Design and Implementation of Heat-Straightening Repair for Composite Deck-Girder Bridges

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Both an experimental and a theoretical analysis have been conducted of the heat-straightening repair of composite steel bridge girders. Tests on full-size girders (W24 × 76) were conducted by simulating a composite deck-girder system. Damage was induced statically and the girders were heat-straightened using line and vee heats. The level of restraining force was varied to evaluate its effect on the progression of movement. Deformation measurements were taken after each heat to assess the effectiveness of the repairs. Outlined here is a methodology for conducting the heat-straightening repair. In addition, an analytical method is presented to determine (a) the residual moments existing after damage, (b) the maximum safe level of restraining force required, (c) procedures for relating the nominal restraining force to the actual moment created in the lower flange at the zone to be heated, and (d) the average amount of expected movement per heating cycle. With the procedures presented, an engineer can design the heat-straightening repair of composite girders and predict the number of heating cycles required. Of particular significance is that brittle cracking occasionally occurs during heat-straightening repairs. Such cracks occurred during the testing and can be attributed to either overjacking to produce high restraining forces or repetitively repairing redamaged girders. Guidelines are presented on how to avoid such cracking during repairs.

A typical type of damage found on steel bridges results from impact of vehicles or freight on the steel girders of composite deck-girder bridges. Heat straightening is an attractive repair alternative because of its low cost and minimal disruption of traffic. However, little information is available to guide either the bridge engineer or the heat-straightening technician on safe and acceptable implementation procedures. The purpose of this paper is to provide such a guide.

The available literature shows little quantitative research related to heat-straightening repair of composite deck-girder bridges. Moberg described a limited field investigation of the heat-straightening behavior of damaged bridge girders (*1*). Shanafelt and Horn addressed the general damage assessment of structures and suggested an approach for using heat straightening as one of several repair alternatives (*2*). A comprehensive summary of the state of the art of heat straightening given by Avent emphasized the lack of quantified engineering data on heat-straightening repair procedures and addressed myths about heat-straightening repair (*3*). To provide quantified data, Avent and Fadous initiated a study of the heat-straightening behavior of composite girders (*4*). Their experiments showed that the plastic rotations during repair increase in a fairly linear manner as a function of external loads until a certain level is reached beyond which the plastic rotations increase dramatically. Basic behavior and repair methodology were defined. However, several questions remain unresolved: Why do the girders sometimes crack during repair? How much jacking can safely be applied? Can movements be predicted analytically? One fundamental parameter that has been overlooked in previous studies is the internal redundancy of the structure. Often, the damaged steel member in the field displays an inherent redundancy due to its structural configuration, which imposes an internal constraint on the heat-straightening mechanism of the member. An understanding of this behavior combined with knowledge of the role of jacking forces in heat-straightening performance is needed to answer these questions.

This paper reports a detailed and controlled set of field experiments designed to provide a more comprehensive data base on the field behavior of damaged composite bridge girders. The objective was to quantify the heat-straightening behavior of composite bridge girders both analytically and experimentally. Emphasis was placed on studying the interaction of the internal redundancy with both the external restraining forces and heat patterns in relation to the heat-straightening process. A number of heat-straightening tests were conducted using two 20-ft-long, A-36 steel girders of different geometries (W10 × 39 and W24 × 76). Each girder was damaged and then repaired using the heat-straightening method. The level of jacking forces was varied in the course of repair to evaluate the effect of external restraining forces. After the experiments, analytical models and guidelines for conducting such repairs were developed.

TEST RESULTS

Some initial tests on composite deck-girder systems have been reported by Avent and Fadous (*4*). The tests described here are a continuation of that series. Details of the testing procedures and results of four test girders (SB-1 to SB-4) can be found in that work.

Damage was induced in the originally undeformed girders by applying a midspan static load transversely to the bottom flange in its own plane, creating a lateral plastic deformation of about 4.5 in. Typical damage is shown in Figure 1. Measure-

