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16. Abstract

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The guide is written in specification format and can be used or incorporated into technical specifications for heat straightening. In addition to a general section, other sections include: damage assessment, material assessment, design of repair sequence, and field supervision of repair.

The report concludes with a summary of the research project upon which the guide is based. Major conclusions of the research as well as recommendations for future research are presented.

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DESIGN PROCEDURES FOR HEAT-STRAIGHTENING REPAIRS: AN ENGINEERING GUIDE

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This report summarizes over four years of research on heat-straightening repairs and provides a prototype engineering guide for the application of heat-straightening to bridge structures. It is based on the research results detailed in a companion report entitled, "Development of Engineering Design Procedures for Heat-Straightening Repair of Damaged Structural Steel for Bridges." This guide is not complete. In particular, repair of localized damage is not addressed. However, methods are provided for implementing procedures for repairing specific cases of global damage.

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PROGRAM IMPLEMENTATION

For many years prior to the initiation of this research, heat-straightening repairs had been conducted on steel bridge structures. However, these repairs were not engineered and depended on the skill and knowledge of the contractor. While intuitive knowledge of the process was understood, a rational, quantitative definition of the method was lacking. This research has defined quantitatively, the behavior of the heat-straightening repair process.

There are two distinct categories of damage that are amenable to heat-straightening repair: Global damage identified by flexural bending or twisting of major structural components; and localized damage characterized by bulges, buckles, and crimps to local regions of the plate elements making up the cross-section of a structural component. Both types of damage usually occur simultaneously. However, the global damage is most often of primary concern for damaged structures. As a result, localized damage has not been addressed in either past or current research. The research results here apply to global damage only. Consequently, methodologies are not developed for the repair of localized damage and the repair methods developed here can only be implemented for global damage. This limitation represents a serious restriction to full implementation of heat-straightening repair by the LDOTD.

The research results developed in this investigation cover a wide range of global repair applications. A summary of the structural categories covered and their degree of readiness for implementation are summarized as follows by damage classification. Details on the classification system can be found in this report, but can be summarized as: strong axis, S, weak axis, W; and twisting, T.

Section Type	Damage Classification	Degree of Implementability
Plate	S	Full
Plate	W or T	Partial
Angle	S, W, or T	Partial
Channel	S, W	Full
Channel	T	Partial
Wide Flange	S, W, or T	Full
Composite Girders	S or W	None

Section Type	Damage Classification	Degree of Implementability
Composite Girders	T	Partial
Non-composite Girders	S or W	Full
Non-composite Girders	T	None
Axially Loaded Wide Flanges	S or W	Full
Axially Loaded Wide Flanges	T	None
Fatigue Sensitive Members	S, W, or T	None
Damage to Previously Straightened Members	S, W, or T	Full

Those categories listed as partially implementable will require more experimental data for complete verification. For the entries listed as having no implementability, these cases have not been studied in this or earlier research.

In summary, a significant number of categories of cross-sections and damage types are now either fully or partially implementable. This report provides a prototype engineering guide for the implementation of heat-straightening repairs. The companion report, "Development of Engineering Design Procedures for Heat-Straightening Repair of Damaged Structural Steel in Bridges," provides the research basis for this guide.

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INTRODUCTION

The concept of heat straightening is relatively simple. Heat applied (usually by a torch) to damaged steel in a specific pattern will cause the steel to undergo permanent deformation in a desired direction upon cooling. The heating process must be applied in various patterns and at different locations along a damaged member to produce straightening. Although heating alone may be used to straighten a bent member, loads may also be applied to increase the efficiency of the process. Many types of heating patterns exist, such as the spot, line, strip, and edge heats. When applied in proper sequence for a number of cycles, dramatic results can be obtained in straightening severely damaged steel.

This 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. However, engineers have had to rely primarily on their own judgment and the advice of experienced technicians in applying heat straightening techniques. Two key issues are 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 writer has conducted research on engineered heat-straightening since 1985. The assessment presented here is based on both laboratory and field experimentation, analytical studies, and an exhaustive review of the published literature (1,2,3). This report is in the form of a standard of practice outline for the application of engineered heat-straightening repair.

THE TRANSITION FROM HEAT STRAIGHTENING TO ENGINEERED HEAT STRAIGHTENING

Fabricators, erectors, and contractors have used some form of heat straightening since steel became a widely used construction material. However, until recently, little thought was given to the engineering aspects. Certain of the following basics were understood by some, but often ignored:

1. Heating temperature should be kept below the phase transition temperature for steel (approximately 1300°F for carbon steel).
2. Average material properties are generally unaffected in the heated zone, although ductility decreases somewhat.
3. Key parameters influencing straightening movements are: vee angle, heating temperature, and restraining forces.

4. Vee, line and spot heats appropriately placed in the yield zones of the damaged steel are effective in straightening members.

The research conducted by the writer has quantified these basics in engineering terms. Specifically,

1. Formulas for computing movements (in terms of plastic rotation) have been developed for plates, angles, channels, and wide flange sections. The formulas are suitable for design office use and include the parameters of vee angle, temperature, restraining force, and steel type.
2. Residual stress patterns in damaged and heat straightened members have been quantified.
3. Material properties may vary significantly over the heated zone and ductility may be greatly reduced. Based on this research, damaged steel should not be repaired more than twice at the same location.
4. Vee heats (whether full or 3/4 depth) produce shortening of the member and can be predicted by formula.
5. Restraining forces must be calculated based on both external and internal redundancy. Methods of analyzing these redundancy effects have been developed so that the proper restraining forces can be computed.
6. In addition to the basic shapes subjected to either strong or weak axis bending, special cases of importance for highway bridges have been studied. These cases include: composite girders; noncomposite girders; and axially loaded members. Analytical methods for determining movements corresponding to appropriate restraining forces have been formulated.
7. The amount of damage (in terms of yield strain) that can be repaired has been quantified as an order of magnitude greater than previously reported.

This research work has included analytical modeling, extensive laboratory testing, and simulated field testing. A large amount of experimental data has been collected which has been used to verify the analytical models. This body of research data forms the basis for designing heat-straightening repairs. However, additional research is needed to enable the comprehensive design of heat straightening repairs to become a reality.

The term "engineered heat straightening" is used here to describe this process wherein the analysis/design procedures normally associated with structural engineering are applied to the heat straightening repair of damaged steel structures. elements of engineered heat straightening typically should include: determination of the damage configuration; selection of tentative heat patterns; performance of a structural analysis to determine levels of restraining forces and expected movements during each cycle; and re-analysis to evaluate whether modifying some design parameters will expedite the repair process. In this fashion, working drawings could be prepared which completely define the repair process. Such plans would allow the field engineering supervisor to exercise quality control over the entire repair process. In particular, certain pitfalls could be avoided which now result in occasional fractures during heat straightening and may otherwise shorten the life of the structure. The specific concerns include: excessive jacking stresses which may cause a brittle fracture during heating; lack of movement; hot mechanical straightening; brittle hot spots; and a build-up of residual stresses.

IMPLEMENTATION OF HEAT-STRAIGHTENING REPAIRS IN PRACTICE: A PROTOTYPE ENGINEERING GUIDE

The use of heat straightening has not gained wide acceptance because of the lack of an engineering guide for its use. Presented here is an outline of such a guide. There are still knowledge gaps which need to be filled through additional research. However, this guide reflects the current state-of-the-art and points toward a more complete guideline.

SECTION 1. GENERAL

1.1 Purpose

The purpose of this guide is to provide an engineering assessment 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 guide 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 in new construction. For design of heat-straightening repairs, the required concepts are listed below.

