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16. Abstract

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IMPLEMENTATION OF HEAT-STRAIGHTENING REPAIRS FOR LOUISIANA BRIDGES

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LOUISIANA TRANSPORTATION RESEARCH CENTER

December 1998

ABSTRACT

The goal of this study was to implement the latest heat-straightening repair technology on a Louisiana Bridge. The bridge chosen was an overpass just east of Lake Charles crossing I-10. Working with both state and district personnel, the bridge was repaired during August 1998. A facia noncomposite beam had been impacted and the bottom flange displaced 18 inches (0.45 m). The repair was designed by the LSU team and implemented in conjunction with DOTD personnel. Described in this report are the design of the repair, the step-by-step implementation, and a discussion of lessons learned. It is concluded that heat straightening is an effective alternative for repairing damaged steel bridges.

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IMPLEMENTATION STATEMENT

Previously, LTRC has funded research to develop engineered heat-straightening techniques for the repair of damaged steel bridges. The goal of this project was to implement the results of that research on an actual bridge. The repair project was conducted in conjunction with both state and District 7 personnel.

This project also complements a study sponsored by the Federal Highway Administration (FHWA). The goal of the FHWA project is to develop training materials on heat straightening. These materials include: a technical guide and manual of practice, a video and a multimedia computer program on CD-ROM, which allows for interactive training. The multimedia program includes the Lake Charles bridge repair as a capstone case study. These materials will be distributed to state DOT's and other interested parties by FHWA.

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INTRODUCTION

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

The ability to repair damaged structural steel members in place, often without 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. The Louisiana Department of Transportation and Development (DOTD) used a heat-straightening contractor to repair at least one bridge prior to 1985. Although the contractor successfully straightened the bridge girders, there were no criteria as to whether the original material properties were restored. To learn more about the process, DOTD initiated research through the Louisiana Transportation Research Center. This research led to the quantification of the methodology, the identification of important parameters, and the means to insure that material properties are not compromised during repair.

The results of this research were reported in a series of technical publications by Avent and his research team [*1-9*]. In addition, a literature review of earlier heat-straightening research was published [*10*]. The results of the research were also utilized for a field repair in the state of Iowa [*11*]. To further demonstrate the utility of the research, the Louisiana DOTD identified a bridge in Lake Charles for heat-straightening repair.

OBJECTIVES OF RESEARCH

The objectives of this research project are to:

1. Conduct an inspection of the damaged bridge and analyze the types and degree of damage.
2. Design a heat-straightening repair scheme for the damaged bridge girder.
3. Implement the repair in cooperation with the DOTD Bridge Maintenance Division.

Document the repair for use as part of a Federal Highway Administration sponsored training program.

SCOPE

This project was a joint effort between LSU, the Bridge Maintenance Division and District 7. The LSU team analyzed the damage, designed the repair, worked with DOTD in conducting the repair, and documented the project. The Bridge Maintenance Division identified the bridge, assisted with the damage inspection and the conduct of the repair. District 7 assisted with the inspection, provided traffic control and assisted with the repair.

The repair was conducted over a two-week interval in August 1998. The bridge is a two-lane structure on a Parish road crossing I-10 just east of Lake Charles near mile marker 37 on the interstate. The damaged bridge is a non-composite deck-stringer superstructure. The overpass is approximately 33 ft. wide; has four spans supported by column bents; has five simply supported steel stringers supporting the deck; and the spans across each of the east and west bound lanes of the interstate are 75 ft. The accident occurred when over-height equipment on a flatbed tract-trailer impacted the fascia beam while traveling in the right, east bound lane.

METHODOLOGY

Introduction

The sequence and procedures of the repair project are described in this section. An initial site inspection was made to evaluate safety and stability. This inspection was followed by a detailed inspection where specific defects were measured. The data were used to analyze the damage. Based on the analysis, a repair plan was developed. Finally, the repair was executed according to this plan.