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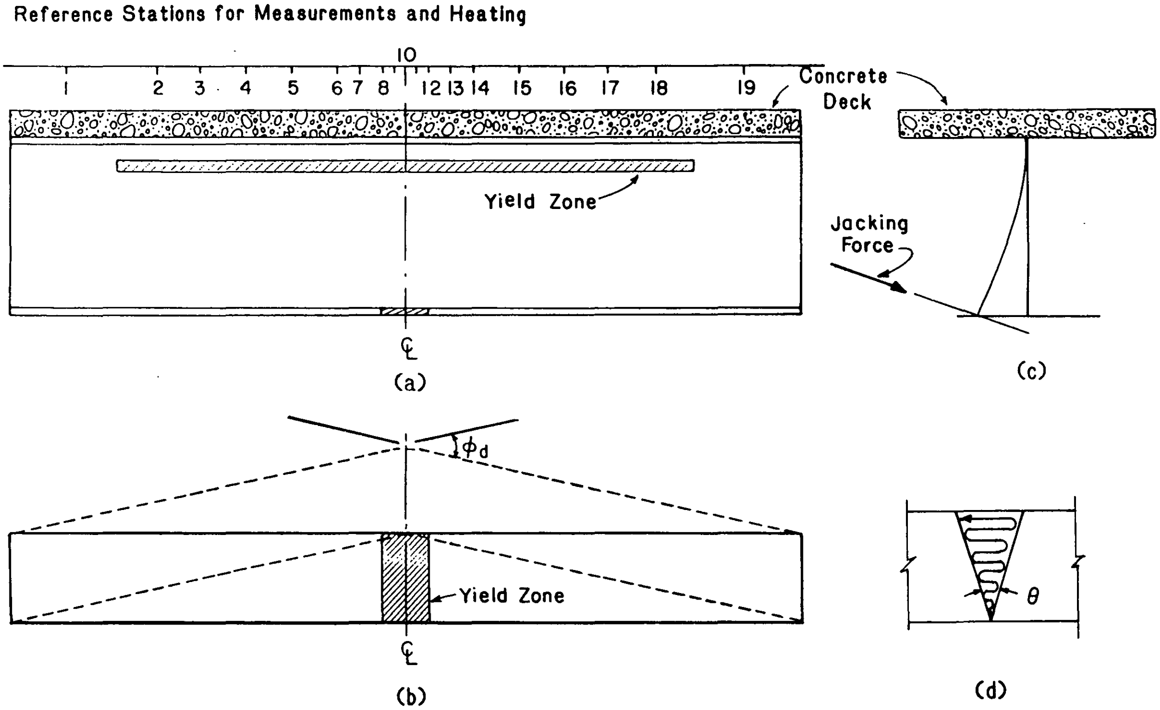

FIGURE 1 Deformed shape and yield zones in W24 × 76 girder: (*a*) front view, (*b*) bottom flange, (*c*) cross-sectional view, and (*d*) vee heat.

ments were taken, and the radii of curvatures at various locations were computed. Damage assessment revealed that the bottom flange had typically yielded as a long, flat plate in bending about its strong axis. Measurements showed that the web had plastically deformed as a flat plate in bending about its weak axis, thus producing a well-defined yield line.

Parameters Studied

Several fundamental parameters are associated with heat-straightening repair. Three heating patterns may be used: vee, line, and strip. The vee is the primary pattern and is shown in Figure 1*d*. The heating begins at the apex of the vee, and progressively the torch is moved in a serpentine pattern to the open end. The speed of the torch movement is such that the entire vee area is raised to the specified heating temperature. The vee angle is defined as θ. Jacking or restraining forces are often used to expedite movement. The moment produced by such forces at the vee, M (positive when acting to close the vee), divided by the plastic moment capacity of the plate or cross section, M_p, is defined as the load ratio. The line heat is formed by making a single pass of the torch in a straight line at a rate that progressively brings the temperature to the specified level along the line. The strip heat is a rectangular pattern heated in a serpentine motion similarly to the vee with the torch moved across the narrow width of the rectangle and progressively from one end to the other. This study was focused on evaluating the role of constraining forces to produce various load ratios in the heat-straightening repair of composite bridge girders. The term "constraining forces" refers to the external restraints as well as the internal redundancy of the member.

Laboratory studies on plates and rolled shapes have contributed a substantial amount of data to quantify the effect of external restraining forces on the heat-straightening response of such simple elements (*5*). However, because of the complicated geometry and boundary conditions involved, the analytical models developed on the basis of these data show serious limitations when used to forecast the response of full-scale composite girders. It has been conjectured that the indeterminacy associated with the structural configuration of these members affects their heat-straightening response. To test the hypothesis, a variable jacking force was applied to a series of test girders to evaluate the effect of external restraining forces and indeterminacy. The jacking force was applied to create a bending moment in the bottom flange about its strong axis in the vee heated region. The bending moment acts as a positive external constraint on the vee heat by impeding the longitudinal thermal expansion during the heating phase, increasing the upset and producing more contraction during the cooling phase. The heat-straightening response of the composite girder is quantified in terms of the angular movement of the bottom flange at the region of damage (the change in ϕ_d as shown in Figure 1 for each heat cycle). This movement is called the plastic rotation. These tests were, therefore, designed to evaluate the relationship between the load ratio and the plastic rotation for the given geometry of the girder.

Case SB-5: Third Damage and Repair of W24 × 76 Composite Girder

The same W24 × 76 girder, which was damaged and heat-straightened twice before, was damaged again (*4*). Damage was induced by statically loading the girder to obtain a lateral plastic deformation of 5 in. at the midspan.

Thirty heating cycles were conducted with three parameter variations. A 30-degree vee angle, three-quarter-depth vee, and heating temperature of 1,200°F were maintained throughout. The heat patterns consisted of vee heat in the plastically deformed portion of the bottom flange accompanied by a line heat applied to the yield line in the web.