1.2.1 Material Selection

Additional materials are not usually required except for occasional reinforcement or replacement of bracing or secondary elements.

1.2.2 Configuration

Rather than determining such parameters as framing type, member spacings or connectivity patterns typical of new designs, the term here includes the selection of heating patterns, number of specific heats and constraining force patterns.

1.2.3 Structural Analysis

The determination of internal stresses forms an integral part of designing repair schemes as related to the introduction of constraining forces during repair and the final stress configuration after repair.

1.2.4 Sizing

Since elements are not usually added in heat-straightening repairs, sizing here refers to number, dimensions, location, and magnitude of parameters such as temperature, heat zones and constraining forces along with the prediction of behavioral response within acceptable limits.

1.2.5 Iteration Process to Finalize Design

Through the analytical prediction of response, various alternatives are evaluated and the most efficient are selected for the final design of the repair.

1.3 Nomenclature

b_s = width of stiffening element

d = depth of wide flange beam

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

d_v = depth of vee

E = modulus of elasticity

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

F_a = allowable design stress for a compression member

$F_L(M)$ = constraining force function

$F_t(T)$ = temperature function

F_s = shape factor

F_y = yield stress

k = axial equation constant

k_c = equivalent flexural stiffness of the bottom flange of a wide flange beam compositely connected to a deck

L, L_r = lengths between offsets

M = moment produced by jacking forces

M_f = apparent moment in bottom flange of composite girder due to an applied jacking force assuming the bottom flange alone resists the entire force

M_p = plastic moment capacity of a member

M_r = residual moment

M_y = moment at initial yield

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

P_u = ultimate load computed from a plastic analysis

R = actual radius of curvature

R_y = radius of curvature at initial yield

T = heating temperature

t_w = web thickness

V = width at open end of vee

W = primary plate element width

y_r = measured offsets

y_{max} = distance from centroid to extreme fiber

ε = actual strain

$\varepsilon_p(T)$ = strain under conditions of perfect confinement at temperature T

ε_y = strain at initial yield of material

θ = vee angle

ϕ_d = degree of damage

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

SECTION 2. DAMAGE ASSESSMENT

2.1 Effect of Damage Type on Design of Repair

2.1.1 Causes of Damage

Knowledge of the specific cause of damage may influence the final decision on repair. Typical damage causes are:

(1) Overheight or overwide vehicle impact
(2) Overweight vehicles or overloads
(3) Out-of-control vehicles or moving systems
(4) Mishandling
(5) Fire
(6) Blast

(7) Earthquakes

(8) Wind

2.1.2 Design Considerations Associated with Damage Type

There are five engineering considerations which may be associated with the damage type.

(1) High heat.--As long as the temperature does not exceed the phase transition temperature of 1330°F for carbon steel, no permanent degradation would be expected to occur in the steel. However, if the damaged steel was exposed to higher temperatures, metallurgical tests should be performed to ensure material integrity before heat straightening is applied.

(2) Large strains.--The strain limit beyond which heat straightening should not be attempted is 100 ε_y, where ε_y is the strain at initial yield. Repairs may be successful at even greater strains. However, research studies have not exceeded 100 ε_y.

(3) Residual stresses.--Plastic deformations during damage inducement may produce residual stresses in the structural system. The type and magnitude of these stresses must be determined as an integral part of the repair design. Procedures for the evaluation of residual stresses are given in Sections 2.2.5.2 and 2.2.5.3.

(4) Hairline fractures.--On occasion, a hairline fracture will occur during an intermediate cycle of heat-straightening repair. The causes are believed to be: (1) Excessive restraining forces being applied during the heating process, and (2) Repetitive damaging and repairing an element. As the former in the primary cause, restraining forces should always be specified at safe limits and should be monitored during actual repair.

(5) Material age and load history.-- Fatigue and fracture considerations may be influenced by these factors. At present, there are no research studies to provide guidance.

2.2 Evaluation of Damage Geometry

2.2.1 Primary versus Secondary Damage

Damage geometry can be categorized as follows:

(1) Primary.--Significant distortion has occurred to an identifiable structural element or group of elements. A bowed member is a typical example.

(2) Secondary.--Significant distortion has occurred to only a relatively small portion of an element cross section. A web bulge is a typical example.

Repair of primary damage is well-defined and requires an analytical evaluation and design of the repair. Repair of secondary damage is not clearly defined. Hot mechanical straightening is often used instead of heat-straightening.

2.2.2 Measurements of Damage

2.2.2.1 Measurements for Primary Damage

Two types of measurements may be required to evaluate damage conditions in primary members.

(1) Measurements for maximum strain.--Measurements for maximum strain should be taken when necessary to verify that strains are less than 100 ε_y. As a rule of thumb for single curvature bends, if the angle of damage is less than 12°, it is not necessary to measure for maximum strain. The only exception would be if the region of damage is concentrated over an extremely short length resembling a sharp crimp as opposed to a plastic hinge type of bend. To measure maximum strain, visually select the region of maximum damage and section of largest curvature. Typically, the length would be in the 3-6 inch range. Take three equally spaced points along the length and measure the offsets from a reference line as shown in Fig. 1. Computations are described in section 3.3.2.

(2) Measurements for degree of damage.--Measurements to establish degree of damage can be taken at two points on each side of a damaged yield zone (non-yielded sections) as shown in Fig. 1.

2.2.2.2 Method of Measurements

(1) Offset method.--Offsets are measured from a taut line or straight edge between two reaction constraints.

(2) Optical measurements.--Optical equipment is used to define the deformed geometry of the system.

(3) Image processing.--Photographic images are analyzed to define the deformed geometry of the system.

2.2.2.3 Measurements for Secondary Damage

No recommendations are made until further research is conducted.

