	1.00	--	--	--	3
	ABS-B	40	1300	1/2	air	--	--	--	--		upper shelf	1.09	- 3	7
			1300	5	air	--	1.07	0.97	0.98		upper shelf	1.14	16	
			1300	5	quench	--	1.10	1.03	1.03		upper shelf	1.29	30	
			1100	1/2	air	--	--	--	--		upper shelf	1.02	20	
			1100	5	quench	--	--	--	--		upper shelf	1.00	- 2	
			800	1/2	air	--	--	--	--		upper shelf	1.10	- 2	
			800	5	air	--	--	--	--		upper shelf	1.14	-14	
			1300	10	air	5% tensile	1.13	1.04	1.02		upper shelf	1.04	15	

LE 1 (continued)

Steel		Heat Conditions					Tensile Coupon Results^3				Charpy Results			
Type	Design.	σ_y (ksi)	Elev. Temp. °F	Time (min)	Cooling	Applied Strains	Yield Stress $\frac{\sigma_y}{\text{nom. } \sigma_y}$	Elong. in 2" $\frac{\Delta\ell}{\text{nom. } \Delta\ell}$	Tensile Stress $\frac{\sigma_{ult}}{\text{nom. } \sigma_u}$	$\frac{E}{\text{nom. } E}$	Temp.	$\frac{\text{Impact Energy}}{\text{Nom. Impact Energy}}$	T_{50} − Nom. T_{50}^{2}	Ref.
			1300	10	air	5% comp.	1.04	0.82	0.99		upper shelf	1.20	29	
			1100	10	air	5% tensile	--	--	--		upper shelf	1.04	18	
			1100	10	air	5% comp.	--	--	--		upper shelf	1.07	26	
Heat-Treated Constructional Alloy	NAXTRA-100	100	1300	1/2	air		--	--	--		upper shelf	1.09	- 4	7
			1300	5	air		0.90	0.84	0.93		upper shelf	1.09	- 4	
			1300	5	quench		0.93	0.82	0.96		upper shelf	1.16	-21	
			1100	1/2	air		--	--	--		upper shelf	1.02	-17	
			1100	10	air		--	--	--		upper shelf	1.00	0	
			900	1/2	air		--	--	--		upper shelf	1.00	10	
			900	10	air		--	--	--		upper shelf	1.00	10	
			800	1/2	air		--	--	--		upper shelf	1.00	0	
			800	5	air		--	--	--		upper shelf	1.00	0	
			1300	10	air	5% tensile	0.83	0.79	0.90		upper shelf	1.36	-54	
			1300	10	air	5% comp.	0.81	0.77	0.89		upper shelf	1.40	- 8	
			1100	10	air	5% tensile	--	--	--		upper shelf	1.24	-11	
			1100	10	air	5% comp.	--	--	--		upper shelf	1.18	-11	
	A514-F	100	1300	5	air		1.01	0.90	1.00		upper shelf	1.02	<-12	7
			1300	5	quench		1.01	0.94	1.00		upper shelf	1.00	<-12	
			1100	5	air		--	--	--		upper shelf	1.00	0	
			800	5	air		--	--	--		upper shelf	1.00	0	
			1300	10	air	5% tensile	0.88	0.78	0.93		upper shelf	1.11	<-12	
			1300	10	air	5% comp.	0.84	0.76	0.92		upper shelf	1.04	<-12	
			1300	10	air	2% tensile	--	--	--		upper shelf	1.16	<-12	
			1300	10	air	2% comp.	--	--	--		upper shelf	1.13	<-12	
			1100	10	air	5% tensile	--	--	--		upper shelf	1.07	<-12	
			1100	10	air	5% comp.	--	--	--		upper shelf	1.04	<-12	
	Armco QTC	100	900	1/4	quench	--	1.02	1.10	1.00		upper shelf	0.98	- 8	9
			1100	1/4	quench	--	1.01	1.08	1.00		upper shelf	1.00	-14	
			1300	1/4	quench	--	1.04	1.03	1.00		upper shelf	1.03	<-21	
			900-1050	1/15	quench	residual	0.98	0.88	1.06		upper shelf	1.03	<-17	
	A517-A	100	1100-1200	--	quench	--	--	--	--		--	--	113^6	47
			1100-1200	--	quench	--	--	--	--		--	--	75^6	
			1300-1400	--	quench	--	--	--	--		--	--	205^6	
			1300-1400	--	quench	--	--	--	--		--	--	108^6	

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[1] Nominal values are from tests of as received steel.

[2] Temp. at which 50% of upper shelf energy was absorbed.

[3] Average of unspecified number of specimens.

[4] Nominals are for A-7: $\sigma_y = 33$, % elong. = 24, $\sigma_u = 60$.

[5] Nominals are for A-36: $\sigma_y = 36$, % elong. = 34, $\sigma_u = 67$.

[6] Results are from drop weight tear test where T_{50} is the transition temperature at which the fracture contains 50% shear area.

Type	Design.	σ_y (ksi)	Elev. Temp. °F	Time (min)	Cooling	Applied Strains	Yield Stress $\frac{\sigma_y}{\text{nom. } \sigma_y}$	Elong. in 2" $\frac{\Delta \ell}{\text{nom. } \Delta \ell}$	Tensile Stress $\frac{\sigma_{ult}}{\text{nom. } \sigma_u}$	$\frac{E}{\text{nom. } E}$	Temp.	Impact Energy / Nom. Impact Energy	T_{50} - Nom. T_{50}	Ref.
			1300	10	air	5% comp.	1.14	0.92	1.03		upper shelf	1.10	45	
			1100	10	air	5% tensile	--	--	--		upper shelf	0.93	29	
			1100	10	air	5% comp.	--	--	--		upper shelf	0.98	11	
	ABS-B		1300-1400	--	quench	--	--	--	--		--	--	18^6	26
High Strength Low Alloy	ABS-C		1300	1/2	air	--	--	--	--		upper shelf	0.99	21	7
			1300	5	air	--	0.98	0.83	0.98		upper shelf	0.99	36	
			1300	5	quench	--	1.03	0.79	1.05		upper shelf	0.96	47	
			1100	1/2	air	--	--	--	--		upper shelf	0.93	26	
			800	1/2	air	--	--	--	--		upper shelf	0.97	23	
			800	5	air	--	--	--	--		upper shelf	0.95	37	
	A441	50	1300	1/2	air	--	--	--	--		upper shelf	0.99	- 3	7
			1300	5	air	--	1.03	0.84	0.99		upper shelf	1.02	13	
			1300	5	quench	--	1.04	0.83	1.02		upper shelf	0.94	30	
			1100	1/2	air	--	--	--	--		upper shelf	0.92	10	
			800	1/2	air	--	--	--	--		upper shelf	0.97	10	
			800	5	air	--	--	--	--		upper shelf	0.92	36	
	A441		1100-1200	--	quench	--	--	--	--		--	--	16^6	47
			1300-1400	--	quench	--	--	--	--		--	--	12^6	
	Not Specified	50	1100-1300	from V-heat	air	residual	1.03	0.83	1.01		0	1.33	--	8
			1100-1300		air	residual	1.03	0.79	1.00		35	1.00	--	
											65	1.17	--	
Heat-Treated High Strength Carbon	A537-A	50	1300	1/2	air	--	--	--	--		upper shelf	1.00	-60	7
			1300	5	air	--	1.06	0.91	0.94		upper shelf	1.00	-51	
			1300	5	quench	--	1.13	0.91	0.96		upper shelf	1.00	- 6	
			1100	1/2	air	--	--	--	--		upper shelf	0.94	-61	
			800	1/2	air	--	--	--	--		upper shelf	0.98	-26	
			800	5	air	--	--	--	--		upper shelf	0.98	-41	
			1300	10	air	5% tensile	1.12	0.87	0.95		upper shelf	0.99	-19	
			1300	10	air	5% comp.	1.10	0.84	0.94		upper shelf	0.99	3	
			1100	10	air	5% tensile	--	--	--		upper shelf	0.92	- 6	
			1100	10	air	5% comp.	--	--	--		upper shelf	0.92	-13	
	A537-A		1100-1200	--	quench	--	--	--	--		--	--	25^6	47
			1300-1400	--	quench	--	--	--	--		--	--	28^6	
	A537-B	60	1300	1/2	air		--	--	--		upper shelf	1.13	36	7
			1300	5	air		1.02	0.81	0.99		upper shelf	1.11	18	
			1300	5	quench		1.05	0.88	1.05		upper shelf	1.10	-29	
			1100	1/2	air		--	--	--		upper shelf	1.00	33	
			1100	5	quench		--	--	--		upper shelf	1.00	8	
	Steel		800	1/2	air		--	--	--		upper shelf	1.00	0	
			800	5	air		--	--	--		upper shelf	1.09	5	
			1300	10	air	5% tensile	1.04	0.86	0.99		upper shelf	1.13	2	