Initial inspection and evaluation for safety and stability

The initial inspection indicated that the bridge remained stable. The lower flange had displaced approximately 17 inches at the impact point (fig. 1). Impact occurred on the lower flange directly over the center of the right, eastbound lane (fig. 2). Located six feet to the left of diaphragm number 2, the flange had a sharp dimple where the impact occurred (fig. 3). Diaphragms 2 and 3 were partially crushed but most bolts remained intact (fig. 4). Very minor crushing was observed at diaphragm 4. No significant damage was found at the end diaphragms, 1 and 5, or at the bearing supports. The top flange had pulled out of the slot on the underside of the concrete deck and had a maximum lateral deflection of 1.5 inches (fig. 5). The concrete deck had not cracked. Since there was no immediate safety concerns and the overpass was lightly traveled by local traffic, the bridge remained open to traffic.

Detailed inspection for specific defects

Progression of damage and primary locations. The progression of damage is illustrated in figure 6. At the impact point, the lower flange began to displace laterally with a plastic hinge forming as it translated and rotated. The lower flange behaved similarly to a beam continuous over supports, with the diaphragms acting as supports (fig. 6a). The force from

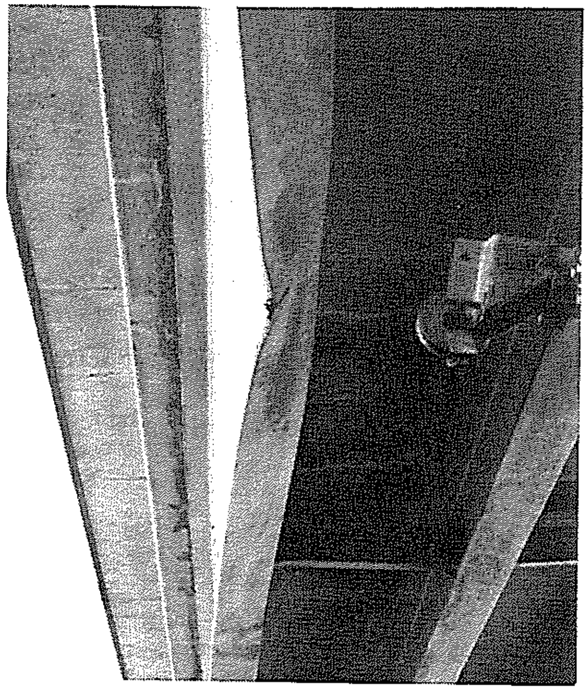


Figure 1
View of damaged beam at region of impact

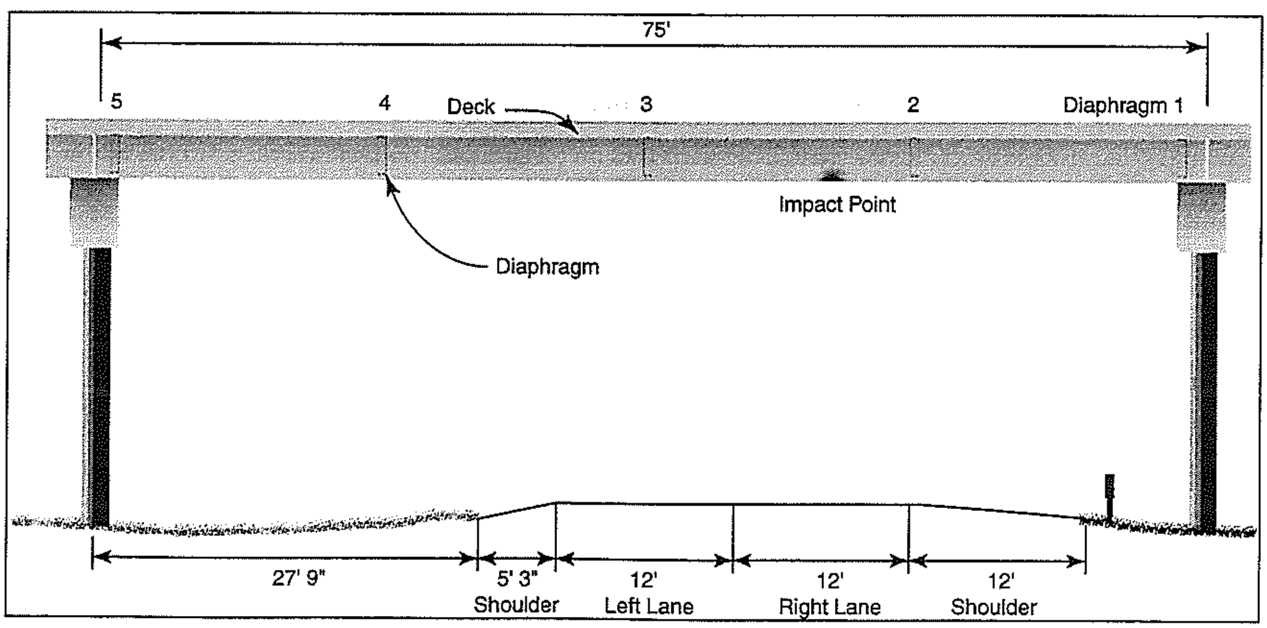


Figure 2
Roadway cross section at damaged span

Figure 3
Point of impact

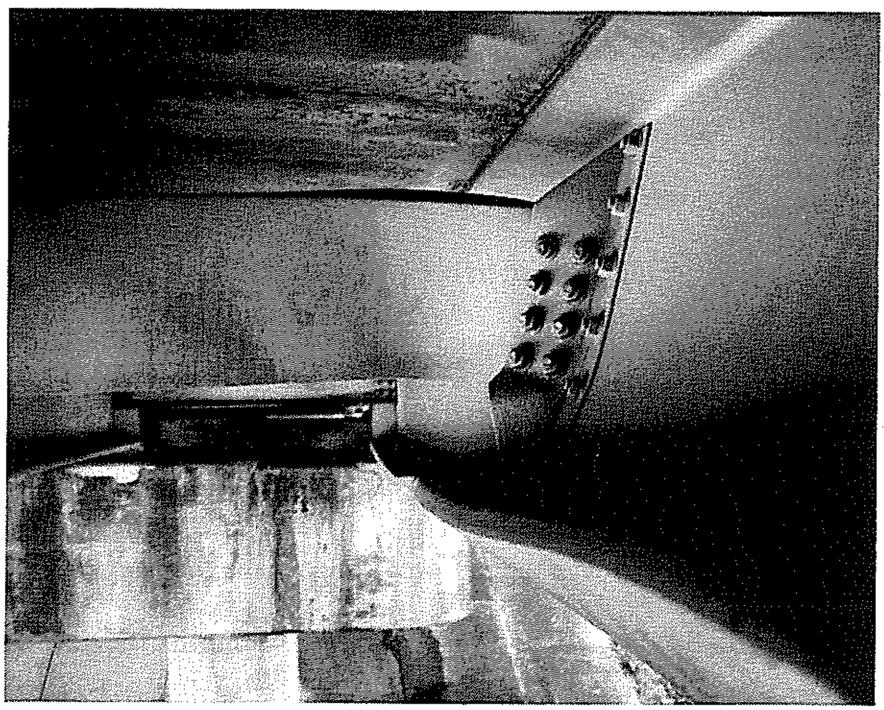


Figure 4
Damage diaphragm number two

Figure 5
Top flange pulled out of slot

impact was translated to the adjacent diaphragms causing them to partially crush (fig. 6b). However, enough resistance was maintained to produce reverse curvature bending at diaphragms 2, 3, and 4. Consequently, plastic hinges also formed in the lower flange at these points (fig. 6c). In addition, a small zone of yielding occurred between diaphragms 1 and 2. As the diaphragms crushed, the beam rotated and produced flexural yielding in the web in addition to web bulges at the diaphragms.