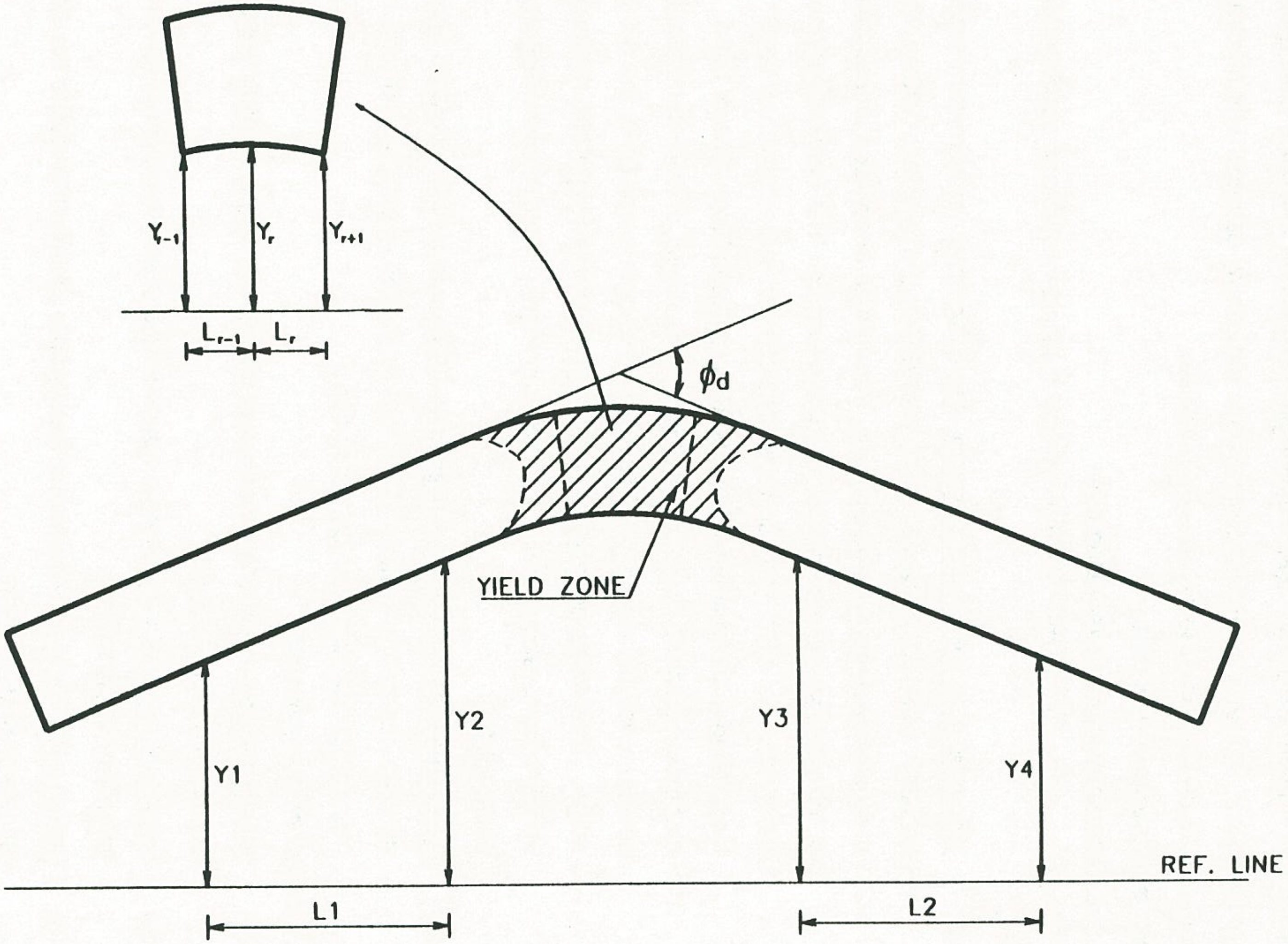


Figure 1. Offset measurements to calculate degree of damage and radius of curvature.

2.2.3 Characteristic Patterns of Primary Damage

Primary damage can be classified into characteristic modes. Elements of the cross section will be distinguished as: (1) major elements which are bent about the strong axis of their local axis, and (2) stiffening elements which are either bent about the weak axis of their local axis, or remain undeformed.

(1) Category W--This damage pattern is usually associated with weak axis bending of the rolled shape.

(2) Category S--The damage pattern is associated with strong axis bending of the shape.

(3) Category T--The damage pattern is one of twisting about the longitudinal axis.

2.2.4 Characteristic Patterns for Secondary Damage

Secondary damage refers to localized problems affecting cross section elements as opposed to damage through the entire cross section. Generally, secondary damage does not lead to structural failure. Secondary damage can be classified as:

(1) Local bulges

(2) Crimps

2.2.5 Structural Analysis

2.2.5.1 Strength of Damaged Structure

The capacity of the damaged structure can be based on the following assumptions:

(1) Base the structural analysis on undeformed geometry except when geometry of the frame or truss system changes by more than 20 percent. Use a nonlinear analysis for these cases.

(2) Compute member stresses based on section properties of deformed geometry of primary members. Such members can be idealized by linearizing the cross section based on element edge deformations and neglecting secondary damage.

(3) Use allowable stresses based on the original properties of the material.

2.2.5.2 Redistribution of Internal Forces Due to Inflicted Damage

A key requirement of damage assessment is to determine the residual forces existing in the system after damage. Residual forces will not exist in determinate structures (although residual stresses may). For indeterminate structures with full cross section yielding, residual forces may be introduced which tend to prevent movement during heat straightening.

The procedure to determine the residual forces is as follows for frames:

(1) Conduct a plastic analysis of the original structural configuration using a concentrated load at point of impact. Then compute the ultimate load, P_u, and the moment diagram associated with the failure mechanism.

(2) Conduct an elastic analysis of the original structural configuration with an applied loading of $-P_u$. Then compute the moment diagram.

(3) Superimpose the moment diagrams of (1) and (2) to get the residual moment diagram.

For trusses, a similar analysis can be conducted by treating the truss as a rigid frame. However, for axially loaded members, an additional component is the P-δ effect associated with the axial forces. The truss is treated as an idealized pin connected system and the residual moment in a damaged member is computed by multiplying the axial force in the member by the lateral deflection of the damaged member (or members). The axial force is computed by a standard elastic truss analysis with a loading equal to the dead and live loads on the structure at the time the repair is conducted.

2.2.5.3 Residual Forces for Composite Girders with Impact at Lower Flange

The residual forces in a composite girder is complicated by the composite connection. Part of the residual moment (as well as any jacking force applied) is transferred through the web to the slab. The approach recommended is to compute an equivalent flexural stiffness, k_c, of the member for lateral loads applied to the bottom flange. The equivalent stiffness can be obtained graphically from Fig. 2. Using this stiffness, the composite girder can be treated as described in section 2.2.5.2. Diaphragms can be considered as rigid lateral supports for analysis purposes.

SECTION 3. MATERIAL ASSESSMENT

3.1 Material Assessment

3.1.1 Yield Stress

The type of steel should be determined in one of the following ways:

(1) Review of design plans

(2) Assumptions based on age of structure

(3) Metallurgical analysis

3.1.2 Hairline Fracture

The yield zones should be examined closely for hairline fractures. Non-destructive testing (NDT) should be employed. Recommended methods are dye penetrant, magnetic

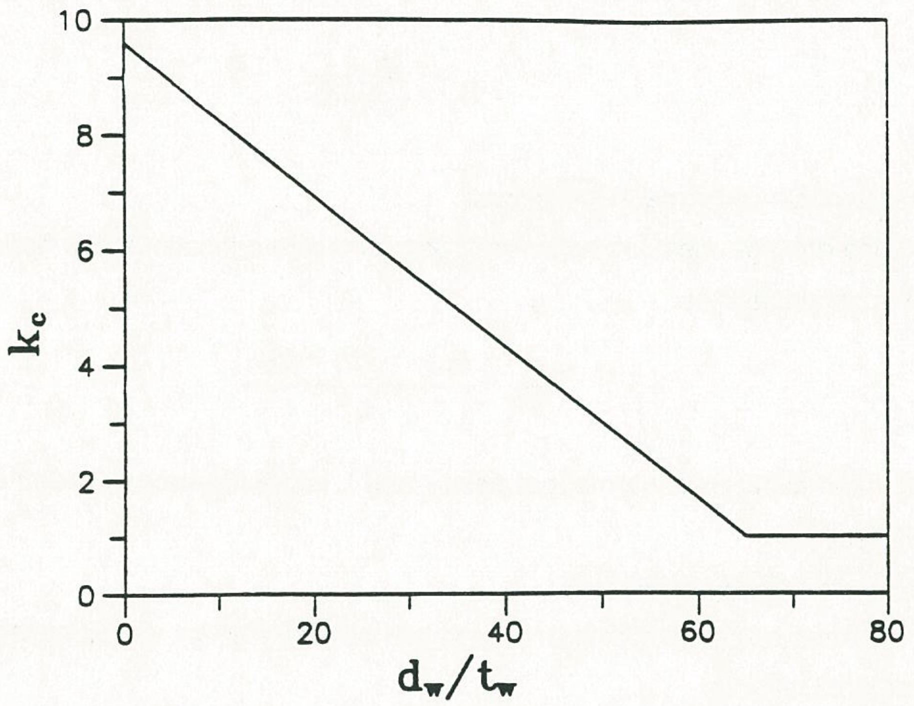


Figure 2. Stiffness modification factor K_c vs. d/t ratio of the web in a composite girder.

particles, or ultrasonics. Heat straightening should not be attempted unless hairline fractures are repaired as part of the process.