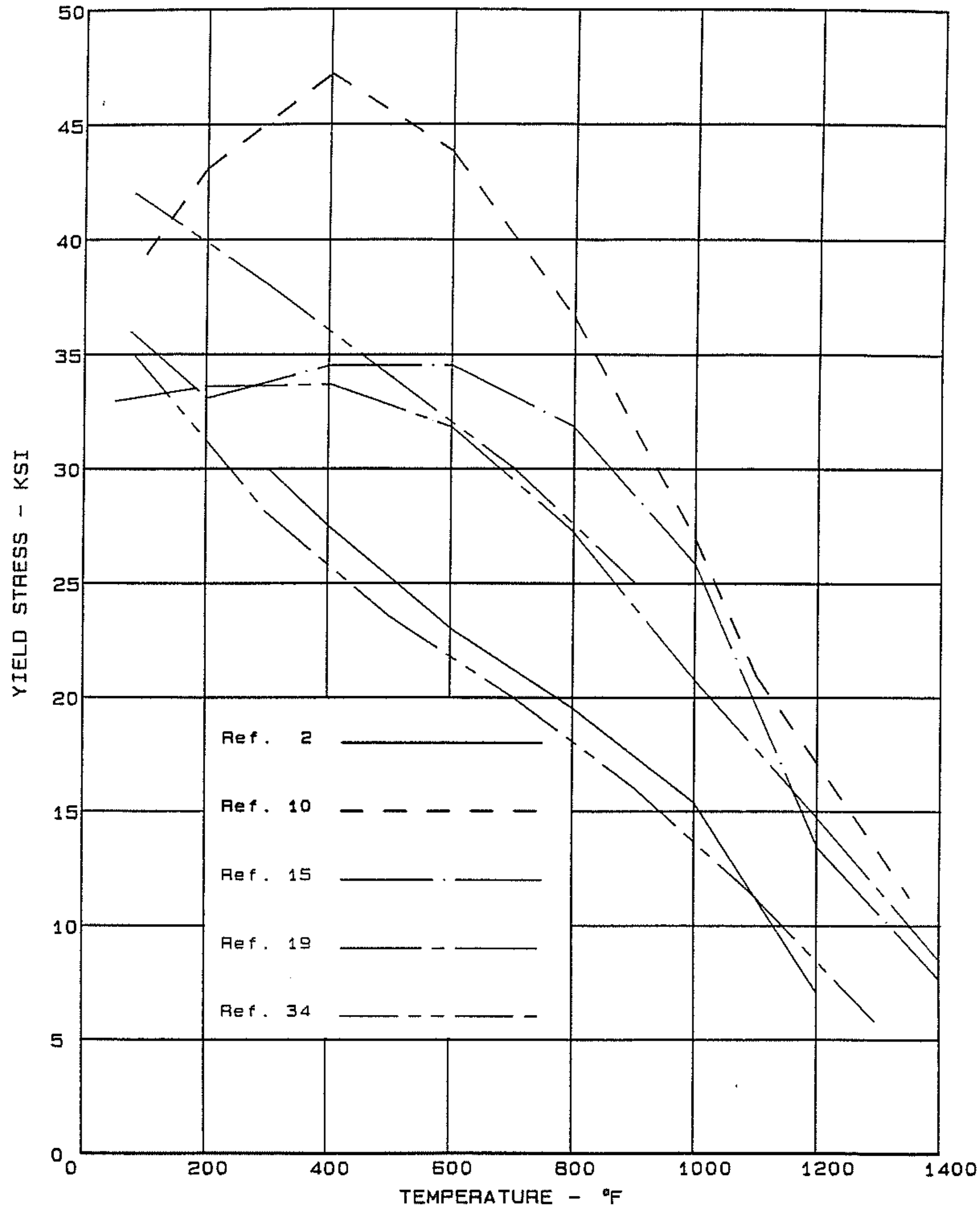


Figure 4. Yield stress vs. temperature.

order of 50 percent of its original value. Consequently, if the design live load of the structure is at least equal to the dead load, heat straightening may be performed without shoring by removing (or controlling) the live loads. In addition, most heat-straightening procedures require that only a part of the cross section be heated. At any given time the average yield stress through a section will therefore be even greater than 50 percent of its original value. As a result, many applications of heat straightening can be safely completed without shoring. However, an engineer familiar with the live and dead load stress distributions should evaluate whether shoring should be used.

Fable.--Heat straightening permanently weakens a steel structure.

Fact.--Two criteria are usually used as a measure of steel strength: yield stress and maximum tensile stress. A number of researchers have measured the yield stress after the heating/cooling cycle of heat straightening to determine the modified characteristics. A summary of these test results is shown in Table 1. The tests on various types of steel represent over 50 specimens from nine investigations. It is apparent from this collection of data that in the long term, the heat-straightening process has a negligible effect on the yield stress when heating temperatures are kept below 1300°F. A similar conclusion can be drawn from an evaluation of the maximum tensile stress. Shown in Table 1 are results for maximum tensile stress corresponding to those for yield stress. Again, these changes are negligible. It should be noted that in most of the test results reported, the stress was measured on samples from the same piece before and after heating. These initial yields were used as the nominal values unless they were unavailable. In general, these initial values were larger than the rated stress for the grade in question. Therefore, the assumption of an unchanged yield and maximum tensile stress after heat straightening is indeed a valid one for all grades of steel as long as the temperature is limited to the practical working range of 1100° to 1300°F.

One early study (18) reported that flame cambering weakened I-beams. However, later discussions (29) indicated that the failure criteria was improperly applied, thus negating this conclusion.

Fable.--Heat straightening reduces steel ductility to unacceptable levels.

Fact.--Ductility is an index of the ability of steel to deform in the inelastic range. It is usually expressed as a percentage by comparing the difference between an initial gage length and its length after tensile fracture to the initial gage length. Ductility is important because it allows redistribution of high local stresses. Shown in Table 1 are comparisons of ductility before and after heat straightening. These data show that there is indeed a 10 to 20 percent decrease in ductility after heat straightening. While these changes in ductility characteristics are significant, the magnitude of the reduction is not large. However, all steel grades have demonstrated adequate ductility in field applications. As such, the measured reductions in ductility after heat straightening are small enough to be of little concern in normal construction applications.

FRACTURE CHARACTERISTICS

Fable.--Heat straightening produces brittle "hot" spots and thus should be avoided.

<u>Fact</u>.--The primary cause of brittle failures in steel is usually associated with geometrical discontinuities such as a sharp discontinuity or notch. Since heat straightening produces no new discontinuities, geometry would not be a factor in evaluating brittle-resistance. However, two other factors which influence brittleness--large strain rates and cold working--are often found during the damage inducement stage. To evaluate its fracture sensitivity, various researchers have tested heat-straightened steel. The resistance to fracture in the presence of a notch is widely used as a guide to the performance of steels in structures susceptible to brittle fracture.

The Charpy V-notch test is one of the most commonly used. A small rectangular bar with a V-shaped notch at its mid-length is simply supported at its ends as a beam and fractured by a blow from a swinging pendulum. The amount of energy required to fracture the specimen is calculated from the height to which the pendulum raises after breaking the specimen. The data are taken at a range of temperatures and a plot of energy versus temperature (on the abscissa) is generated. The resulting curve is S-shaped with an upper-limit asymptote of energy absorption as the temperature increases and a lower-limit asymptote as the temperature becomes small. These limits are referred to as the upper and lower shelf. One measure of brittleness is the upper energy limit. As can be seen from Table 1, there is no significant change in the upper-shelf energy absorption before and after the heat-straightening process for any grade of steel.

A second measure of the notch toughness can also be obtained from the Charpy tests. As shown in Table 1, the temperature at which 50 percent of the upper shelf energy was absorbed, T_{50}, is tabulated in terms of the difference between T_{50} and the nominal T_{50}. Positive differences represent a decrease in notch toughness, while negative numbers represent an increase. There is a considerable variation within a given steel grade. However, the average values indicate that only the high-strength, low alloy steels have a significant positive shift (32°F) and even this is relatively small.

Another measure of notch toughness is the fracture transition temperature. This temperature is the one in which the percentage of shear fracture is 50 percent of the cross section. Since plastic deformation is associated with shear fracture, a rating of the brittle-fracture resistance is obtained. Pattee et al. (<u>47</u>) used this criteria in evaluating several grades of steel that had been heat-straightened. The drop weight tear test was used instead of the Charpy test with the results also shown in Table 1. The fracture transition temperature changes are modest for all cases except the A517-A steel. Here there is a significant positive shift indicating a larger fracture sensitivity. It is interesting to note that a similar situation did not occur with the heat-treated constructional alloy steels given in Table 1.

In addition to the Charpy tests, Rockwell hardness tests have also been used on heat-straightened steel specimens. Changes in surface hardness before and after heating would indicate changes in mechanical properties. Pattee et al. (<u>47</u>) conducted Rockwell hardness tests on a range of steels from mild to constructional alloys. Harrison (<u>26,28</u>) conducted similar tests on mild steel specimens. Seven specimens compared by Pattee et al. had differences of less than six percent except for one specimen with a 15 percent difference. A comparison of 18 readings by Harrison taken within the heated vee portion of the two specimens showed a 3-percent difference or less. Both researchers found that the hardness values did not change appreciably before and after heat straightening.

An overview of the research data offers no basis for concluding that heat straightening should be avoided because of brittle-fracture concerns. Rather, it can be concluded that such strength reductions, if they exist, are minor.

Fable.--Fracture-critical members cannot be heat-straightened.

Fact.--Fracture-critical members are tension members, or tension components of members, whose failure would be expected to result in the collapse of the structure. Current research data such as shown in Table 1 provide no grounds for excluding fracture-critical members from heat straightening. Rather, results in this table provide there is strong and consistent evidence that properly executed heat straightening has no degrading effect on mild carbon steels and only minor effects on high-strength steels. Strength and brittleness aspects have already been discussed. The only other failure possibility of concern is fatigue.

Only one series of fatigue tests on flame-straightened members was found in the literature (2). In this case, three eye bars of A-7 steel were heat-shortened and then fatigue-cycled. When compared to similar specimens which had not been heated, the fatigue strength at both 500,000 and 1,000,000 cycles were similar. Although data is sparse, there is no indication that carbon steels will have a shortened fatigue life after heat straightening. However, more research is needed to evaluate this important aspect.

Shanafelt and Horn (55) have recommended that heat straightening be avoided on fracture-critical members without offering any justification other than conservatism. Since there is no hard evidence to justify the avoidance of heat straightening, the questions is not whether fracture critical members can be heat-straightened, but rather should they.

At this time there is one critical factor that must be considered. One ingredient is missing in heat-straightening technology: engineering analysis tools. The more accurate the analysis, the less conservatism is required. At present heat straightening is in the hands of the contractor. Even with guidelines such as Reference (55), the engineer has practically nothing similar to the analytical tools usually associated with structural engineering. For example, criteria as to number, location and angle of vee heats; effects of internal restraints; control of external restraints such as jacking; and effect of residual stresses have not been developed into analytical tools. As a consequence, even though evidence indicates that heat straightening can be used for fracture-critical members, it should probably not be used until more engineering control is available through analysis/design procedures.

TEMPERATURE CHARACTERISTICS

Fable.--Temperature is unimportant in heat straightening as long as the steel does not glow "red-hot."

Fact.--Because of the deleterious effect of high temperature on steel, the engineering community has tended to reject the heat-straightening method as a viable repair alternative. For example, a survey of 35 state transportation departments (55) indicated that only about one-half use heat straightening to repair steel bridges and only one-quarter use it more than occasionally. As a consequence, much of the research to date has addressed the effect of temperature on structural properties. Most structural steels used in the United States are carbon or low alloy steels. The fundamental behavior of all these steels at uniformly elevated temperatures is believed to be the same. The molecular structure remains unchanged at temperatures below the transition temperature of 1330°F (723°C). In average light, a very faint red glow will be visible at or around this point. As temperatures are increased above the transition temperature, molecular changes occur and the color brightens until the classic "red-hot" level is reached at around 2000°F. As long as the temperature changes occur slowly and uniformly throughout the member, cooling produces a complete reversal to the original molecular state without mechanical property changes. However, if the cooling is too sudden, phase reversal may not occur and brittleness or other property changes may result. In addition, concentrated applications of elevated temperature to small areas may produce permanent property changes, unusual residual stress patterns, and strain history retention. Control of temperature is therefore one of the most important aspects of heat straightening.

Fable.--Each grade of steel has a narrow temperature range for producing the heat-straightening effect and temperatures above or below this range will neither increase nor decrease the contraction effect.