Measurement of damage. The primary areas of inelastic damage were: lateral bending of the bottom flange, localized damage to the lower flange at the impact point, and web bulges at the diaphragms along with bending of the web. Offset measurements were used to quantify damage. A taut line was stretched from end-to-end of the beam, and lateral offsets were measured at 3-foot (ft.) increments for both the upper and lower flange. The transverse slope of the bottom flange was also measured at key locations. Offsets were used to measure lateral web movement. In areas of web bulges, measurements were taken on a grid pattern of six inches both

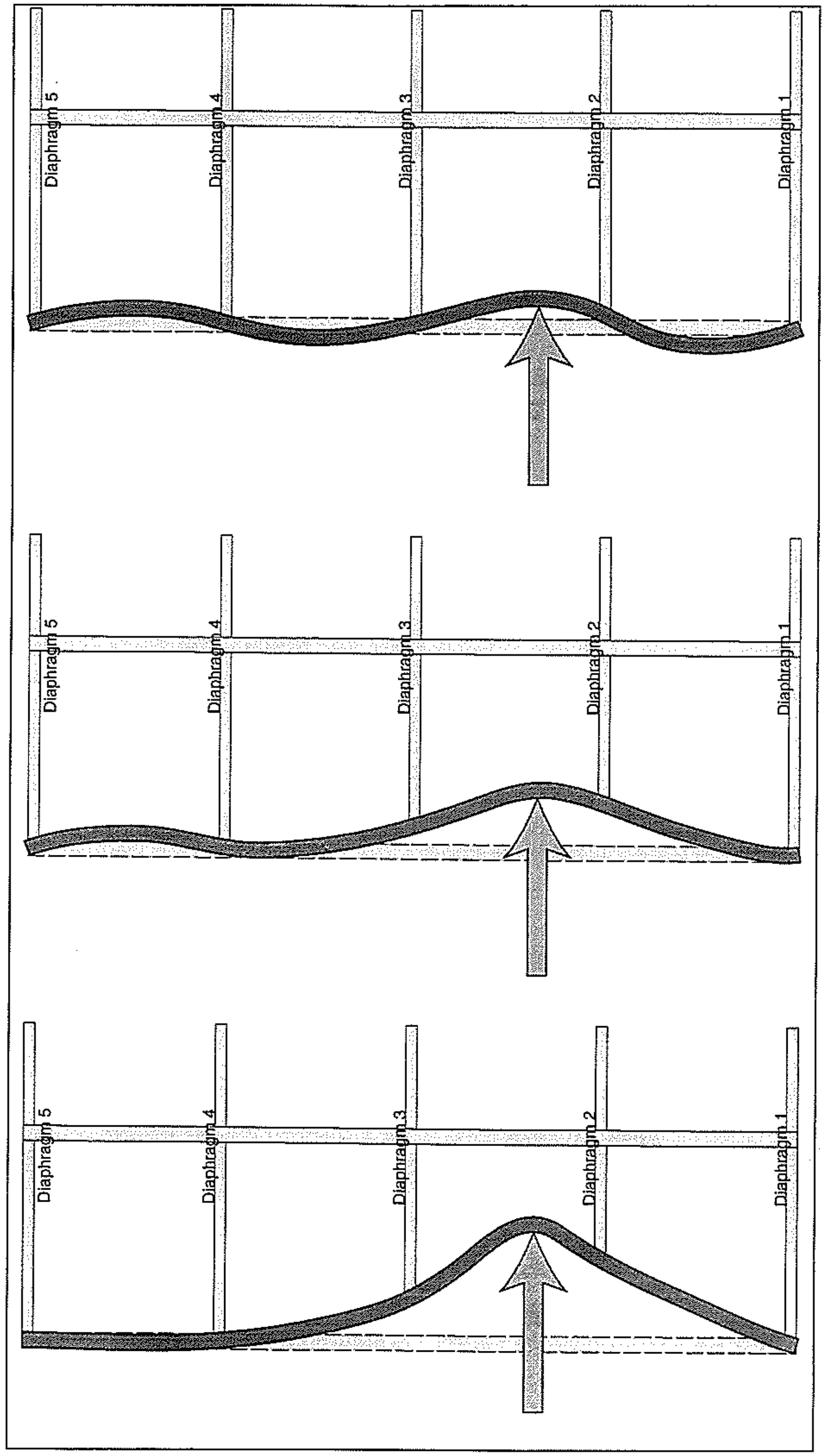


Figure 6
Stages of lower flange movement during impact

horizontally and vertically. All web movements were referenced to the fillet of the top flange. In zones of large localized strains such as the impact point, a contour gauge was used to obtain a continuous measure of curvature. Finally vertical movement was measured with reference to the underside of the concrete deck.