3.2 Yield Lines

The only portions of damaged steel that should be heated are zones of plastic deformation. One type of characteristic yield zone is the yield line. Yield lines are typical of weak axis bending of plate elements. Computations should be made to determine all yield line locations.

3.3 Plastic Hinges

Plastic hinges are characteristic of strong axis bending of plate elements. They may be single hinges at sharp bends or a string of hinges forming a zone.

3.3.1 Radius of Curvature at Yield Point Strain

Plastic hinge regions can be approximated as those with a radius of curvature less than R_y, where R_y is the radius of curvature producing yield at the extreme fiber. Yield zones are thus defined as

$$R < R_y \tag{1}$$

where

$$R_y = \frac{E\ y_{max}}{F_y} \qquad (2)$$

3.3.2 Calculation of Damage Curvature

Since damage measurements are taken at discrete locations, the radius of curvature must be approximated as

$$\frac{1}{R} = \frac{y_{r-1} - 2y_r + y_{r+1}}{L^2} \qquad (3)$$

where y_r is the offset measurement at point r and L is the distance between equally spaced measuring points.

3.4 Local Buckling or Bulges

Localized bulges, buckling or crimps can be identified by visual inspection. Rarely are measurements required.

3.5 Evaluation of Residual Forces Affecting Heat Straightening

Residual forces induced by the damage effects can either expedite or restrain repair by heat straightening. At all regions of primary plastic deformation, the residual moments should be computed as discussed in section 2.2.6. Define positive moments as those which tend to act in a direction to straighten that portion of the member.

3.6 Effect of Residual Stresses after Heat-Straightening

Residual stresses generated during heat straightening have maximum values at or near the material yield stress. However, distributions will vary depending on the heating pattern.

3.7 Degree of Damage Evaluation

Degree of damage is a valuable indicator as to time and effort required to repair a member. Based on measurements taken as described in section 2.2.2.1, degree of damage can be calculated as follows:

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

where ϕ_d is the degree of damage or angle of permanent deformation at a plastic hinge and y_i is a measured offset.

3.8 Decision to Repair

A number of factors must be considered prior to deciding on a heat-straightening repair. Since overall engineering judgment should always be the deciding factor, it is recommended that heat straightening not be undertaken without competent engineering analysis. Relatively few quantitative limits have been established through research data. Most previously published limits result from the idea that if data does not exist, set extremely conservative limits. While not disagreeing completely with this philosophy, each case should be analyzed on its own merits before accepting such conservative limits. The following issues should be analyzed in the process of deciding whether to repair by heat straightening.

3.8.1 Member Type Limitations

There are no specific limitations to heat-straightening repair based on member type. Tension, compression, flexural or various combinations have been successfully repaired in the laboratory and field. In addition, rolled or built-up member can be repaired. As long as the heat can be applied at the proper locations and restraining forces can be placed as needed, repairs can be affected.

The primary question raised in the past is whether fracture critical members can be repaired. No data currently exists to answer this question. Therefore, the engineer should examine the risks associated with location, indeterminacy, stress level and cyclic load characteristics before deciding.

3.8.2 Strain Limitations

Since strains are related to radius of curvature, it is recommended that radius of curvature be used for evaluation purposes. Research data has established that damage strains are not a significant factor if

$$R > 100\ R_y \tag{5}$$

or, in terms of strains

$$\varepsilon < 100\ \varepsilon_y \tag{6}$$

Since research data does not extend past this level, the engineer must use his own judgment in this range.

3.8.3 Steel Grade Limitations

Carbon steels can be heat straightened as long as the heating temperature does not exceed the phase transition temperature (approximately 1300°F). High strength heat-treated steels require a lower heating temperature (less than 1100°F is recommended).

SECTION 4. DESIGN OF REPAIR SEQUENCE

4.1 Development of Constraint Plan

Constraints are passive forces, usually applied by hydraulic jacks prior to heat straightening.

4.1.1 Location of Jacks

Jacks to produce constraining forces should be located to produce a maximum moment effect at the plastic zones. Jacks should be placed so that stresses are controlled at safe levels throughout the structure.

4.1.2 Computation of Residual Moments

Residual moments should be calculated as outlined in section 2.2.5.2. For indeterminate structures in which all plastic hinges cannot be heated simultaneously, the distribution of residual moments will change after each heating cycle. Thus, jacking forces should be adjusted to account for these changes as the heat straightening progresses.

4.1.3 Magnitude of Jacking Force

Jacking forces should be measured at the time of application and limited to produce moments as follows:

(1) For cases where the residual moments, M_r, at the heating zone are negligible:

$$M \leq \frac{M_y}{3} \tag{7}$$

where M = moment produced by jacking force at the heated zone.

(2) For cases where residual forces exist

$$M \leq \frac{1}{3}(M_y \pm M_r) \tag{8}$$

where the sign of M_r is positive when acting to straighten the member and negative when acting to resist straightening.

4.1.4 Direction of Jacking Forces

Jacking forces should be directed to produce positive moments (moments tending to reduce damage curvature).

4.2 Development of Heating Patterns

4.2.1 Heating Zones

All plastically deformed zones should be heated, while no elastic zones should be heated.

4.2.2 Heating Patterns for Specific Cross Section Shapes

(1) For plates with strong axis bends, use vee heats as shown in Figure 3. Vee heats for any shape should follow the serpentine pattern shown in Figure 3.

(2) For Category S or W angles, use the vee and rectangular heat combination shown in Figure 4.

(3) For Category S or W wide flange beams, use the vee and rectangular heat combination shown in Figure 5.

(4) For Category S or W channels, use the vee and rectangular heat combination shown in Figure 6.

4.2.3 Plastic Rotation Computations for Plates and Rolled Shapes

The amount of plastic rotation removed per vee (or vee/rectangular) heat can be calculated from the following formula for various structural shapes. Multiple vee heats increase the plastic rotation in direct proportion as long as spacing between vees in greater than W.

$$\phi_p = F_t(T)\ F_L(M)\ F_s\ \varepsilon_p(T)\ \sin\frac{\theta}{3} \qquad (9)$$

where F_t is the heating temperature factor ($F_t(T) = 0.5 + 0.0025\ (T\text{-}750)$ for all shapes), F_L is the restraining force factor, F_s is the shape factor, ε_p is the perfect confinement strain at the heating temperature, and θ is the vee angle.

For T = 1200°F and A36 steel

$$\phi_p = 0.0079\ F_L(M)\ F_s\ \sin\frac{\theta}{3} \qquad (10)$$

(1) For plates with strong axis bends $F_s = 1$ and

$$F_L(M) = 0.9 + 3.4\ \frac{M}{M_p} \qquad (11)$$

(2) For Category S or W angles

$$F_L(M) = \left(0.9 + 3.4\ \frac{M}{M_p}\right)\left(1 + 2\ \frac{M}{M_p}\right) \qquad (12)$$

$$F_s = 1 + \frac{1}{2}\ \frac{d_s b_s}{W^2} \qquad (13)$$

(3) For Category S or W channels $F_L(M)$ is defined by Eq. 11, F_s is defined by Eq. 13 for Category S channels, and