Fact.--Theoretical studies considering perfect confinement have suggested that the minimum steel temperature to produce any permanent contraction in mild steel ranges from 450° to 500°F (55). However, Roeder (50,52) has found that a more practical minimum temperature for producing permanent deformations is between 600° to 700°F.

Above this minimum, investigators have differed as to the effect of temperature level on expected plastic rotation or permanent movement. The comprehensive testing program by Roeder (50,52) has shown that the resulting contraction from vee heats is directly proportional to the heating temperature up to at least 1600°F and is repeatable. It is likely that earlier researchers reached an erroneous conclusion on this limiting temperature because of a lack of test data combined with the fact that heat straightening does not lend itself to theoretical modeling where the conditions of restraint and heating are not ideal. The range of temperatures for heat straightening is quite large (600° to 1600°F), with the degree of movement proportional to the temperature.

Fable.--There is no ideal temperature for heat straightening.

Fact.--The ideal temperature for heat straightening depends on the grade of steel and type of heat. For carbon and low alloy steels, the theoretical limit is the phase transition temperature of 1330°F (50,52). For the constructional alloy steels, the limiting value is the tempering temperature of 1150°F (55). However, heat-straightening experiments at levels up to 1600°F for carbon steels (50,52) and 1300°F for constructional alloy steels (53,54) have been conducted without serious detrimental effects on the material properties (see Table 1). In addition, theories suggest that heats above a specified value will not increase the amount of straightening (55). Although experiments have shown that these theoretical maximums (which are based on simplifying assumptions) are too low (50), it is likely that practical limits do not greatly exceed the transition temperature. Researchers (50,52,55) have also observed that heats above the transition temperature have an inclination to produce: (1) out-of-plane distortion, (2) plate buckling, and (3) pitting and surface damage to the steel.

Taking all of these aspects into consideration, the consensus of researchers is that a temperature of about 1200°F should be used for carbon and low alloy steels while 1100°F should be used for constructional alloy steels. These values provide a safety factor of 200 to 400 degrees to account for operator errors and also produce relatively large movements as a result of the heat-straightening process.

Fable.--Temperature cannot be controlled manually to the degree necessary for heat straightening to become an accepted engineering procedure.

Fact.--The degree to which temperatures can be controlled by practitioners is an important consideration. Factors affecting the temperature include: size of the torch orifice, intensity of the flame, speed of torch movement, and thickness of the plate. Roeder (50,52) made careful temperature measurements and used experienced practitioners to make the vee heats in his experiments. He found that these practitioners, when judging the temperature by color, commonly misjudged by 100°F and in some cases as much as 200°F. The use of temperature-indicating crayons can be helpful. However, the flame tends to distort the results by blackening the crayon marks. The marks can be placed on the back side but this does not allow for the operator to see the results and make adjustments during the heating process. Contact pyrometers have not been widely used and tend to give erroneous results (55). Experiments by Graham (25) indicated that pyrometers gave readings of approximately 200°F below the value indicated by temperature crayons. Tests conducted by the writers verified that a contact pyrometer will give temperature values of 200°F below the actual. Thus, pyrometers must be calibrated for use in heat-straightening applications.

In practice, the most common procedure to determine temperature is by the color of the material adjacent to the tip of the torch. Since background lighting will influence this color, temperature crayons should be used to correlate the lighting to the color of the steel. In normal daylight or interior lighting conditions, a 1200°F temperature will be indicated by a satiny silver color near the torch tip. After cooling, the area should be gray in color. A cherry-red color during heating or a black color after cooling indicates that the heat was too hot. With little training, it is not unreasonable to expect practitioners to be able to meet tolerances of ± 200°F. This tolerance level can be reduced to ± 100°F with checks using temperature crayons or pyrometers. This obtainable level of accuracy should not limit the application of heat straightening in practice.

Fable.--Quenching should never be used to cool the steel after heat straightening.

Fact.--As can be seen from Table 1, quenching has been used on carbon, low alloy, and constructional alloy steels without adverse effects (53,54). In addition, Roeder's studies (50,52) showed that quenching increased the plastic deformation significantly. The advantage of quenching is that it allows for a rapid repetition of the heating/cooling cycle, thus expediting the repair. If quenching is used, care should be taken to ensure that temperatures remain below the transition temperature. Measurements by the writers have shown that the steel temperature at the tip of the torch (initially at 1200°F) drops approximately 200°F during the first few seconds after the torch is moved. Within 30 seconds, an additional 100°F decrease typically occurs (24). Roeder (50,52) has recommended that if quenching is used, it be applied at 30 seconds after completion of the heat to insure that temperatures are well below the phase transition temperature of the steel. Evidence thus indicates that quenching can be used with proper care in controlling the heating temperature.

APPLICATIONS FOR STRUCTURAL ELEMENTS

Fable.--While heat straightening may work under controlled laboratory conditions or in uncontrolled field applications, there are no documented field studies in which parameters were carefully measured and controlled.

Fact.--Moberg (41) has been the only investigator to conduct a controlled field study of heat-straightening repair for damaged members. Careful daily measurements were recorded on the Bothwell bridge in the state of Washington which was hit by an over-height vehicle. The initial damage was measured and daily measurements were taken as heat-straightening progressed. The restraining forces used were also carefully recorded. This work illustrated that heat-straightening repairs can be engineered.

Fable.--Heat straightening only works for simple bends of single curvature.

Fact.--Vee heats are used primarily for strong axis curvature correction in plate elements, while line heats and spot heats are used for weak axis corrections. Practically any type of damage can be heat-straightened. A vee heat produces a sharp point of curvature of small magnitude at the apex of the vee.

Since the plastic deformation is restricted primarily to the area of the vee heat (45,50,52), the angle change is a convenient measure of the distortion. This angle is shown in Figure 5 and will be referred to as the plastic rotation, ϕ. To produce a visually smooth curve over the length of the plate, a series of vee heats spaced along the length can be utilized. While in reality this approach will produce a series of discrete curvatures, the small angle changes will give the appearance of a smooth curve. By alternating the direction of the vees and varying the spacing, practically any type curvature (sharp, gradual, single, or multiple) can be removed. Since each heat produces small changes in curvature, a number of heating/cooling cycles are usually required to completely straighten a damaged member. In a similar manner, line and/or spot heats can be used to remove weak axis damage such as bulges or buckles.

Fable.--Heat straightening only works on thin plates.

Fact.--The bulk of the experimental data on vee heating plates can be found in two studies by Nicholls and Weerth (45) and Roeder (50,52), plus current work by the writers (8). In each of these investigations a number of plates were vee-heated and the deformations measured. Researchers have generally considered plate thickness to have a negligible effect on plastic rotation. The only reservation expressed has been that the plate should be thin enough to allow a relatively uniform penetration of the heat through the thickness (55). The practical limiting value is on the order of 3/4 to 1 inch. Thicker plates can be

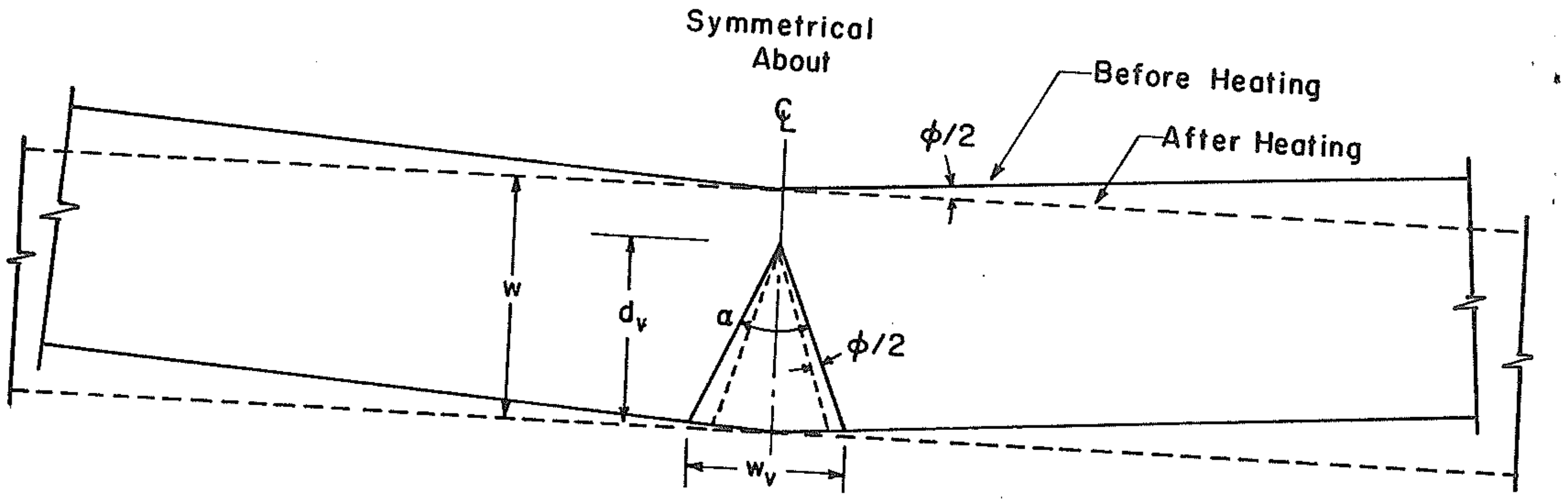


Figure 5. Vee heat geometry.

heated on both sides simultaneously to ensure a uniform distribution through the thickness. Members with cover plates usually require heating from both sides because of the interface. Results from the heating of plates with varying thicknesses as taken from current work by the writers and references (45,50,52) are shown in Figure 6 for various vee angles heated from 1100° to 1300°F. Also plotted is a second order parabola least squares curve fit for each thickness. The variations appear random, indicating that thickness is not a factor which influences plastic rotation during heat straightening as long as the heat fully penetrates the thickness.

Fable.--While heat straightening may work for simple plate elements, bends in rolled shapes are too complex for a rational approach.

Fact.--A wide variety of rolled shapes, including wide flanges, channels, angles and assemblies, have been straightened (or curved) in both laboratory (16,26,28,35,43,47,48,50,52,53,54) and field applications (17,20,22,26,28,30,31,32,37,41,42,43,46,49,56,57,59,61). Rolled shapes generally require a vee heat in combination with a rectangular heat. The rectangular heats are necessary because of the perpendicular planes of the plate elements forming the shape. A set of typical heating patterns (32) are shown in Figure 7. By using the proper pattern of vee and rectangular heats, sweep, camber, or twisting type of movements can be obtained resulting in repair for a wide variety of damage conditions. While there is general agreement on the vee pattern, there have been no published studies directed toward quantifying the optimum heating patterns for rectangular heats in combination with the vee.