The heat-straightening parameters used are shown in Table 1. The yield line on the web was heated first with the two operators moving a single-orifice oxyacetylene torch from each end toward the center. A short distance from the center, one of the operators discontinued the line heat and started the vee heat on the bottom flange. The other operator continued the line heat, with the result that both the vee and the line heats were completed simultaneously. The length of the line heat was adjusted in the subsequent heats to ensure that only those portions of the web were heated that still showed plastic curvature. The plastic rotations observed for the individual cycles are given in Table 1.

The first sequence was without a jacking force, and the other heat sequences were performed with a load ratio of 0.50. At the completion of nine heats of this sequence, it was observed that the web had developed considerable bulging about the minor axis in the lower half of its depth extending over a central span of 18 in. It was suspected that the longitudinal contraction in the heated bottom flange had created enough residual stresses in the unheated web to cause buckling. Because the girder had been damaged and straightened several times, the flange shortening had become significant. To alleviate the problem, it was decided to apply half-depth strip heats on the web at the location of the vee heat. The width of the strip heat was kept equal to the width of the vee at the flange fillet. Sequence 3 consisted of this modified pattern with a 0.5 load ratio. The application of the strip heats did not improve the plastic rotations. However, they were effective in relieving the buckling in the web. At the end of 10 cycles of Sequence 3, the girder was restored to practically its original configuration. The plastic curvatures in the bottom flange as well as the web were corrected. Only a minor local

TABLE 1 Summary of Experimental Results for SB-5 Under Influence of Each Heating Cycle

Heating Sequence (1)	Heating Cycle (2)	Vee Heat Location (point number) (3)	Line Heat Location (point number) (4)	Load ratio (M/M_p) (5)	Plastic Rotation/Vee radx10^3 (6)
1	1	10	2-18	0.0	9.221
1	2	11	2-18	0.0	3.740
1	3	10/11	2-18	0.0	3.158
1	4	10	2-18	0.0	4.240
1	5	9/10	2-18	0.0	2.328
1	6	9	2-18	0.0	2.827
1	7	10	2-18	0.0	4.658
1	8	11	2-18	0.0	-0.582
1	9	10/11	4-16	0.0	4.242
1	10	11	4-16	0.0	1.331
1	11	10	4-16	0.0	3.910
				Average	3.552
2	1	9	4-16	0.50	7.490
2	2	11	4-16	0.50	-2.164
2	3	9/10	4-16	0.50	8.823
2	4	10/11	4-16	0.50	3.830
2	5	9	4-16	0.50	5.579
2	6	10	4-16	0.50	5.247
2	7	9	4-16	0.50	2.998
2	8	11	4-16	0.50	5.331
2	9	9	4-16	0.50	1.499
				Average	4.005
3	1^R	10	5-15	0.50	4.415
3	2^R	9	5-15	0.50	1.999
3	3^R	9/10	5-15	0.50	2.999
3	4^R	10/11	5-15	0.50	5.582
3	5^R	10	5-15	0.50	9.165
3	6^R	9/10	5-15	0.50	-1.583
3	7^R	10/11	5-15	0.50	2.666
3	8^R	10/11	5-15	0.50	6.666
3	9^R	9	5-15	0.50	0.917
3	10^R	9/10	5-15	0.50	5.333
				Average	3.750

R - Rectangular heat applied to the web
x/y - Vee heat applied between points x & y

kink remained in the bottom flange at the center of damage. The local bulge was still discernible in the web because of the earlier buckling, but it was less severe.

Case SB-6: Fourth Damage and Repair of W24 × 76 Composite Girder

The same W24 × 76 girder was redamaged statically by a midspan jacking load as described. A permanent lateral deflection, 4.5 in. in magnitude, was obtained at the center of damage. The heating patterns and repair procedures were identical to those used in Sequence 2 of Case SB-5. The strip heats were not included in the heat pattern, because the damage had stretched the web to its unbuckled configuration. A load ratio of 33 percent was selected for evaluation to establish a pattern of variation in the heat-straightening response of the girder with this specific load ratio and compare the results with those obtained from the heat-straightening tests performed previously in the project by different operators under same load ratio. The purpose was to check for inconsistencies due to the human factor involved. Nine heating cycles were performed in this sequence. In the course of the ninth heating cycle, a crack, as shown in Figure 2, was formed on the convex side of the web yield line (which was not line heated), extending over a length of 5 in. The results from the ninth heating cycle were discarded. The reasons for the cracking will be discussed later. However, enough heating cycles had already been completed for evaluating the response of the girder under a 33 percent load ratio. The heat patterns and plastic rotations obtained as a result of the first eight heating cycles are shown in Table 2.