Analysis of damage

Lower flange. The most serious damage occurred on the lower flange. The offset measurements were used to compute the strain ratio (actual strain to yield strain) based on the use of three offsets at a time. The formula for converting offsets to strain ratio is given by:

$$\mu = \frac{E y_{max}}{R F_y} \tag{1}$$

where

$$\frac{1}{R} = \frac{y_{r-1} - 2y_r + y_{r+1}}{L^2} \tag{2}$$

Since offsets were taken at 3-ft. increments over the 75-ft. span, the 26 stations (including the end points) can be used to compute strain ratios at each of the 24 interior measuring points. Yield zones in the lower flange occurred at diaphragms 2, 3, and 4 as well as the impact point. In addition, a small yield zone occurred about half way between diaphragms 1 and 2. The yield zones and strain ratios are shown in figure 7. Referring to the bending moment at the impact point as negative, the length of this yield zone is approximately 5.5 ft. The moment reverses to positive at diaphragm 2, with the length of the yield zone being approximately 6.5 ft. At diaphragm 3 the yield zone moment is positive and is about 14 ft. long. Diaphragm 4 has a positive moment yield zone that is about 7.5 ft. long. The yield zone between diaphragms 1 and 2 is positive with a length of 4 .5 ft. Note that the magnitudes of the strain ratios are relatively