RESTRAINING FORCES

Fable.--Internal and external restraining forces are unimportant in heat straightening.

Fact.--Of equal importance to temperature are the constraints and forces acting on the member during the heat-straightening process. Practitioners have recognized this fact and usually employ some type of jacking or constraining force. The basic principle is that an applied force in the direction of the desired movement will impede the reverse expansion during the heating phase, increase the plastic strain, and thus produce more contraction during the cooling phase. Experiments show that the application of external forces can have a significant effect on the amount of plastic rotation that occurs in a plate. A series of tests was conducted by the writers in which various levels of external force were applied to a plate. The force applied produced a bending moment about the major axis, tending to close the angle of the vee. For comparison purposes, the moment is non-dimensionalized by computing the load ratio, which is the ratio of the moment at the vee due to the applied load to the plastic moment capacity of the section, M/M_p. Nicholls and Weerth (45,60) and Roeder (50,52) also measured the behavior of vee-heated plates for various load ratios. Their results, along with those of the writers, are plotted in Figure 8. A second order parabolic regression analysis for each vee angle and load ratio producing a least squares curve fit is also plotted. The curves are nearly linear with respect to vee angle and reflect that the plastic rotation is proportional to the load ratio and is fairly linear.

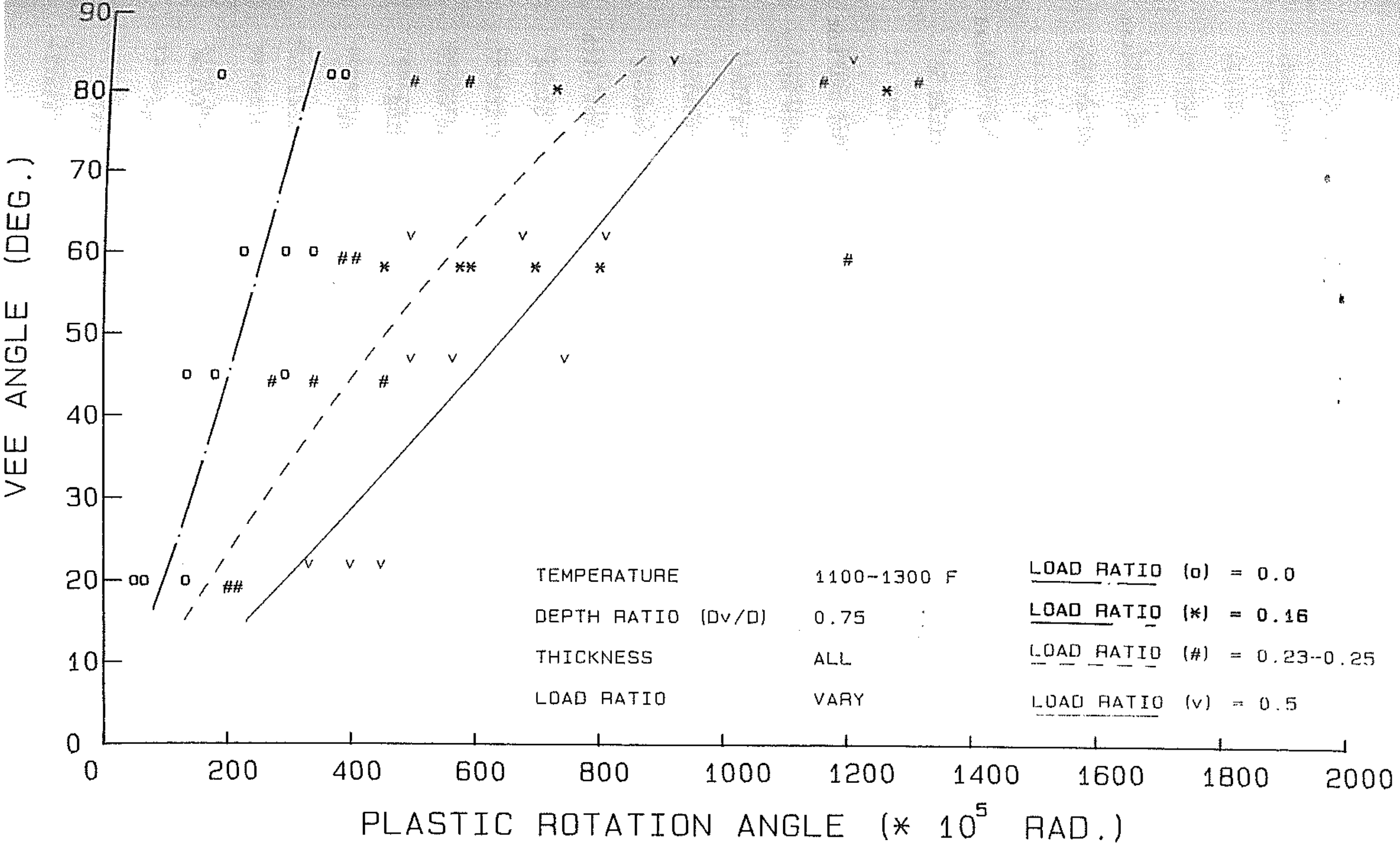


Figure 8. Vee heat angle vs. plastic rotation for vee-heated plates with variations in the load ratio (8,45,52).

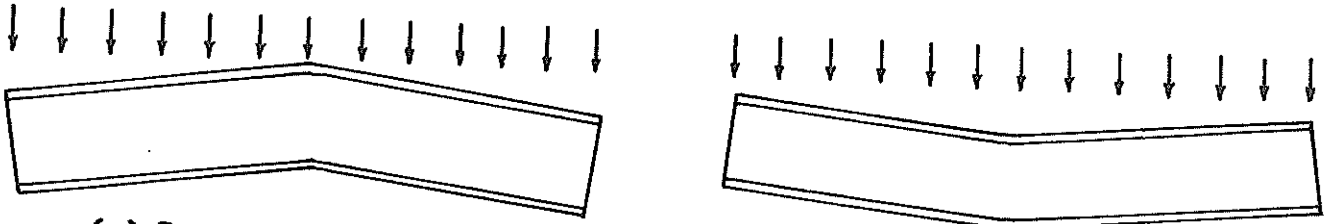
It can be seen from these results that there is a distinct advantage to using an external force during the heat-straightening process. However, the constraining force should be used as a passive force rather than an active force once the heating has begun. The standard procedure is to apply the external force first and then proceed with the vee heats. The external force should not be increased at any time during the heating and cooling process. However, it can be adjusted to maintain the original level, since the force will be relaxed as contraction takes place. All the test data shown here utilized a constant force during the entire process.

The level of the constraining force for a given application has not been addressed in the literature. Apparently, most practitioners apply the force by "feel." The primary limit on the external force is the buckling capacity of the vee area during the heating or overstressing when the yield stress is reduced by the heat. For the plates tested, some buckling difficulties have been encountered only for the case with a combination of the largest vee angle and largest load ratio. Since the yield stress is typically reduced to approximately one-half its original value when heated to 1200°F, a load ratio of 50 percent would be a theoretical upper limit to avoid hot mechanical straightening.

<u>Fable</u>.--Heat straightening is unlikely to be developed as an engineering process because sometimes a properly heated member does not straighten.

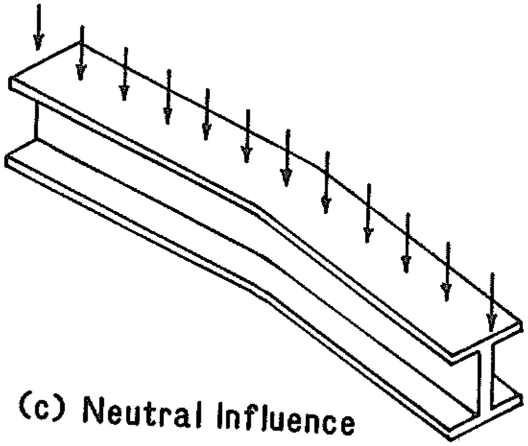
<u>Fact</u>.--In addition to external restraints, a second type of force must also be considered in many structures, that is, internal constraints. These constraints are a result of structures which are: (1) carrying some load (e.g., dead load) during heating, and (2) stati-

cally indeterminate. Since many structures are partially loaded during the heat-straightening process, a structural evaluation is required to determine whether the loading will be beneficial or harmful. For example, three types of damage are shown in Figure 9 for a wide flange beam subjected to a gravity loading. For case (a) the loading acts in the direction of the desired straightening and therefore will have a positive effect during heat straightening. For case (b) the loading is acting in the opposite sense of the desired movement. Roeder (50,52) has shown that not only will the straightening process be impeded, but it could well be reversed such that the damage gets worse. Successful heat straightening on such members would require an upward external jacking force to overcome the negative gravity load influence. Case (c) illustrates an example where the loading effect is neutral since the desired movement is perpendicular to the direction of loading. Other types of internal constraints are more subtle in their effects, particularly those associated with static indeterminancy. A good example is the case where a damaged member is restrained axially against longitudinal expansion, as typified by indeterminate frames or compression members in trusses. In order to evaluate the effect of an axial restraint, a series of tests was conducted on plate elements (8). A superimposed axial load was applied through a hydraulic jack to produce a ratio of axial load to yield load of 56 percent. The load was applied prior to heating and the jack acted to prevent any longitudinal expansion but not contraction. The resulting curves (based on averaging three single vee heats) are shown in Figure 10 for a 60° vee. The axial constraints produce a significant increase in the plastic rotation when compared to an identical plate without the axial restraint.



(a) Positive Influence

(b) Negative Influence



(c) Neutral Influence

Figure 9. Typical dead load conditions and their influence as a constraint to aid heat straightening.