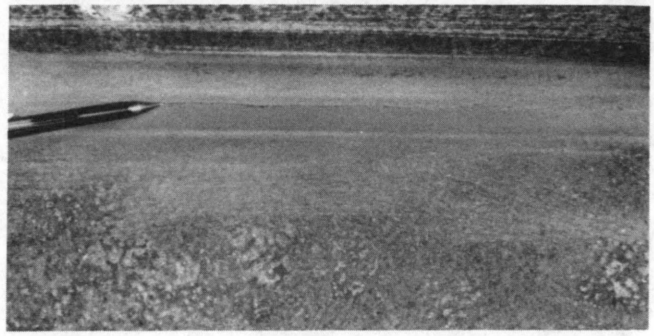

FIGURE 2 Crack in web of Girder SB-6.

Case SB-7: Damage and Repair of New W24 × 76 Girder

The newly installed W24 × 76 composite girder was damaged by a midspan static load to obtain the characteristic damage pattern. The repair was conducted using the previous methodology. The load ratio was increased to 75 percent. This load ratio was rather high and had seldom been used in laboratory studies. It was applied in an attempt to find the limiting load ratio that would replicate the hot mechanical straightening phenomenon encountered in the past studies on W10 × 39 composite girders. The sequence consisted of eight heating cycles. The plastic rotations achieved in the individual cycles are given in Table 2. As expected, the plastic rotations encountered in this sequence were abnormally high, averaging 11.474 mrad. Thus, the average plastic rotation increased by 124 percent on raising the load ratio from 50 to 75 percent.

TABLE 2 Summary of Experimental Results for SB-6 and SB-7 Under Influence of Each Heating Cycle

Heating Sequence	Heating Cycle	Vee Heat Location (point numbers)	Line Heat Location (point numbers)	Load Ratio (M/M_p)	Plastic Rotation/Vee radx10^3
(1)	(2)	(3)	(4)	(5)	(6)
SB-6					
4	1	10	2-18	0.33	8.235
4	2	9	2-18	0.33	4.243
4	3	10	2-18	0.33	6.075
4	4	10	2-18	0.33	6.659
4	5	11	2-18	0.33	4.829
4	6	10	2-18	0.33	2.082
4	7	9	2-18	0.33	4.164
4	8	11	2-18	0.33	2.248
				Average	4.817
SB-7					
5	1	10	2-18	0.75	20.367
5	2	10	2-18	0.75	8.736
5	3	10	2-18	0.75	8.904
5	4	10	2-18	0.75	10.823
5	5	9/10	2-18	0.75	6.412
5	6	9	2-18	0.75	11.661
5	7	11	2-18	0.75	13.413
				Average	11.474

x/y - vee heat applied between points x and y

Most surprisingly, this beam fractured during the eighth heating cycle. The crack initiated on the convex longitudinal edge of the bottom flange at the point of application of the vee heat as shown in Figure 3 and continued over a length of 1 in. to the apex of the vee. Causes for this cracking will be discussed later.

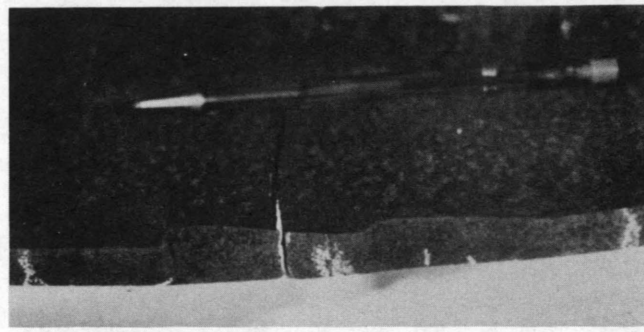

FIGURE 3 Crack in bottom flange of Girder SB-7.

EVALUATION OF FACTORS AFFECTING HEAT-STRAIGHTENING BEHAVIOR OF COMPOSITE GIRDERS

Heat Patterns

The term "heat patterns" refers to the combination and layout of vee heats, line heats, and strip heats used to conduct the heat-straightening repair. Conceptually, vee heats are used to repair plate elements with plastic bending about the major axis, while line heats are applied to repair plate elements with flexural damage about the minor axis. Hence, a vee heat on the bottom flange in conjunction with a line heat on the top flange, applied to their respective plastically yielded portions, is the proper heat pattern to repair such a damage.

Care was taken to continually adjust the span of the line heats, so that only those portions of the web were heated that showed plastic curvatures after the last heating cycle. Similarly, it was ensured that the vee heats were confined to the portion of the bottom flange with plastic deformations.

An important modification introduced in this study was the inclusion of a half-depth web strip heat during one sequence. The purpose of this heat was to reduce the differential shortening between web and flange. By heating the web with a half-depth strip, the web can deform and relieve some of these stresses. The application of strip heats on the web in Sequence 3 did not influence the average plastic rotations appreciably. However, it did tend to reduce the buckling of the web near the center of damage.