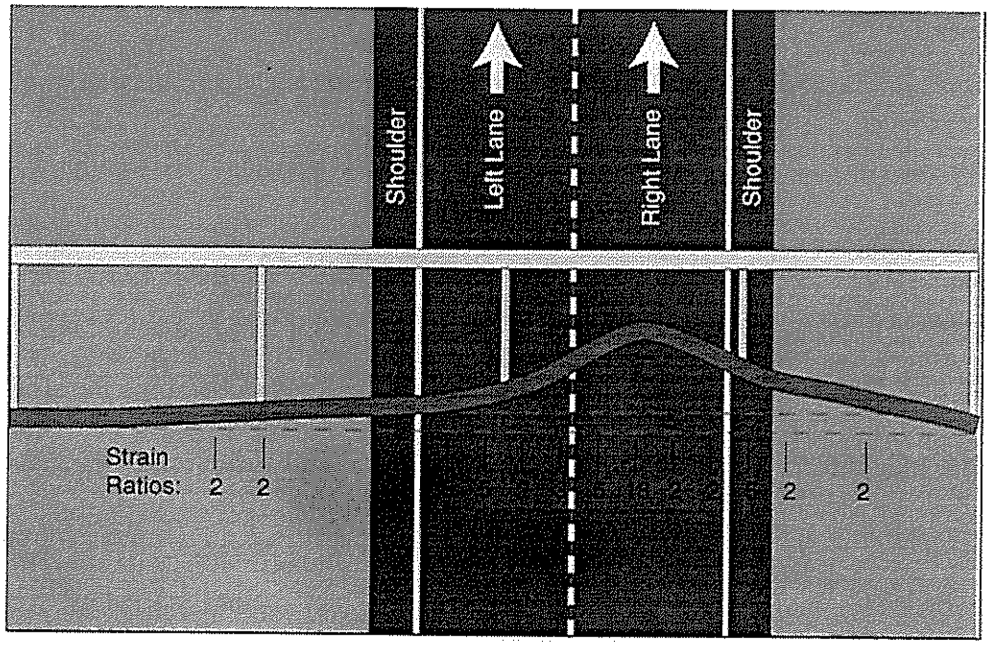


Figure 7a
Strain ratios for lower flange

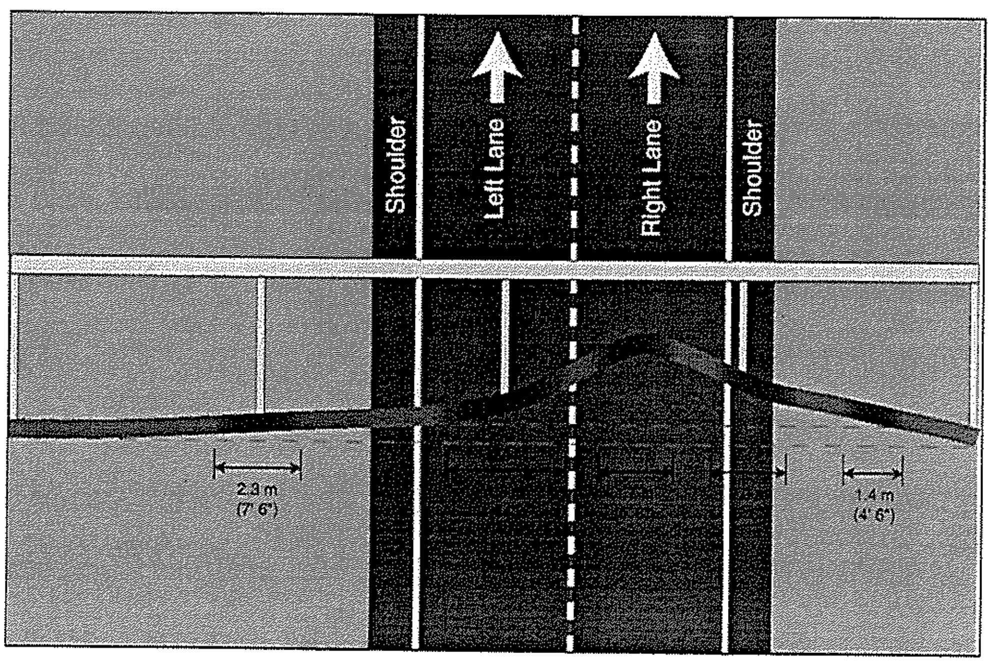


Figure 7b
Yield Zones for lower flange

small (five or less) except at the impact point where the actual strain exceeds the yield strain by a factor of 18. These ratios are well below 100 and are thus repairable. The degree of damage was measured graphically by extending tangents from the elastic portions and measuring the angle of the tangents. At the impact region as shown in figure 8, the degree of damage is 11.7 degrees or 204 milliradians. The degree of damage at the diaphragms is considerably smaller as shown.

Upper flange. Similar computations were made for the upper flange where minor yielding occurred at the diaphragms. The results are shown in figure 9.

Web and flange bulges. The offset method was also used to compute the strain ratios of the web and flange bulges as shown in figure 10. The maximum strain ratios are much less than 100 and are repairable with one exception. At the impact point (fig. 11), a sharp hump was made over about a four inch length. This damage was very localized and the transitions were smooth. However, the maximum strain ratio at this hump was 394, which greatly exceeds recommended limits for heat straightening.

Web flexural. In addition to the web bulges, there was flexural yielding of the web as it bent to accommodate lower flange movement. Frequently, this type of movement results in clearly defined yield lines. However, in this case, the web flexure resulted in a yield zone of plate bending. The only other significant damage was to the diaphragms. No measurements were taken since it was decided to replace the diaphragms.