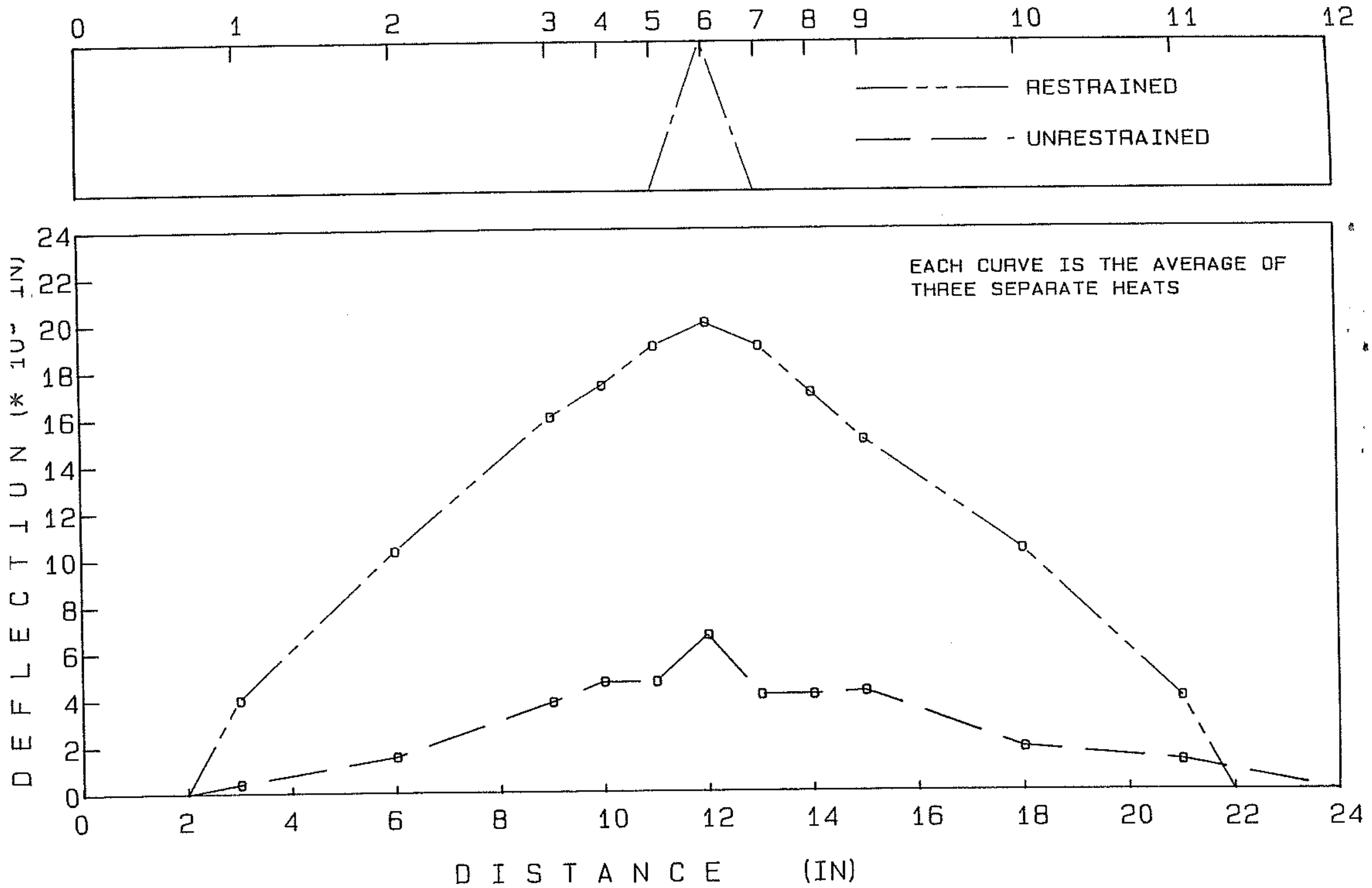


Figure 10. Comparison of deflections for full-depth 60 degree vee heats on 1/4 x 4 x 24 inch plates with axial or unrestrained conditions.

In summary, restraining forces are very important in the heat-straightening process and the effects may be either harmful or beneficial. Relatively little research has been directed toward this aspect of heat straightening. In practice, jacks are usually used to provide external constraints. However, often the level of such jacking forces are not measured. Caution should be exercised whenever jacking is used in heat straightening.

ANALYSIS OF BEHAVIOR DURING HEAT STRAIGHTENING

Fable.--Heat straightening is an art and the actual magnitude of movements cannot be predicted.

Fact.--Several analytical methods have been developed for applications to plates. One approach (32,33,41), generally referred to as the Holt formula, is a formula based on the assumptions of: ideal single axis confinement, linear strain variation across the width of the plate, and a uniformly distributed temperature of 1200°F. This formula was modified by Moberg (41) to include partial depth vees, giving an equation

$$\phi = 2 \frac{S_p d_v}{w} \tan \frac{\alpha}{2} \qquad (1)$$

where as shown in Figure 5, ϕ = the angle of plastic rotation, S_p = plastic strain associated with perfect single axis confinement, d_v = the depth of the vee, α = the vee angle, and w = the width of the plate. For A36 steel, Shanafelt and Horn (55) give a value of $S_p = 0.00864$. Equation 1 is quite approximate in nature, since typical vee heat behavior is not a perfect single axis confinement case and since the effect of restraining forces is neglected. However, these two effects sometimes cancel each other, resulting in fairly good agreement with actual measurements (41) in a few cases. The principle weakness of this formula is its neglect of the effect of constraining forces. At present, no simple formulation exists which accounts for this effect.

The alternative approaches offered in the literature (12,24,35,50, 51,52,60) all basically combine a thermal analysis with an inelastic finite element or finite strip stress analysis. These methods require excessive computer time and have only been applied to a few simple plate cases. Thus, while some analytical formulations exist, they are limited to plates and cannot be conveniently used in general design applications for rolled shapes. Because of these limitations, emphasis has been placed on the art of heat-straightening rather than the science.

Fable.--A vee heat over the full depth of the member is always better than a partial depth vee heat.

Fact.--The depth of the vee in comparison to the depth of the plate element influences the plastic rotation. Both Nicholls and Weerth (45) and Roeder (50,52) have stated that the plastic rotation is proportional to the vee depth. However, an examination of their test data, as shown in Figure 11 for a specific heating temperature and load ratio, indicates that there is little discernable difference for ratios of vee depth to plate width greater than 2/3. All data was compared using least squares curve fits. Only for the ratio of 50 percent does the plastic rotation show a significantly lower value. The number of experimental data points is small; thus additional study is needed to determine how the vee depth influences behavior. It should be noted that full-depth vees usually produce member shortening. Such member shortening can be minimized with the partial-depth vee. Full-depth vee

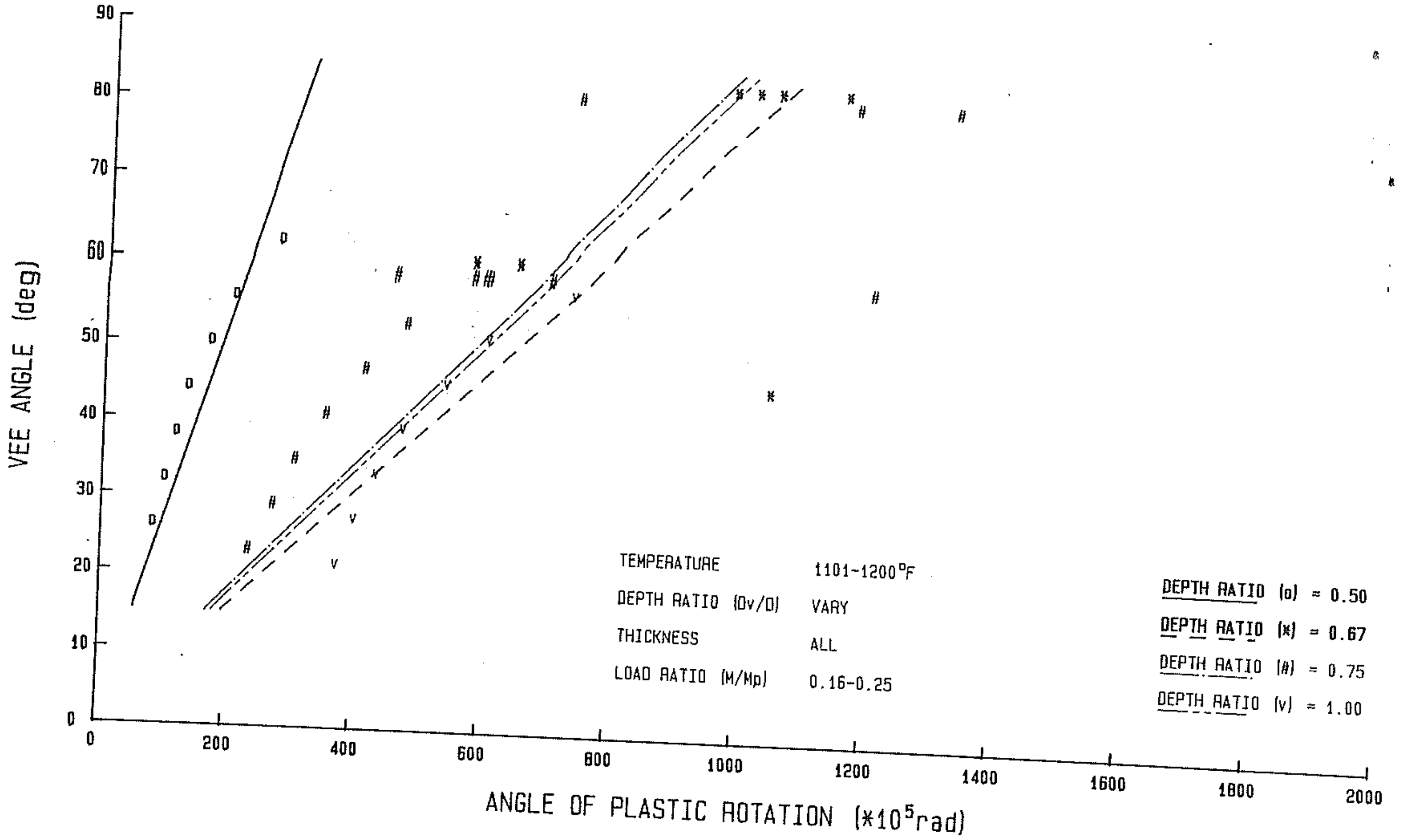


Figure 11. Vee heat angle vs. Plastic rotation for vee-heated plates with various ratios of vee depth to plate width (45,52).

heats should not be used in situations where member shortening would be detrimental to the structure.

Fable.--The angle of a vee heat is unimportant.

Fact.--A number of authors (32,41,45,50,52,60) have concluded the amount of plastic rotation resulting from a vee heat is directly proportional to the angle of the vee. The test results in Figure 6 illustrate this effect. A parabolic regression curve shows that the relationship between vee angle and plastic rotation is nearly linear. Several researchers (32,41) have developed simplified analytical models which account for this effect. Others have developed finite element models (12,50,52). However, large angle vee heats may produce out-of-plane distortions (50,52) or buckling (55). Caution should be used to minimize such effects. Holt (32) and Shanafelt and Horn (55) recommend that the maximum width of the base of the vee be limited to 10 inches.

SECONDARY EFFECTS

Fable.--Residual stresses are not a serious concern in heat straightening.