Restraining Forces

The simplest way of providing constraining forces is to allow the unheated metal within the member to restrict thermal expansion by using a suitable heat pattern (as in the case of a vee heated plate). This is a form of an internal constraint. Internal constraint may also be imposed by the self-weight, axial loading, or statical indeterminacy of the member. Frequently, external restraining forces are used to complement or even substitute for the internal constraints required for the heat-straightening phenomenon. The importance of restraining forces in the heat-straightening process has been recognized in the field for many years. Hence, jacking forces have often been used to enhance the heat-straightening repair of a wide range of damaged structural steel members. These tests were designed to evaluate the effect of external restraining forces on the heat-straightening behavior of such members.

Figure 4 shows the plots of the applied load ratios (based on actual tensile coupon yield stress) versus average plastic rotations for various heat sequences conducted here as well as composite girders tested by Avent and Fadous (*4*). A trend was noted in these and earlier tests that the first few heating

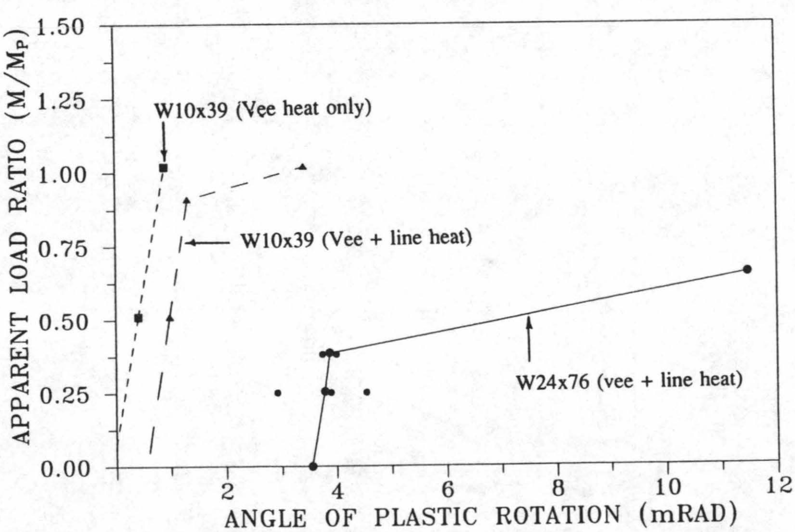

FIGURE 4 Apparent load ratio versus angle of plastic rotation on tested specimens.

cycles produced significantly larger plastic rotations than the subsequent heats. Since about 10 heats were used in the current tests as opposed to 20 in the previous, an accurate comparison of average plastic rotation necessitates considering only the first 10 heats in all cases. The average values for each load ratio were connected with a straight line. As shown in Figure 4, the load ratio–versus–plastic rotation curves exhibit a sharp discontinuity at higher loads. This behavior will be explained later.

Internal redundancy affects the heat-straightening response of a composite girder. Caused by the interaction of the bottom flange and the web, this interaction produces redundant forces at the web-flange interface that impede the plastic rotations by acting as a negative internal constraint to the vee action in the bottom flange. A comparison of the load ratio–versus–average plastic rotation curves (Figure 4) reveals that the lower portion slopes of both curves were almost equal. This implies that for the same increment in the load ratio, both the shallow and deep beams exhibit an equal increase in the plastic rotation. However, for zero or any given load ratio, significantly large plastic rotations were encountered in case of the deeper beam. It may be concluded that the redundant forces produced by the web-flange interaction in composite girders inhibit the straightening effect more in a shallow beam than in a deep beam. The damage to the composite girder produces plastic curvatures in the web about its minor axis along the yield line. This plastic deformation resists any elastic bending of the web about its minor axis during the straightening process of the bottom flange. Hence, the presence of the yield line in the web tends to magnify the counterproductive redundant forces and further inhibits the straightening effect of the bottom flange vee. By using a line heat on the web along with the vee heat in the bottom flange, these inhibiting forces are mitigated. This conclusion was verified in an appraisal of the influence of the web line heat on the heat-straightening response of the composite girder by Avent and Fadous (*4*).

When applying a lateral load to the bottom flange near the center of the composite girder, the moment produced is transferred to the end reactions by two mechanisms: the bottom flange acts as a flexural beam supported at the ends, and the web acts as a flexural plate (and, at large deformations, a membrane plate) supported by the deck and end diaphragms. A shallower girder would be expected to have greater stiffness and thus smaller lower flange moments than that of the deeper girder subjected to the same lateral load. The data tend to verify this observation since the load ratio has less effect on the shallow girder. By adopting a load ratio definition with the plastic moment of the bottom flange by itself in the denominator, the implication is that most of the load transfer is through the bottom flange. With the W10 × 39 composite girder showing relatively small plastic rotations at load ratios greater than 100 percent, it is obvious that the web carries a significant portion of the jacking force. A primary question then becomes, How is the distribution of jacking forces between the flange and web to be determined?