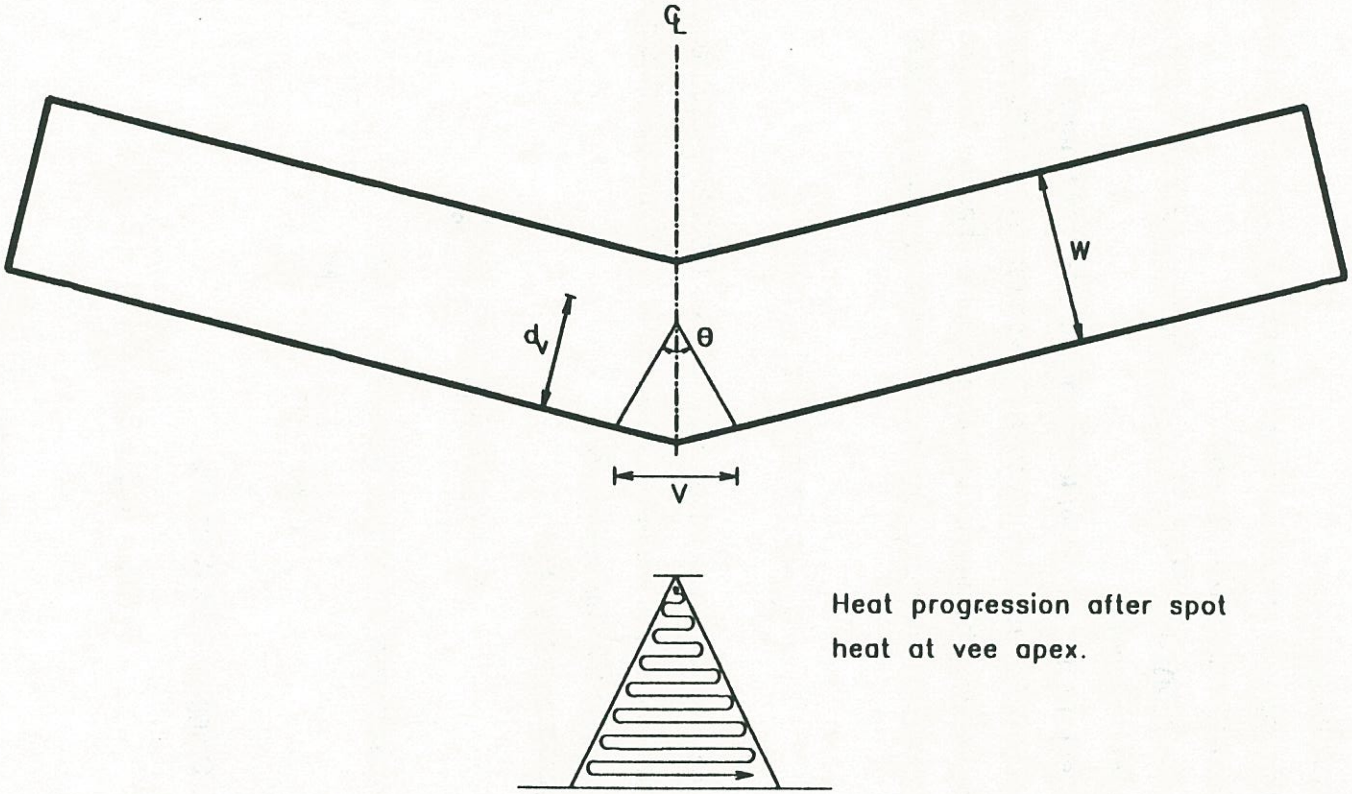
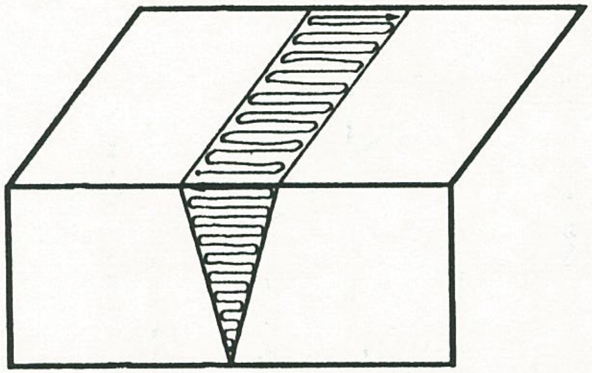
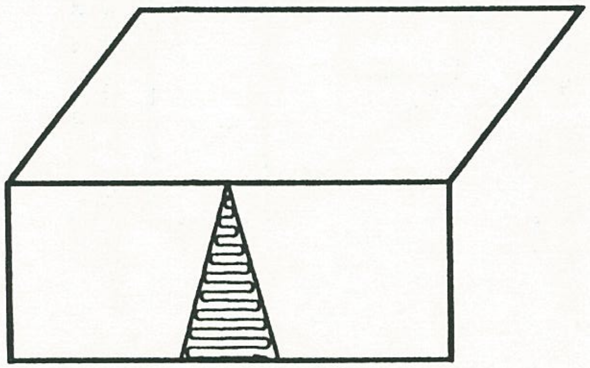


Figure 3. Illustration of vee heat.

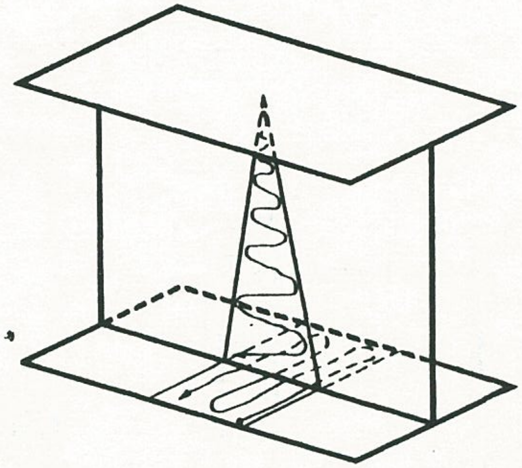


(a) Stiffening element at open end of vee
(Heat vee first and then rectangle)

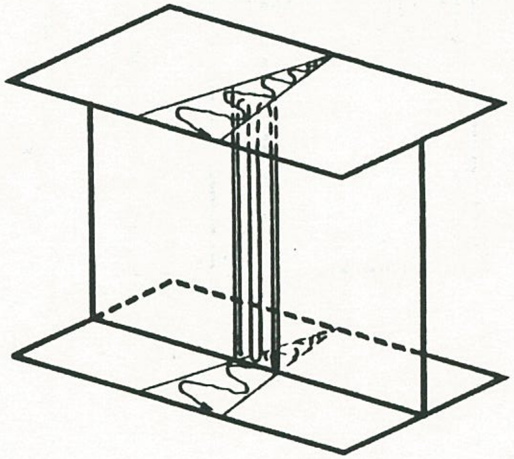


(b) Stiffening element at apex of vee
(Vee heat only)

Figure 4. Heating pattern for category S or W angles.