Design of the heat-straightening repair plan

Select heating patterns for each region. The first phase was to focus on the lower flange and web bending. To correct this damage, vee heats were used on the lower flange yield zones and line heats in the web yield zones. Since there were no distinctive yield lines in the web, a series of line heats were used. Several key aspects must be considered in designing the

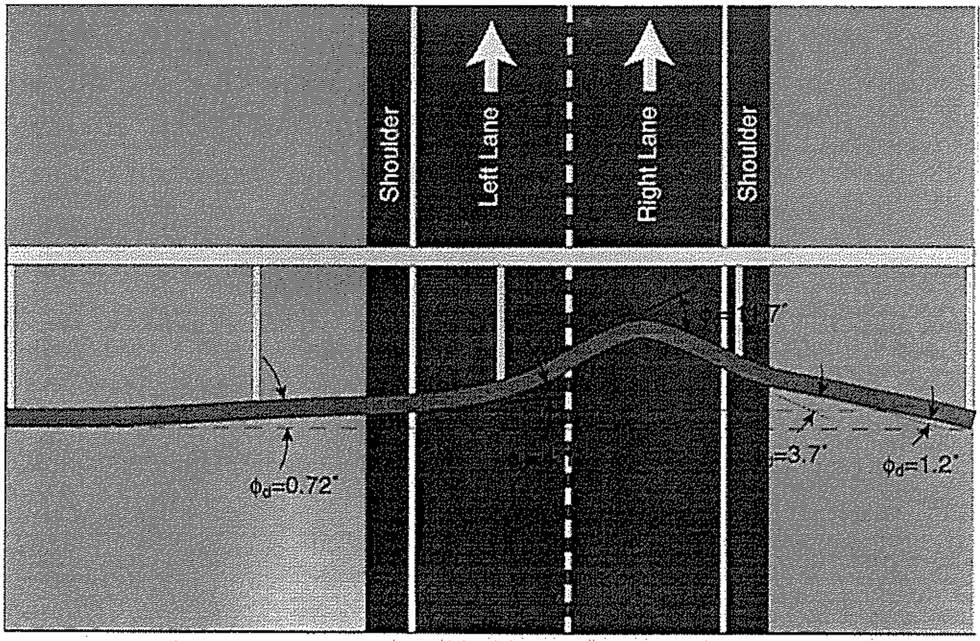


Figure 8
Degree of damage for each yield zone of lower flange

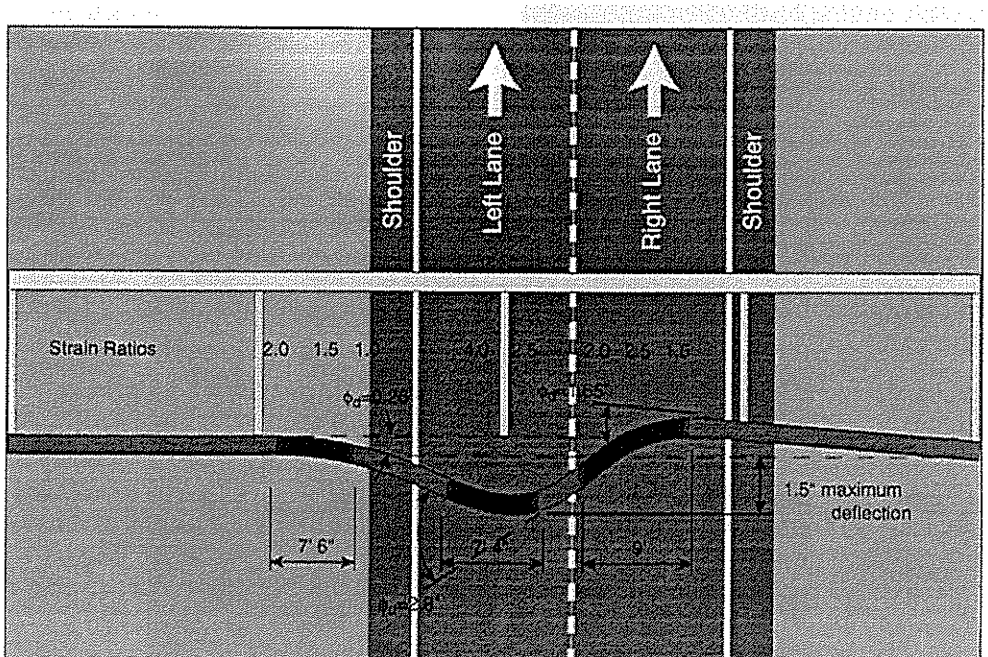


Figure 9
Degree of damage at each yield zone for lateral movement of upper flange