Stiffening Effect of Web

Normalizing the load ratio to the plastic moment capacity of the bottom flange is misleading if the web interaction effects are significant. That fraction of the total bending moment that is distributed to the bottom flange provides external restraint to the vee heat. Hence, the load ratio as defined earlier for a composite girder does not reflect the moment in the bottom flange and may be considered only as a nominal load ratio. It is more relevant to calculate the load ratio using this fractional bending moment, called the effective load ratio.

Hot Mechanical Straightening

A large increase in plastic rotations was observed using Sequence 5, when a nominal 65 percent load ratio was applied to the W24 × 76 composite girder. The average plastic rotation obtained for this load ratio was almost three times the value extrapolated from the straight-line fit through the data points for the lower load ratios. Similar observations were made in the previous study (*4*) for the W10 × 39 composite girder. However, the shallow girder that was studied exhibited this digression at a higher nominal load ratio of 135 percent. The past studies on the temperature characteristics of steel have shown that the yield stress of steel decreases with increasing temperature. It is known from these studies that a heating temperature of 1,200°F may reduce the yield stress in an A-36 steel member to as little as a third of its original value. Thus, the elevated temperatures associated with heat-straightening enable the member to yield at the relatively low stresses produced by the external jacking forces. In effect, during hot mechanical straightening of a steel member, the jacking forces are merely pushing the member mechanically because of the reduced yield stress. Such straightening occurred at the higher jacking forces for the test girders.

Cracking

An unusual phenomenon observed in the course of these experiments was the cracking in the girders subjected to heat-straightening. The crack that appeared in Beam SB-6 occurred during the fourth damage and repair cycle. It occurred in the web parallel and adjacent to the line heat. The crack also corresponded to the tension side of the web with respect to the application of the jacking force. It has been observed that the yield stress increases and ductility decreases dramatically after more than two damage-repair cycles. The implication is that the stress-strain characteristics become similar to brittle materials. It has also been found that high residual stresses occur in areas of concentrated heats such as the apex of the vee. Line heats are similarly concentrated. It is therefore concluded that repetitive damage combined with high residual stresses led to a brittle failure.

The crack in SB-7 occurred under quite different circumstances. The beam cracked during the first damage-repair cycle on the tension side of the bottom flange (as defined by the applied jacking force). An unusually high jacking force was used (75 percent nominal load ratio). Similar fractures have also been reported during field repairs. The probable cause was the high jacking force combined with the somewhat reduced ductility due to the heating and the residual stresses, which may tend to increase the total stress above ultimate. This behavior reinforces the concept that the jacking forces should be evaluated analytically and never applied without a gauge to control the magnitude. Recommendations for maximum jacking forces are given in a later section. Adhering to these recommendations will greatly reduce the likelihood of brittle cracking. Should such cracking occur, the heat straightening must be stopped and the crack repaired. One procedure is to cut out the crack zone and weld the slot with a full penetration weld. Then continue the heat straightening. An alternative for cases in which welding is deemed inappropriate is to finish the heat straightening with the crack present. Then a splice plate can be bolted to the flange for load transfer across the crack.

THEORETICAL MODEL FOR HEAT-STRAIGHTENING RESPONSE

Modeling of Simple Span Composite Girders

The theoretical modeling developed in this section requires an effective stiffness to be developed from which the actual moment in the bottom flange can be computed in terms of a distribution factor. The effective load ratio can be computed by multiplying the nominal load ratio with the flange distribution factor, 1γ, for the composite girder.

In terms of stiffness factors, this relation can be expressed as

$$K_e = \gamma K_f \quad (1)$$

where

K_e = effective stiffness of composite girder associated with lateral load applied to bottom flange,
K_f = flexural stiffness of bottom flange alone about its strong axis, that is $(4EI_f)/\ell$, and
γ = proportionality factor.

The distribution of moment to the flange will be proportional to the stiffness factors, thus

$$\frac{M}{K_e} = \frac{M_f}{K_f} \quad (2)$$

where M is the apparent moment associated with the applied lateral load and M_f is the actual moment in the bottom flange. Using Equations 1 and 2

$$M_f = \frac{K_f}{K_e} M = \frac{1}{\gamma} M \quad (3)$$

For a concentrated load at the midpoint, the moment for a simply supported beam, $M = P\ell/4$, can be related to lateral deflection, Δ, in terms of effective stiffness, K_e, as

$$M = 3\, K_e \frac{\Delta}{\ell} \quad (4)$$

The lateral deflection, Δ, was measured for known applied loads so that K_e could be determined experimentally. For the W10 × 39, the distribution factor $1/\gamma$ was determined to be 0.183 and for the W24 × 76, $1/\gamma = 0.427$. Using these factors, the ratio of plastic rotation versus effective load was plotted in Figure 5 for the experimental results.