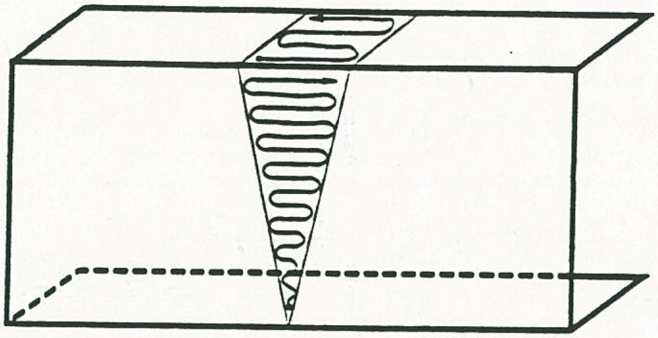


(a) Heating configuration for category S wide flange
(Heat vee first and then rectangle)

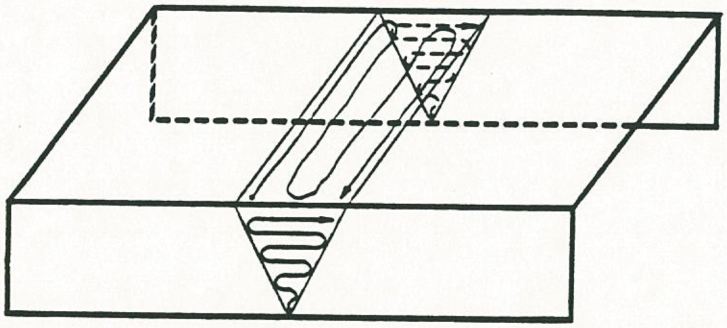


(b) Heating configuration for category W wide flange
(Heat vees simultaneously and then rectangle)

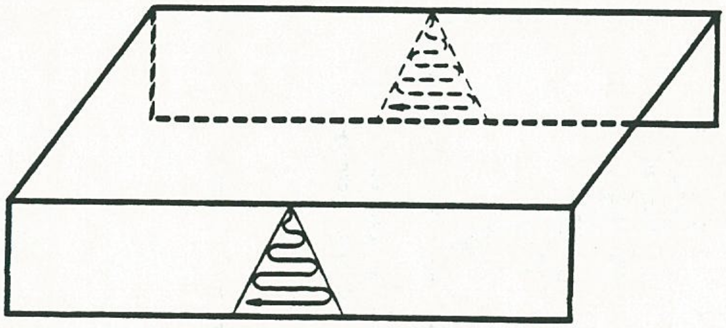
Figure 5. Heating configuration for category S or W wide flange beams.



(a) Category S damage
(Heat vee first and then rectangle)



(b) Category W damage with stiffening element at open end of vee
(Heat both vees simultaneously and then rectangle)



(c) Category W damage with stiffening element at apex of vee
(Heat vees simultaneously)

Figure 6. Heating pattern for category S or W channels.

For Category W channels

$$F_s = 1 + \frac{1}{4}\,\frac{d_s b_s}{W^2} \quad \text{for Category W channels} \tag{14}$$

(4) For Category S or W wide flange beams $F_L(M)$ is defined by Eq. 11 and F_s is defined by Eq. 13 for Category S, and Eq. 14 for Category W wide flange beams.

4.2.4 Deck-Girder Systems

4.2.4.1 Composite Girders

(1) Use the heating pattern shown in Fig. 7.

(2) The amount of plastic rotation removed from the bottom flange per vee heat can be calculated by Eqs. 9 and 10 where $F_s = 1$ and

$$F_L(M) = 0.9 + 0.1\,[\frac{d}{t_w} - 37] + 3.4\,\frac{M_f}{M_p} \tag{15}$$

and M_f = the apparent moment in the bottom flange at the heated zone due to an applied jacking force assuming the bottom flange alone resists the entire force.

4.2.4.2 Noncomposite Girders

Use heating pattern shown in Fig. 8.

4.2.5 Axially Loaded Wide Flange Beams

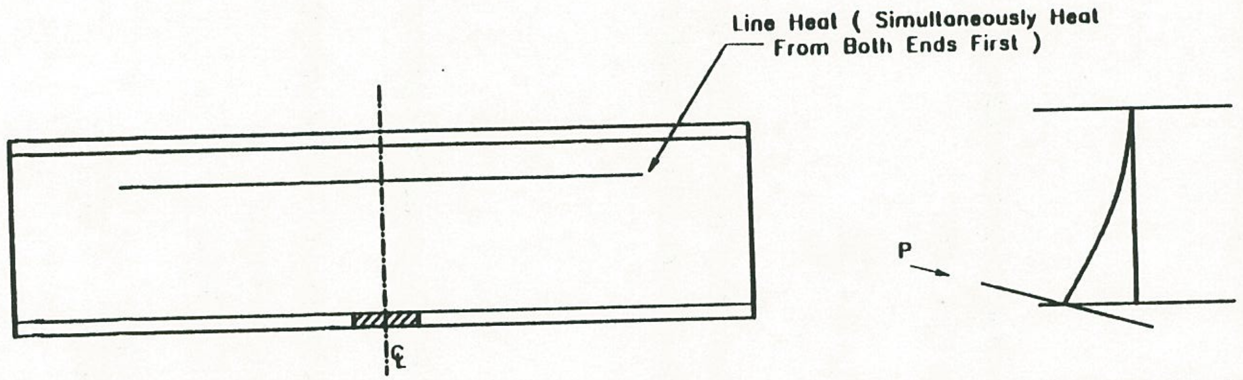
(1) Use vee heat patterns similar to those of wide flange sections without axial loads.

(2) The plastic rotation removed per vee heat from axially loaded wide flange beams can be calculated by using Eqs. 9 or 10 where

For Category S damage F_s is defined by Eq. 13 and

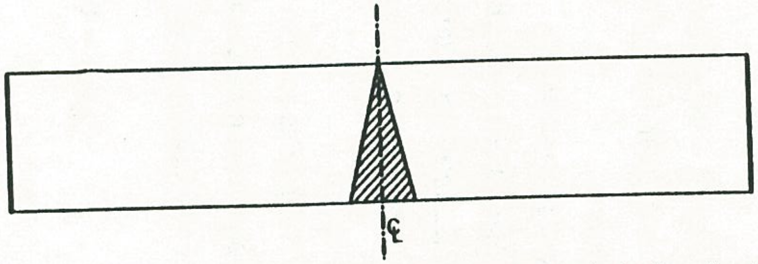
$$F_L(M) = 0.9\,(1 - k\,\frac{f_a}{F_a}) + 3.4\,\frac{M}{M_p}\,(1 + k\,\frac{f_a}{F_a}) \tag{16}$$

and k = 1.40.



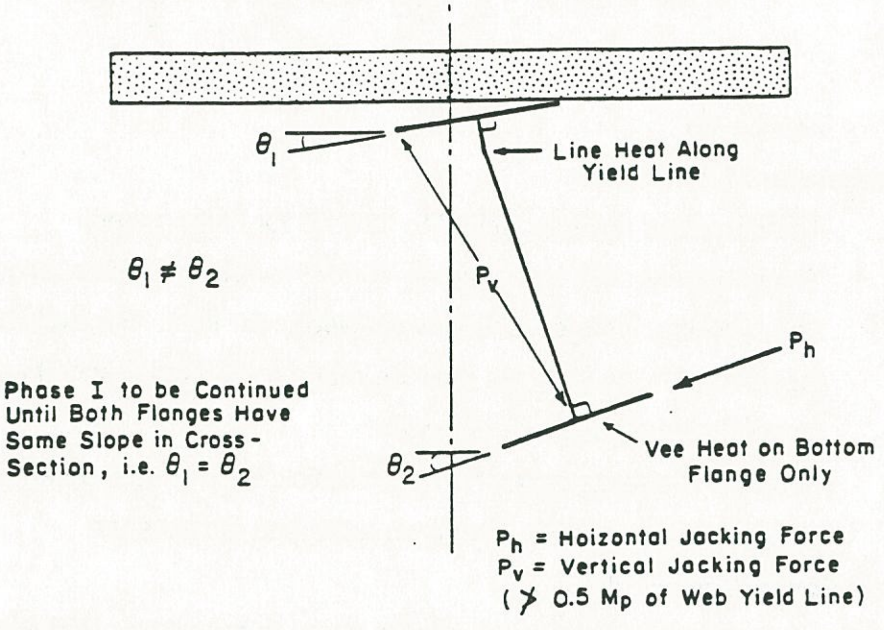
(a) Front View (Showing Line Heat)