Fact.--At this time, the magnitude and effects of residual stresses in the heat-straightening process are not well understood (36,38,39,40). Although Roeder (50,52) has measured residual strains, these cannot be extrapolated into stresses because of the plastic flow that occurs during heat straightening. Brockenbrough and Ives (14) measured residual stresses by the sectioning method for a heat-curved girder in which line heats were used. He later developed criteria for heat curving based on this work (13). The residual stresses were characterized by yield-point tensile stresses along the heated flange and smaller tensile stresses in the opposite flange. Compressive stresses dominated the web. In a companion paper, Brockenbrough (12) developed a theoretical approach for computing the same residual stresses, as did Roeder (50,52) and Nicholls and Weerth (45,60) for the vee-heated plate. These researchers concluded that, as in welding, the residual stresses caused by heat straightening may be high. Since residual stresses primarily cause strength reductions in compressive members, these stresses should not be ignored in such cases. It is also suspected, but as yet unproved, that residual stresses may influence the degree of movement during heat straightening by acting as either a positive or negative constaining force. Harrison and Mills (27) found that light hammering (peening) on the transverse face of a stressed plate produces plastic elongation. By applying peening during the cooling cycle of the heat-straightening process, residual stresses may be reduced and the level of contraction increased. Although recommended by some researchers (55), there is no research data on peening related specifically to heat straightening. It is therefore premature to make a recommendation on its effectiveness. Until additional research evidence becomes available, caution should be used when contemplating a heat-straightening repair of compression elements, since residual stresses are related to buckling strength.

Fable.--No matter how light or severe the damage, heat straightening can be used if no fractures have occurred.

Fact.--Surprisingly little information is available on the effect of damage level (strain history). It is known that cold bending into the yield range reduces the ductility of steel in general (15). However, the application of heat tends to restore the original material characteristics. Shanafelt and Horn (55) recommended that the maximum allowable strain be limited to 15 times the yield strain and/or 5 percent nominal strain for repair of tension members. The limit approximately defines the delineation between the plastic region and the strain hardening region. No limits are suggested for compression members. The specific limits given for tension members in two categories are as follows:

Primary--Straighten if strain is less than 5 percent

For $F_y = 36$ ksi, the strain must be less than 40.3 x yield

For $F_y = 50$ ksi, the strain must be less than 29 x yield

For $F_y = 100$ ksi, the strain must be less than 14.5 x yield

Primary with severe fatigue--Straighten if strain is less than 15 x yield or less than 5 percent

However, these recommendations are not backed by specific research data. Until additional data become available, judgment should be exercised for tension members and particularly fatigue-sensitive members.

Shanafelt and Horn (55) also suggested limits on the maximum radius of curvature for which heat straightening should be applied. The logic is that if the radius of curvature exceeds that which produces material yielding, heat straightening will be ineffective. Curvature in the non-yielded portions will be elastic and will be restored when the plastic zones are straightened. The radius of curvature at yield is given by

$$R_y = wE/(2F_y) \tag{2}$$

where w = plate width, E = modulus, and F_y = yield stress. Heat straightening should not be applied for regions with larger radii of curvature than this limiting value, or in general, to the portion of the member which has not plastically deformed.

SUMMARY AND CONCLUSIONS

Research results as reported in the literature show near unanimous agreement that temperature-controlled heat straightening will not have a deleterious effect on the mechanical properties of steel. The general consensus is that a heating temperature of 1200°F is appropriate for carbon steel with somewhat lower temperatures recommended for high strength steels. Within these limits, researchers have found no permanent harmful effects associated with modulus of elasticity, yield stress, tensile strength, brittleness or fracture. A slight reduction in ductility (10-20 percent) has been noted, but this reduction is considered small because there is no problem with fatigue.

Some data is available on the behavior of plates subjected to vee heats, although there is a need for additional research. Relatively little experimental data is available for rolled shapes. Measurements of actual bridge behavior are nearly nonexistent.

An area of particular importance is the need to develop simple yet accurate analytical models to predict behavior during heat straightening which includes not only angle and depth of vee, temperature, and steel grade, but also includes constraint conditions and residual stress patterns. Another area of research need relates to the effect of damage loading rate and strain history on repair effectiveness. Little hard evidence is available as to limits beyond which repairs will not be acceptable. Data on possible material degradation is also scarce for cases of repair followed by future damage and successive repairs. A final area involves the development of guidelines for the proper application of constraining forces including their number, location and magnitude.

To date, heat straightening has been used on a relatively limited basis to repair damaged steel structures. That limited use has produced a good track record and illustrates the potential of the method for providing safe and economical repairs.

3. BEHAVIOR OF PLATES SUBJECTED TO HEAT STRAIGHTENING

INTRODUCTION

Although the heat-straightening repair process is relatively simple, it has not been widely used. There are two main factors responsible. First, the practitioners 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. The second reason is that many engineers have the notion that any application of heat to steel will permanently weaken it. Since 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 phenomena. The purpose of this chapter is to describe an experimental and analytical study of heat straightening as applied to plates and to present related engineering design criteria for its use.

Previous laboratory studies have been concerned with identifying the member behavior associated with curving slender members. Two types of heats are associated with member curving, edge heats and vee heats. Edge heats are simply line heats applied along the edge of a plate element which produce smooth, continuous curves, as in fabricating curved members. 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. Since damage is usually of varying curvature, vee heats are the most suitable for structural repairs.

Several detailed studies have been conducted for vee heats applied to plates. These studies have attempted to identify parameters which influence vee heats and to develop predictive models based on this data. Weerth (60) and Nicholson and Weerth (45) describe the bends produced by 21 vee heats whose apex angle varied from 24° to 60° in 6° increments applied to 3/8 in. thick ASTM A36 steel plate. The vee depth was also varied over full depth, 3/4 depth, and 1/2 depth. No attempt was made to evaluate the effect of these parameters other than the general observation that the greater the vee angle and depth, the greater the bend produced. Roeder (52) also conducted a study on plates. He employed sophisticated monitoring equipment such as thermocouples, contact pyrometers, and strain gauges, as well as more conventional tools such as a vernier caliper and a steel ruler. Roeder considered a wide range of parameters which included vee geometry, specimen geometry, heating temperature and time, steel grade, restraining force, initial residual stresses, and quenching. This was by far the most extensive study done to date. These two studies provide a reference base and starting point for the current study. 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, easy to apply and allow for such considerations as different vee geometries, temperature ranges, external loadings, and support restraints. At present there are the two extremes of overly simplistic models (32,33,41) which cannot take into account the effect of either temperature variations or internal and external restraint and comprehensive computer models (2,24,35,50,51,52,60) based on elastic-plastic finite element or finite strip stress analysis combined with a similar thermal analysis. However, there is as yet unavailable an analytical model that offers both practicality and a comprehensive inclusion of all important variables to accurately predict behavior.

Of interest here are the currently available simplistic models. Holt (33) developed one of the first and simplest methods for predicting plastic rotations from vee heats. Moberg (41) modified the Holt equation to account for the depth of vee by considering the experimental work of Weerth (60). In addition to Holt's assumptions, he assumed that the plastic rotation is proportional to the depth ratio d_v/w, where d_v = the depth of the vee heat. The resultant equation was Equation 1 of the previous chapter (page 40).

An important consideration not included in these formulations is the influence of external and internal restraining forces. The external forces producing compression in the vee during heating will increase the available confinement and therefore increase the rotation produced per heat. The field applications cited by both Holt and Moberg involved the use of restraining forces. Since in most cases the material restraint alone will be less than perfect, it seems likely that the good correlation between the predicted and actual movement in the structures being repaired as noted by both Holt and Moberg was due to the influence of the external forces. An improved analytical model should include the effects of both internal and external restraints.

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. The approach chosen was to first identify all parameters which 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. After synthesizing this experimental data, an analytical procedure for predicting member response was developed.

Vee-shaped heats are used to repair plate elements with bends about their strong axis while line and spot heats are used to remove weak axis plate bends. Since the majority of damage is in the form of strong axis plate bends, the vee heat can be considered the fundamental heating pattern for heat straightening. Thus only the behavior of vee heats on plates is considered in this study.

EXPERIMENTAL PROGRAM

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. While this data will be presented graphically here, specific results of all tests are given in Appendix I.

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 of them had dimensions of 1/4 in. x 4 in. x 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 (52) that the plastic deformation developed by a vee heat occurs primarily within the vee area. Thus a very sharp but small curvature is obtained, which can be expressed in terms of plastic rotation as shown in Figure 5. For initially straight specimens, the portion of the plate from the ends to just outside the vee heat remains straight. This fact was used to compute the plastic rotation based on the straight line tangents. To reduce the influence of possible errors in the measured deflection, a straight line was first fitted through the four points on either side of the vee heat within the straight portion outside the yield zone using the least squares method. The acute angle formed between these two lines is the angle of plastic rotation, ϕ.

Practically all of the existing experimental data on vee heated plate behavior is found in two studies (45,50,52,60). 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 were 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.

EVALUATION OF RESULTS OF EXPERIMENTAL PROGRAM

The available data on plate behavior can be found in three studies: Nicholls and Weerth (45), Roeder (52), and the current study. 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 are used, while reference numbers are given for other data. An evaluation of each parameter is considered separately in the following sections.

Vee Angle.--Researchers agree that one of the most fundamental parameters influencing the plastic rotation of a plate is the vee angle. The data shows 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 (52) 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 (45) 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.

Since a significant level of scatter does exist, an evaluation was conducted of data samples. The coefficients of variation for typical cases were on the order of 50 percent. Since 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 10-15 percent. Similarly, the control of the heating temperature could introduce an error of 10-15 percent. A third possible cause is the development of residual stresses. Both Holt (32) and Roeder (52) suggest that residual stress is not significant in the heat-straightening process. However, a small number of tests conducted as part of this study indicates that very large residual stresses are possible as a result of the heating process. Thus, due to 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 researchers (52,60) have concluded that the plastic rotation is proportional to the ratio of vee heat depth to plate width. Figure 11 shows the data which is available from past studies. From this plot it is apparent that past data does not support this conclusion. The trend is that depth ratios greater than 1/2 will produce only slightly larger rotations, but not proportional to the vee depth. Rather, the plate rotations are all approximately the same when using the curve fit. A similar situation exists when considering the data from the current study (Figure 12). Therefore, even though it would seem intuitive that increasing the vee depth would increase the plastic rotation, there appears to be no justification for such a general statement. While additional research is needed, it can be tentatively concluded that the variation for vee depths greater than 50 percent of the plate depth have little influence on plastic rotation.

Plate Thickness and Geometry.--The results from tests involving different plate thicknesses are plotted in Figure 6 and were discussed previously in Chapter 2. It is concluded that plate thickness will not have an important influence on heat straightening.

Roeder (52) 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 deemed an important factor.