For the purpose of design, it can be assumed that the distribution factor $1/\gamma$ varies linearly with the ratio of girder depth to web thickness. From theoretical considerations, the upper bound for the stiffness modification factor is infinity, which corresponds to a girder of zero depth. The lower-bound value of the factor is 1.0, which corresponds to a free plate. A bilinear plot can be used to approximate this relationship in the form

$$\gamma = 9.74 - 0.136 \frac{d}{t_w} \geq 1.0 \quad (5)$$

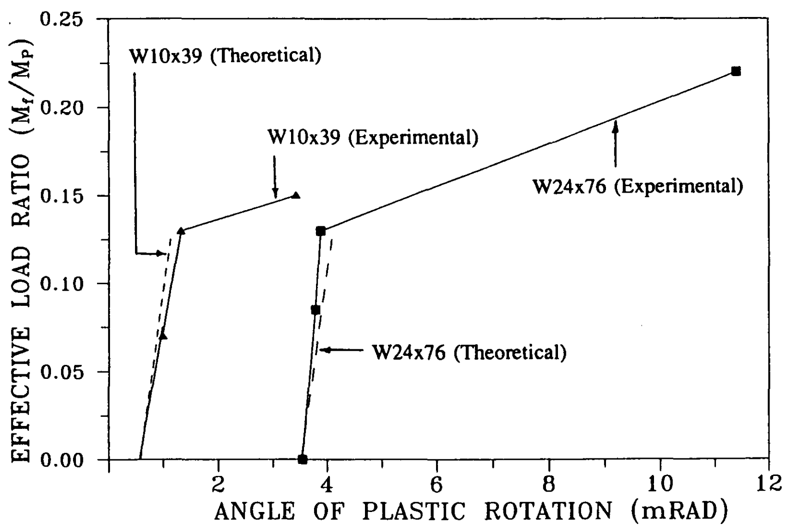

FIGURE 5 Effective load ratio versus angle of plastic rotation on tested specimens.

A model for plastic rotation in a composite girder can be based on the simple plate formulation by Avent (*6*). He assumed that longitudinal plastic strains occur only in the central two-thirds of the vee zone and that they are constant; planes defined by the sides of the vee lines remain plane after the heating-cooling cycle and rotate about the apex of the vee; confinement during heating is perfect, single-axis in the longitudinal direction.

The effect of the internal constraint in the composite girder can be modeled by making the following assumptions:

- The internal constraint in the bottom flange of a composite girder varies linearly with depth-to-thickness ratio (d/t_w) of the web, Equation 5; and
- The internal constraint in a composite girder with a d/t_w of 37 equals that in an isolated vee heated plate element.

From these assumptions, a simple formula can be written for evaluating the plastic rotations in the bottom flange of a composite girder:

$$\phi_{comp} = F_t(T)\, F_l'(M)\, \varepsilon_p(T) \sin\frac{\theta}{3} \qquad (6)$$

where

ϕ_{comp} = plastic rotation in bottom flange of composite girder,
θ = vee angle,
F_l' = modified load ratio function = $0.9 + 0.1[(d/t_w) - 37] + 3.4(M_f/M_p)$,
$F(T)$ = temperature function = $F_t(T)$ = $0.5 + 0.00125(T - 750)$, and
$\varepsilon_p(T)$ = confinement function = $\varepsilon_p(T) = (.001T^2 + 6.1T - 415)\,10^{-6} - \left[\frac{(-720{,}000 + 4{,}200T - 2.75T^2)}{806(500{,}000 + 1{,}333T - 1.111T^2)}\right]$

For the standard heating temperature of 1,200°F, Equation 6 reduces to

$$\theta_{comp} = 0.00792\left[0.9 + 0.1\left(\frac{d}{t_w} - 37\right) + 3.4\left(\frac{M_f}{M_p}\right)\right]\sin\frac{\theta}{3} \qquad (7)$$

The theoretical plastic rotation for the W10 × 39 and W24 × 76 composite girders was superimposed on the experimental plots in Figure 5 in which effective flange moment ratio was the ordinate. Excluding the load ratios associated with the hot mechanical straightening phenomenon, the analytical formula fits the available experimental data very well.

The experimental evidence indicates that the degree of plastic rotation per heat cycle is proportional to the magnitude of the restraining force up to a certain limit. For higher forces, the behavior becomes nonlinear with increased plastic rotations, as illustrated in Figure 5. This phenomenon is attributed to a combination of (a) the jacking forces creating stresses greater than the reduced yield stress in portions of the heated zones (often referred to as hot mechanical straightening), and (b) the spreading of the yield zone and the associated redistribution of moments. Since little evidence exists as to the safety of such high jacking forces, a load limit is advised.

It is recommended that an approximate limiting value of the jacking force be estimated from the data presented here. Since the W10 × 39 and W24 × 76 composite girders represent a wide range of section geometries, a conservative value can be chosen from the two cases. It is also recommended that the effective load ratio in the heat-straightening of composite girders be limited to 12.5 percent. The corresponding limiting nominal load ratio can be obtained for the specific girder by multiplying this value by the stiffness modification factor (γ) for that girder.