(c) Horizontal Jacking Arrangement

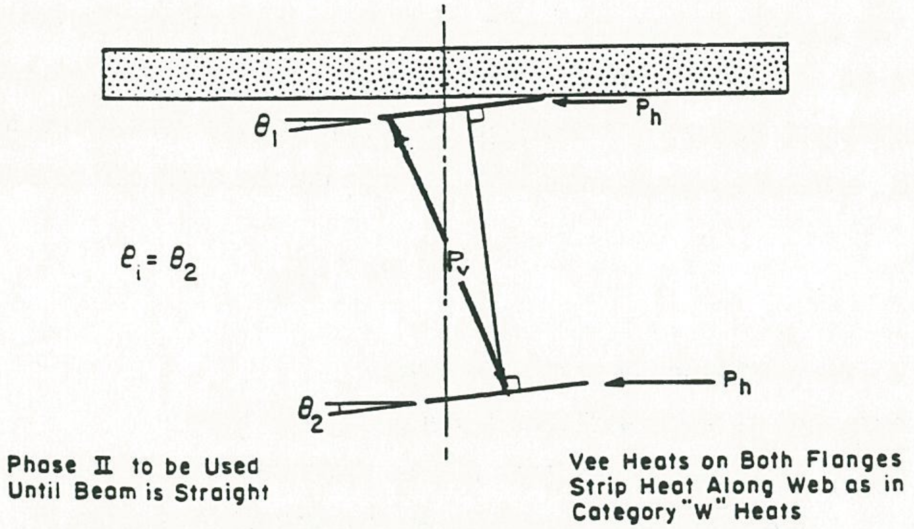


(b) Bottom Flange (Showing Vee-Heat to be heated after line heat)

Figure 7. Heating patterns for composite girder



(a) SET-UP FOR PHASE I



(b) SET-UP FOR PHASE II

Figure 8. Methodology for non-composite girder repair.

For Category W damage F_s is defined by Eq. 14 and

$$F_L(M) = 0.9\left(1 - \frac{k}{2}\frac{f_a}{F_a}\right) + 3.4\frac{M}{M_p}\left(1 + \frac{k}{2}\frac{f_a}{F_a}\right) \tag{17}$$

and k = 1.4.

4.3 Temperature Limitations

(1) Temperatures shall be limited to 1200°F for carbon steel.

(2) Temperatures shall be limited to 1000°F for constructional alloy steel.

(3) After heating, the steel shall be allowed to air cool. For ambient temperatures less than 20°, an analysis shall be made to determine whether heat straightening should be performed.

(4) For plate elements greater than 3/4" thick, heat should be applied from both sides simultaneously to insure an adequate temperature.

4.4 Selection of Vee Depth

In general the depth of the vee should be equal to the width of the plate element being heated. Shortening of the member will not be reduced by using shallower vee depths (between 1/2 and full depth) and residual stresses may be intensified.

4.5 Selection of Vee Angle

The angle of the vee to be used should be as large as practical for heating with a point source torch. A good measure of practicality is to limit the open end vee width to approximately six inches. The vee angle will thus depend on the depth of the vee. If the vee depth, d_v, equals the plate element width, W, then the vee angle can be computed as

$$\theta = 2\tan^{-1}\frac{V}{2W} \tag{18}$$

where V = the width at the open end of the vee.

4.6 Selection of Number of Simultaneous Vees to Heat

(1) Simultaneous vee heats may be performed in a single plastic hinge zone provided they are spaced at least a plate element width, W.

(2) Simultaneous vee heats should be performed if the damage mechanism of a structural unit has produced multiple plastic hinges. Each hinge should be heated simultaneously.

4.7 Computation of Number of Vee Heats Required to Straighten an Element

The number of heats required may be computed by taking the plastic rotation, ϕ_p, from Eq. 9 or 10 and dividing into the degree of damage, ϕ_d; that is,

$$n = \frac{\phi_d}{\phi_p} \tag{19}$$

4.8 Location of Vee Heats within Plastic Hinge Zones

Vee heat locations with a hinge zone should be varied with each heat by at least the width of the plate element. The same exact location should be re-heated only after at least three heats at other locations.

4.9 Selection of Constraining Forces

The largest constraining force practical within the limits of section 4.1.3 should be used. When necessary, a structural analysis should be used to insure that adjacent members are not over-stressed as a jack reaction. The techniques of sections 2.2.5.2 and 4.1.3 should be employed to determine the optimum jacking force required.

4.10 Repair of Previously Heat-Straightened Members

Repair of previously heat-straightened members may be conducted once but further repetitions are not recommended.

SECTION 5. FIELD SUPERVISION OF REPAIR

5.1 Control of Constraint Forces

Jacking forces should be monitored and controlled by the use of calibrated gages.

5.2 Approval of Heating Patterns

The engineer should review and approve all heating patterns .

5.3 Monitoring Temperature

Heating temperature should be monitored by one of the following:

(1) Use of temperature sensing crayons.

(2) Use of contact pyrometers.

(3) Observations of steel color (satiny silver at torch tip to produce a temperature of 1200°F).

5.4 Tolerances

Tolerances for straightening should be similar to that of new construction.

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS OF RESEARCH PROJECT

Reported here are the results of over four years of research on heat-straightening of damaged steel. The study began with an exhaustive investigation of simple plate elements in the laboratory to establish the important parameters associated with the method. Not only were the various factors affecting heat-straightening quantified, but a rational formula was derived to predict the amount of straightening which would occur after a single vee heat as a function of these parameters. The key parameters were found to be heating temperature, vee angle, and constraining force. The formula developed is suitable for hand computations and design office use.

The next step was to extend the study to rolled shapes. Angles, channels and wide flange beams were damaged and heat straightened under controlled laboratory conditions to determine the factors affecting behavior. While the factors affecting plates were found to be equally important for rolled shapes, two other variables were determined to influence rolled shape behavior. Rolled shapes can be viewed as consisting of two types of cross section plate elements: primary and stiffening. The primary elements consist of plate elements bent about their local major axis when damaged. Vee heats are applied to these elements during repair. Stiffening plate elements are perpendicular to primary elements and are typically either bent about their minor axis or experience tension or compression when damaged. Strip heats are applied to these elements during repair. The sections may or may not be symmetrical. The cross section geometry introduces two effects. One is identified as the geometric effect and relates to the location of the stiffening elements at either the top, center, or bottom of the primary element. The other is the principle axis effect which relates to whether the primary elements coincide with the principle axis or not. Both factors have been quantified through extensive laboratory testing. In addition, an analytical investigation led to the conclusion that degree of straightening could be predicted by formulas using the plate equation as their basis. In essence, multiplication factors reflecting both the geometric and principle axis effects were introduced into the plate equation. The results were simple formulas to predict heat-straightening movements in angles, channels or wide flange beams about either their major or minor axis. Again, the formulas developed are suitable for hand computation and design office use.

The next phase of the research moved to large scale experimentation in which full-size steel bridge components were investigated. The focal point has been deck-girder systems in which the steel girder is compositely connected to the deck. However, noncomposite girders were also studied. The bottom flange of such structures is frequently damaged by over-height vehicles traveling the underpass. Tests were conducted in an outdoor facility in which 20 ft. long girders, ranging in depth from 10 to 24 inches, were damaged and repaired. All tests were conducted with a deck loading in place. Analytical studies were also conducted which have resulted in simple formulas for predicting behavior during heat-straightening. An additional factor influencing behavior was the role of the constraining force in indeterminate structures. When a lateral constraining force is applied to the bottom flange, a portion of the force is transferred through the web to the top flange and deck. Thus, the apparent moment induced in the bottom flange (based on assuming the entire force is carried by the bottom flange) is considerably higher than the actual moment. Since the actual flange moment is the governing factor related to constraining force, this behavior must be accounted for in developing analytical models. In addition, the diaphragms typically found in this type of structure result in an indeterminate beam over rigid supports for lateral loads applied to the bottom flange. Even adjusting for the web effect, an indeterminate analysis is often required when diaphragms are present. Procedures were developed to: (1) determine the effective stiffness of the bottom flange; (2) compute the residual moments caused as a result of the damage; (3) compute the effective bottom flange moment due to a specified applied constraining force; and (4) predict the rate of restoration per heat cycle. This phase of the study led to the refinement of heating patterns to be used for both composite and noncomposite girders. However, an analytical treatment of noncomposite girders was not developed because the experimental data base was too small for an adequate comparison. As a capstone to this phase of the project, a damaged girder in an actual bridge was repaired. Measurements were taken to verify the results determined analytically.