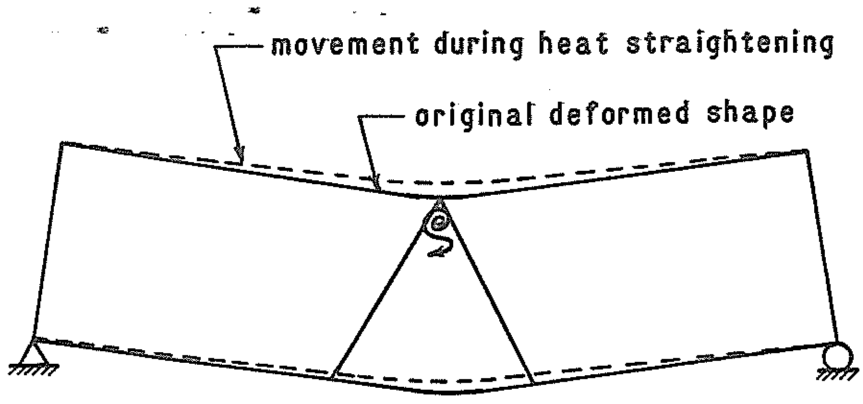
Temperature.--One of the most important and yet difficult-to-control parameters of heat straightening is the temperature of the heated metal. Factors affecting the temperature include: size of torch orifice, intensity of the flame, speed of torch movement, and thickness of the plate.

Assuming 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 have differed in answering this question. For example, Shanafelt and Horn (55) state that heats above 1200°F on carbon and low alloy steels will not increase plastic rotation. Rothman and Monroe (54) concluded that reheating areas where previous spot heats were performed will not produce any useful movements. However, the comprehensive testing program by Roeder (52) 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. Plots of vee angle versus plastic rotation for the data from the current study are shown in Figure 13. These results are combined with Roeder's in Figure 14. Both figures indicate that the plastic rotation generally increased with increasing temperature. The most important difference between these two plots is that the increased plastic rotation is nearly linear with temperature for the data of the current study, while the composite data shows the same trend although somewhat more irregular.

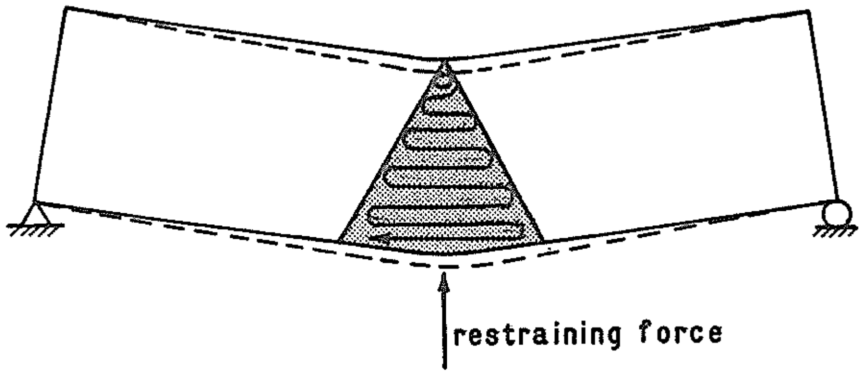
The maximum temperature recommended by most researchers is 1200°F for all but the heat-treated high strength steels. Higher temperatures may result in greater rotation; however, out-of-plane distortion becomes likely and surface damage such as pitting (52) will occur at 1400°-1600°F. Also, temperatures in excess of 1600°F may cause molecular composition changes (<u>54</u>) 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 (<u>54</u>). The conclusion that heat-treated constructional alloy steels can be heat-straightened is contrary to that of Shanafelt and Horn (<u>55</u>); however, Roeder (<u>52</u>) 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 set, a low intensity torch moved slowly to maintain a 1200°F temperature, while in the other a high intensity torch was moved more quickly while again maintaining the same temperature. The rotations in either case were similar.

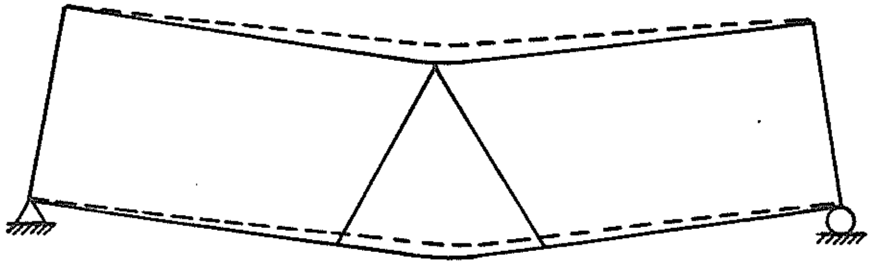
<u>Restraining Forces</u>.--The term "restraining forces" can refer to either externally applied forces or internal redundancy. These forces, when properly utilized, can expedite the straightening process. However, if improperly understood, restraining forces can hinder or even prevent straightening. In its simplest terms, the effect of restraining forces can be explained by considering a plate element, such as that shown in Figure 15. The basic mechanism of heat straightening is to create plastic flow, causing expansion through the thickness (upsetting)



(a) Plate Movement during Early Heating Phase



(b) Plate Movement near the Completion of Heating



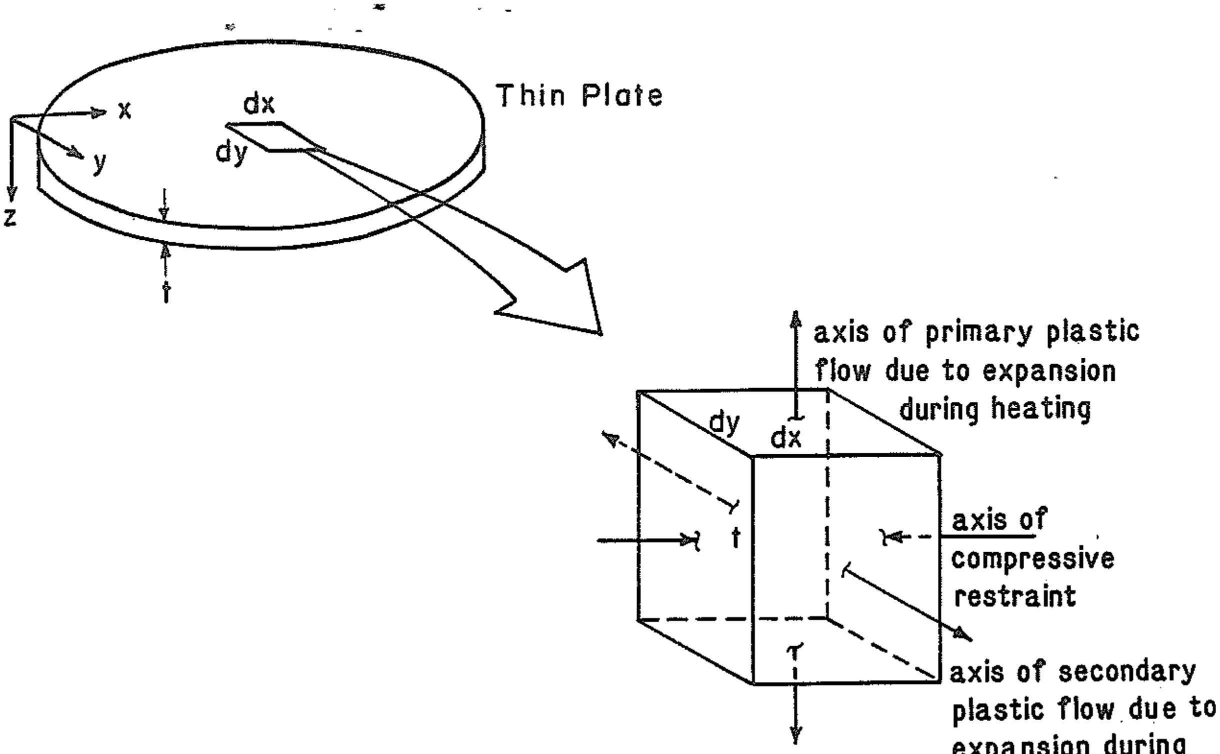
(c) Final Position after Cooling

Figure 15. Progression of movement for a plate during heat-straightening process.

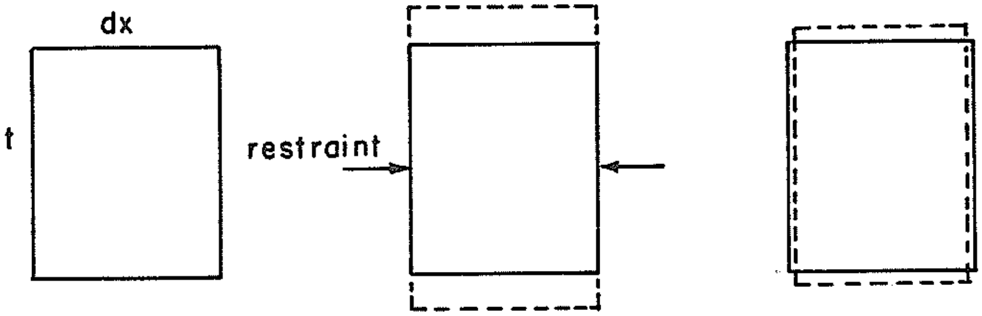
during the heating phase, followed by elastic longitudinal contraction during the cooling phase. This upsetting can be accomplished in two ways. First, as the heat progresses toward the base of the vee, the cool material ahead of the torch prevents complete longitudinal expansion of the heated material, thus forcing upsetting through the thickness. However, as illustrated in Figures 15a and 15b, some longitudinal expansion does occur 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 15b, 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 illustrated in Figure 16. A small element from a plate, when constrained in the x-direction and heated, will expand and flow plastically primarily through the thickness (Figure 16c). Secondary plastic flow will occur in the y-direction. However, this movement will be small in comparison to that of the z-direction, since the plate is much thinner than its y dimension and offers less restraint to plastic flow. Upon



(a) Element from a Thin Plate



(b) Original Element

(c) Plastic Flow during Heating with Full Restraint in x Direction

(d) Final Configuration of Element after Cooling

Figure 16. Characteristics of plastic flow and restraint during heat straightening.

cooling with unrestrained contraction, the final configuration of the element will be smaller in the x-direction and thicker in the z-direction, Figure 16d. 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. This criteria applies for internal as well as external constraints.

1. Constraints should be passive during the heating phase; i.e., they should be applied prior to 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 heating phase.

From a practical viewpoint, this criteria means that: (1) the vee angle should be kept small enough that local buckling is avoided; (2) the jacking forces must be applied prior to heating and be self-relieving as contraction occurs; and (3) the maximum level of any external jacking forces must be based on a structural analysis which includes the reduced strength and stiffness due to the heating effects.