Modeling Statical Indeterminate Spans Due to Intermediate Diaphragms

An important consideration for composite girder repair is the residual stresses associated with both the damage and the repair. For diaphragm-braced girders, a lateral force into the lower flange can be approximated as a continuous beam over interior supports. The result of the damage inducement process is the creation of residual moments. These moments can be computed by first performing a plastic analysis on the continuous beam to determine the ultimate load (impact force), P_u, and the plastic moment diagram, M_u. A modified stiffness of $K_e = \gamma K_f$ can be used for these computations. The second step is to take the computed P_u, apply in the opposite direction, and compute the elastic moment diagram, M_e. Finally, the superposition of these two moment diagrams yields the residual moment distribution, M_r, due to the impact loading. These residual moments may either aid or hinder heat straightening depending on their directions. The jacking forces may be applied to produce the desired level of moment at the zone of heating. The moment in the heating zone of the bottom flange, M_f, can be expressed as

$$M_f = \frac{1}{\gamma}(M \pm M_r) \qquad (8)$$

where M is the nominal moment resulting from the application of the jacking force (computed from an elastic analysis of the continuous beam previously described). Once the flange moment is computed, Equation 7 can be used to predict the movement per heat. Note that the movement associated with each heat will reduce the residual moment proportionally to the decrease in deflection. Thus, the jacking moment must be adjusted after each heating cycle to reflect the change in residual moment. When the diaphragms are damaged on impact and require replacement, the structure may be considered as determinate. However, in many cases, the diaphragms remain undamaged and the redundancy must be considered.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Reported here are the results of a study on heat-straightening repair of damaged composite steel bridge girders. Three full-size girders were tested. Combined with previous test results, the pattern of behavior for composite girders has been documented for a wide range of parameters. A recommended repair procedure has been used; it can be summarized as follows:

1. Visually or by measurements, determine the yield zone in both the flange and web.
2. Compute the restraining force required for the heat-straightening repair. It is recommended that the maximum effective load ratio on the bottom flange be limited to 12.5 percent of M_f/M_p. A good approximate method for determining M_f is to use the d/t_w to compute the distribution factor from Equation 5. For a simply supported span without diaphragms, the moment computation can be based on simple beam statics and divided by the reduction factor, γ. For girders with diaphragms, an indeterminate analysis can be conducted in which the girder is considered as a beam over continuous supports as represented by the diaphragms. Again, the reduction factor γ is used.
3. Conduct the repair by heating the web yield line (usually from each end simultaneously) and subsequently vee heating the bottom flange with a full-depth vee with apex pointing in the direction of desired movement. Temperature should be limited to 1,200°F. The expected movement per vee heat can be predicted from Equation 7.
4. After cooling, repeat the heating procedure taking care to shift the vee over the width of the yielded lower flange zone. Continue until the girder is straight.
5. Local bulges, buckles, and crimps frequently occur along with the overall damage. While not addressed in this study, such damage can be repaired in conjunction with the overall straightening.

Several cautions should be emphasized in conducting such repairs. First, excessive jacking forces can lead to brittle cracking in the heated zone of the flange. Jacking forces should be computed by engineering analysis and limited to 12.5 percent of the effective load ratio M_f/M_p. Jacking forces should always be monitored in field repairs. Second, repairing a girder by heat straightening more than twice may result in cracking in the flange or web. Third, heating temperature should be limited to 1,200°F.

Using the methodology described here, composite girders can be successfully heat straightened by incorporating engineering principles into the design of the repair. The methodology does not directly apply to noncomposite or open deck girders. However, similar procedures can be used (*6*). The method might not be applicable if the concrete has cracked and created a partially restrained condition. These conditions must be evaluated case by case.

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REFERENCES

1. K. L. Moberg. *Damage Assessment and Contraction Straightening of Steel Structures*. Master's thesis. University of Washington, Seattle, 1979.
2. G. O. Shanafelt and W. G. Horn. *NCHRP Report 271: Guidelines for Evaluation and Repair of Damaged Steel Bridge Members*. TRB, National Research Council, Washington, D.C., June 1984.
3. R. R. Avent. Heat-Straightening of Steel: Fact and Fable. *Journal of Structural Engineering*, ASCE, Vol. 115, No. 11, 1989, pp. 2773–2793.
4. R. R. Avent and G. M. Fadous. Heat-Straightening Prototype Damaged Bridge Girders. *Journal of Structural Engineering*, ASCE, Vol. 115, No. 7, July 1989, pp. 1631–1649.
5. R. R. Avent, G. M. Fadous, and R. J. Boudreaux. Heat-Straightening of Damaged Structural Steel in Bridges. In *Transportation Research Record 1319*, TRB, National Research Council, Washington, D.C., 1991, pp. 86–93.
6. R. R. Avent. Designing Heat-Straightening Repairs. *Proc., National Steel Construction Conference*, American Institute of Steel Construction, Chicago, Ill., 1992, pp. 21–23.

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