Finally, full scale wide flange rolled shapes were tested and evaluated in axial compression to simulate truss members. The experimental results for both major and minor axis damage differed from that of wide flange sections without axial loads. For small or negligible lateral constraining forces, the rate of straightening was less. The implication being that axial forces hinder straightening movements without significant applied constraining forces. However, for large lateral constraining forces, the straightening movements were larger than an equivalent member without axial loads implying that the axial forces magnify movements under these conditions. An analytical model was developed which incorporates the axial load effect. Again, the basic plate equation forms the basis for this formula with multiplication factors employed to compensate for the axial loads.

As the research progressed from simple plate elements in the laboratory to full scale field tests, a continually decreasing number of experiments were conducted. A part of the reason was that as certain factors were identified and evaluated, it was not necessary to re-evaluate at the next stage. Additionally, as the specimens became larger and the structural configuration more complex, only a limited number of tests could be conducted within the scope of the project. However, some aspects require additional testing for a complete assessment of the behavior. To put the scope of the entire testing program in perspective, the following summary is presented.

Type of Element	Number of Specimens	Number of Heats
Undamaged elements		
Small plates	94	383
Small angles	6	18
Small Channels	12	36
Small wide flanges	29	164
Sub-Total	141	601
Damaged elements		
Small plates	10	336
Small angles	5	29
Small channels	1	14
Small wide flanges	5	297
Sub-Total	21	676
Damaged structural systems		
Large composite girders	3	137
Large noncomposite girders	1	69
Large axially loaded girders	2	73
Field repair of actual bridge	1	10
Sub-Total	7	289
Total	169	1566

As a result of using this experimental data to verify analytical formulations, some reliable formulas for predicting behavior have been developed. The most highly reliable is the basic plate equation for plastic rotations which forms the basis for all the analytical work. The research here differs from past work in that the emphasis has been placed on straightening damaged members in which a large number of heating cycles are employed. Previous research has been almost exclusively limited to heating initially straight members for only a few cycles. As a result of this emphasis, reliable data has been obtained for angles, channels and wide flange beams as well as composite girders and axially loaded wide flange members. This data has been used to verify the analytical modeling. The primary limitation on the modeling for rolled shapes is that a full range of different size sections have not been tested. More testing of damaged rolled shapes and noncomposite girders is needed to fine-tune and complete the analytical study.

From an engineering perspective, the most significant result of this research are the analytical procedures developed.. These results will enable engineers to assess damage, analyze the required parameter variations, design the heat-straightening repair, and compute the type and number of heating cycles to complete the repair. In most cases, the design formulations are suitable for hand computations and either field or design office use. While it was originally envisioned that a computer program would be required to facilitate the design of heat-straightening repairs, the simplicity of the formulas means that hand computations are feasible. The only required use of a computer analysis is for the treatment of indeterminate systems to determine constraining force effects. For most cases, any standard frame analysis package will be satisfactory. The only possible exception is for composite girders with intermediate diaphragms. However, most standard programs can handle this aspect also with the coefficients provided in this report. A computer program has been developed for the analysis of all basic cases and is given in an appendix.

An important issue that has limited the use of heat-straightening is the concern about material property changes. Most previous research has evaluated material properties after the application of only a small number of heats and usually on undamaged members. The investigation was also conducted on members that had been damaged and repaired. It can be concluded that yield stress and tensile stress increase slightly after repair, although higher values were typically located near the apex of the vee. The modulus of elasticity showed a decrease at the open end and varied at other locations. There were no indications that the material property changes should limit the use of heat straightening.

Residual stress distributions were measured for angle, channel and wide flange sections. The peak values were typically in the 20 ksi range which is similar to those found in welded built-up sections. This level of residual stress should not be detrimental.

The results of this research have shown that heat-straightening repair is a valid procedure for repairing structural steel. It has been found that the degree of damage can best be defined as the angle of rotation between non-yielded portions on both sides of a plastic hinge yield zone. The length of the yield zone is a relatively unimportant consideration. More important is the type of damage. A classification system has been developed to more clearly define damage in three categories: S for major axis bending, W for minor axis bending, and T for torsional damage. Methodologies for heat straightening each type have been defined.

However, there are limiting situations in applying heat-straightening repair. One consideration is the occurrence of sudden cracking during repairs. While reported occasionally in field applications, no explanations have been advanced. The cracking phenomena has been reproduced in an experimental environment while repairing a composite girder. An unusually high jacking force was being used when the crack occurred. The failure is attributed to this excessive force. Since jacking forces are rarely measured in field repairs, it is not surprising that cracking sometimes occurs. It is recommended that jacking forces be limited to that which produces a moment in the heated zone not to exceed one-third of the plastic moment capacity. It is also recommended that jacking forces not be allowed unless the jacks are gauged to control the applied force and a structural analysis is performed to determine what the limiting force should be.

A second limiting factor may be the degree of damage. This study is the first to explore this facet. Specimens were damaged so that the extreme fiber strain equalled 100 times the yield strain. These members were successfully repaired indicating that limiting strains are at least that high.

A third limiting factor is repetitive damage and successive heat-straightening repair. In one test, a fatigue type crack appeared during the fourth damage/repair cycle. In a second test series, plates were damage and repaired up to eight different times. Material properties varied little after two cycles but began to change significantly after the fourth cycle. In particular, yield stresses increased dramatically, while tensile stress did not change. As a result, the material takes on the stress-strain characteristics of a brittle material. Based on these considerations, it is recommended that damaged steel members not be repaired more than twice by heat straightening.

One area which has not been addressed is the heat-straightening repair of localized damage such as bulges and crimps. These localized damage zones can be quite severe. Current field practice is to use hot mechanical straightening to correct this type of damage. It is believed that effective patterns and methodology can be developed so that this type of damage can be engineered in a manner similar to that presented here for overall member damage.

A second area of need is to apply the research of this project to actual repair situations. A selected number of bridges with the various categories of damage should be field repaired with careful instrumentation and monitoring of the results. This data will allow for the fine-tuning of both the analysis and methodology of heat-straightening.

A third need is to investigate the fatigue characteristics of heat-straightened members. At present, no guidance exists as to possible limitations. As a result, some authors recommend that fracture critical members not be heat straightened. It is the opinion of the writers that this is too severe of a limitation. However, research is needed to verify this concept.

A fourth need is to develop procedures for assessing the degree of damage in terms of the reduced capacity of the structure. Factors to be evaluated include the effects of unsymmetrical damaged cross-sections, lateral and torsional buckling strength reductions due to distortion, and strength losses due to localized bulges and buckles. Such analysis would enable the engineer to base the decision to repair on a quantitative analysis.

A final need is to conduct additional laboratory experiments on rolled shapes and built-up members typically used in bridge design. A greater variety in member sizes would provide further verification of the analytical models. Built-up member tests have not been conducted and may require special considerations.

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