While practitioners have long recognized the importance of applying jacking forces during the heat-straightening process, little research has been conducted to quantify its effect. A series of tests designed to evaluate this parameter involved applying a jacking force to a plate such that a moment is created about the strong axis in a direction tending to close the vee. This moment 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 included load ratios of 0, 0.16, 0.25 and 0.50 with four different vee angles and vees extending over 3/4 the depth of the plate. The results are shown in Figure 17 (the theoretical curve will be discussed later). Roeder (52) also studied the effect of load ratio variation, and his results along with those of this study are plotted in Figure 18. Both plots indicate that the variation is generally proportional to the load ratios and that using external loads can greatly expedite the heat-straightening process.

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 stress to yield stress ratio of 56 percent. These results are shown in Figure 19 in comparison to the results from the bending load ratios of 0 percent 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 which were found to have an important influence on the plastic rotations produced by vee heats are: (1) vee angle; (2) heating temperature; and (3) external restraining force. While the influence of the depth of the vee requires more evaluation, it appears to have a small effect 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.

Residual Stresses in Heat-Straightened Members.--A study was initiated to evaluate the magnitude and distribution of residual stresses due to heat straightening. The basic procedure was to take representative samples from heat-straightened members during the course of this project and measure the residual stresses.

The procedure used here to measure residual stresses was the sectioning method. Initial extensometer readings were taken in the zone of heating. Then the section was cut into thin longitudinal strips, which relieves the residual stresses. Finally, the extensometer measurements were repeated and both residual strains and stresses are calculated.

Eight plates have been tested to date. A plot of a typical residual stress distribution is shown in Figure 20. 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.

ANALYTICAL DEVELOPMENT

Two general approaches to developing an analytical procedure for predicting member response during a heat-straightening repair have been used. One approach involves finite element/finite strip thermal and stress analyses including inelastic behavior. The stress and strain equilibrium is evaluated over small time steps and takes into account the influence of the non-uniform temperature distribution. This approach is a lengthy computational task which is only possible using computer techniques. Even so, a typical analysis for a single vee heat can require several hours of computer time.

The other approach considers the global action of the vee. The Holt equation, Equation 1, which is based on such an approach, assumes that perfect confinement is provided at all times during the heating phase and that the resulting longitudinal displacements through the vee are linear. With this equation the number of vee heats required to remove a bend in a steel member can be simply calculated. Since an analytical procedure must be simple and easy to apply in order for it to be practical in design applications, this second approach was used in the current study.

The goal of the analytical development was to develop an equation which could be used to predict the angle of plastic rotation produced by a vee heat. The most common assumptions previously used in this type of development have been that: (1) longitudinal plastic strain occurs only in the vee heat zone (and in a similar vee area reflected about the apex for partial depth vees); (2) these strains are constant in the longitudinal direction over the width of the vee; (3) the planes defined by the sides of the vee remain planes after heating and rotate about the apex of the vee; and (4) confinement during heating is perfect single axis in the longitudinal direction. Roeder (50,52) has been the only researcher to experimentally investigate the validity of these assumptions. He found that the statistical correlation of plane sections remaining plane was typically less than 0.5, although the apex of the vee was close to the center of rotation. While he found that most of the plastic strain occurred in the vee zone, the strain was not constant in the longitudinal direction. Rather than the strain variation through the plate depth being constant, he found it to be fairly linear except possibly near the open face of the vee (for which no data points were given). While it is recognized that the assumptions listed above are approximate, the poorest is that of perfect single axis confinement. This assumption can be improved using the results of the experimental program as a guide. Figure 5 illustrates the geometry of a plate, before and after heating, based on the first three assumptions listed previously. The change in the width of the open end of the vee, δ, can be writen as

$$\delta = 2d_v \left[\tan\frac{\theta}{2} - \tan\left(\frac{\theta}{2} - \frac{\phi}{2}\right)\right] \tag{3}$$

If $\varepsilon_p'(T)$ is defined as the final plastic strain at the specified heating temperature, T, in the longitudinal direction after a heating/cooling cycle, then

$$\varepsilon_p'(T) = \frac{\delta}{w_v} \tag{4}$$

or using trigonometric relations from Figure 5

$$\delta = 2d_v\varepsilon_p'(T)\tan\frac{\theta}{2} \tag{5}$$

Equating Equations 3 and 5 gives

$$d_v\varepsilon_p'(T)\tan\frac{\theta}{2} = d_v\left[\tan\frac{\theta}{2} - \frac{\tan\frac{\theta}{2} - \tan\frac{\phi}{2}}{1 + \tan\frac{\theta}{2}\tan\frac{\phi}{2}}\right] \tag{6}$$

Since the experimental data shows that both ϕ and $\varepsilon_p'(T)$ are small, it is assumed that $\tan(\phi/2) \cong \phi/2$ and $\varepsilon_p'(T) << 1$. Equation 6 can then be solved for ϕ:

$$\phi = 2\varepsilon_p'(T)\sin\frac{\theta}{2} \tag{7}$$

The actual plastic strain, $\varepsilon_p'(T)$, depends on the heating temperature (which is usually known) and degree of confinement (usually unknown). If the restraint is perfect single axis confinement with the strain designated as $\varepsilon_p(T)$, then $\varepsilon_p' = \varepsilon_p$. In terms of the total unconfined thermal strain, $\varepsilon_t(T)$, and the elastic strain, $\varepsilon_e(T)$

$$\varepsilon_p(T) = \varepsilon_t(T) - \varepsilon_e(T) \tag{8}$$

where

$$\varepsilon_t(T) = \int\alpha(T)dT \tag{9}$$

$$\varepsilon_e(T) = \frac{F_y(T)}{E(T)} \tag{10}$$

and $F_y(T)$ is the yield stress at temperature T, E(T) is the modulus of elasticity at temperature T, and $\alpha(T)$ is the coefficient of thermal expansion. In order to obtain values for ε_t and ε_e, equations are needed for F_y, E, and α as a function of temperature. Weerth (<u>60</u>) and later Roeder (<u>52</u>) used the same equations to approximate these parameters in their analytical work. For temperature between 800°-1200°F, Weerth's equations substituted into Equations. 9 and 10 and then used in Eq. 8 yields

$$\varepsilon_p(T) = (.001\ T^2 + 6.1\ T - 415)\ 10^{-6}$$

$$- \left[\frac{(-720000 + 4200\ T - 2.75T^2)}{806(500000 + 1333T - 1.111T^2)}\right] \tag{11}$$

It should be noted that in all references reviewed, $\varepsilon_t(T)$ was computed as

$$\varepsilon_t(T) = \alpha(T)(T - T_{room}) \tag{12}$$

which is an approximate formulation. As an example of the difference between these two methods, the approximate formula gives an $\varepsilon_t(T) =$

initial yield load although an exact value cannot be found because of the complex interaction of the flanges and web of the composite girder system. Based on the curves themselves, initial yield corresponded to a load ratio of about 3. Based on the degree of elastic rebound, the yield load ratio was in the range of 2 to 2.7. However, residual forces in the system would likely reduce the elastic rebound effect. The determination of this initial yield is important because during heat straightening at 1200°F, the yield stress of the steel is reduced by 1/2 to 2/3 its room temperature value (4). Should the yield strength of the system be reduced to values below that produced by the external restraining force, then hot mechanical straightening would occur. While expediting the straightening process, the effects of such procedures on the properties of steels are largely unknown. If a load ratio value of 3 is used to define initial yield of the laterally loaded W 10 x 39 at room temperatures, then the initial yield load ratio could be reduced by 2/3 to a value of 1.0 during heat straightening. The load ratios used during sequences 9 and 3 were 1.0 and 1.12, respectively. It is therefore believed that the large increase in plastic rotation which occurred during sequence 3 can, to some degree, be attributed to hot mechanical straightening. This conclusion is reinforced by comparing the similarity of sequences 1 and 2 to 4 and 9 as indicated in Figure 35. Similar comparisons cannot be made for the W 24 x 76 because only one load ratio was used.

A final geometric effect to be considered is the girder depth. Both girders have somewhat similar flanges: 7.985 x 0.53 in. for the plastic rotation occurred on the deeper beam, even though the load ratio was much smaller. The implication here is that interaction of web and flange reduces the straightening effect per cycle for shallow beams. The lateral load-deflection curves for both beam sizes verified this behavior. The level of flange web interaction was twice as great for the W 10 x 39 as the W 24 x 76.

SUMMARY AND CONCLUSIONS

A comprehensive testing program has been conducted in which two beams were repetitively damaged and repaired using the heat straightening process. The beams were supported in a frame to simulate a bridge girder-slab system. A W 10 x 39 and a W 24 x 76 were damaged and repaired twice each.

Ten different heating sequences were applied to plastically deformed areas of the damaged girders in order to study the effect of the external jacking forces and the heating patterns on the behavior of the heat-straightened members. This study verified many of the trends found in earlier laboratory testing but also has shown that additional study of large systems is needed. General conclusions drawn from this research are:

1. A distinct advantage is obtained by applying an external jacking force to the heat-straightened girder. Increasing the jacking force increased the plastic rotation proportionally.
2. Another distinct advantage is obtained by heating all of the plastically deformed zones in the girder. The addition of the web line heat along the yield line greatly increases the

amount of plastic rotation. Heating the yield line in the web reduces the counter-productive action of the yield stresses acting at this yield line. Therefore, all subsequent vee heats in the flange become more effective.

The line heat is most effective when the middle portion of the web is heated.

Heat straightening should only be applied to regions where plastic deformation has taken place. Heating elastic portions of the girder could cause an over-straightening in those regions.

There is evidence that the plastic rotation angle is proportional to the number of vee heats applied during a single cycle.

Deep girders require less constraining force to achieve the same level of plastic rotation as shallow members.

Repetitive damaging and straightening of moderately damaged girders did not change the load-deflection characteristics of the system.

6. IMPLEMENTATION OF HEAT-STRAIGHTENING REPAIRS IN PRACTICE: AN ENGINEERING GUIDE

The use of heat straightening has not gained wide acceptance because of the lack of an engineering guide for its use. The purpose of this chapter is to provide such a guide in preliminary form. There are still knowledge gaps which need to be filled through additional research. The outline of this guide is comprehensive in nature to illustrate the required scope of a finalized guide. Those sections with little or no content reflect the current lack of a research base. It is anticipated that a comprehensive version can be completed after another year of additional research, as has been submitted in a separate proposal.

Section 1. General

1.1 Purpose

The purpose of this manual is to provide an engineering guide for the heat-straightening repair of damaged steel structures. Included will be damage assessment, analytical considerations, design of the repair, and field supervision of the repair.

1.2 Scope

This manual addresses engineering issues related to the analysis and design of heat-straightening repairs for damaged structural steel. Details associated with contractor implementation of heat-straightening repairs are included only to the extent necessary for engineering considerations. The intention is to provide the structural engineer with analysis and design procedures for heat-straightening repairs of a similar form to procedures associated with traditional structural design