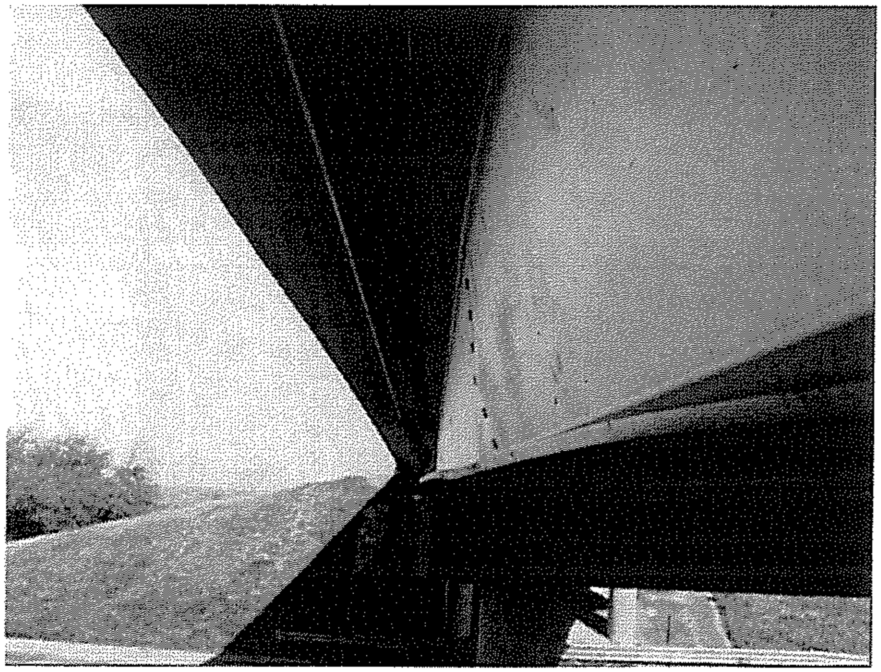


Figure 10
Localized web and flange damage

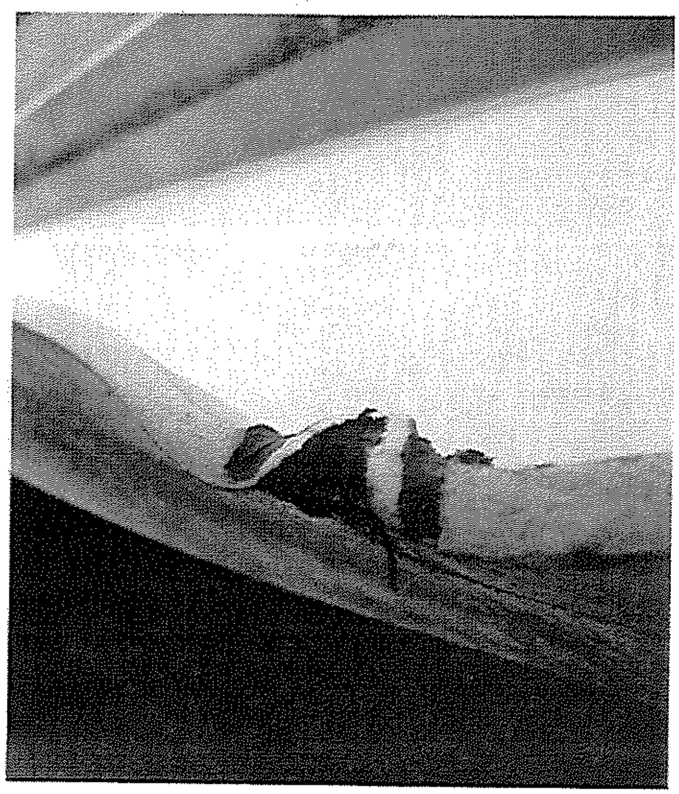


Figure 11
Deformations at lower flange impact point.

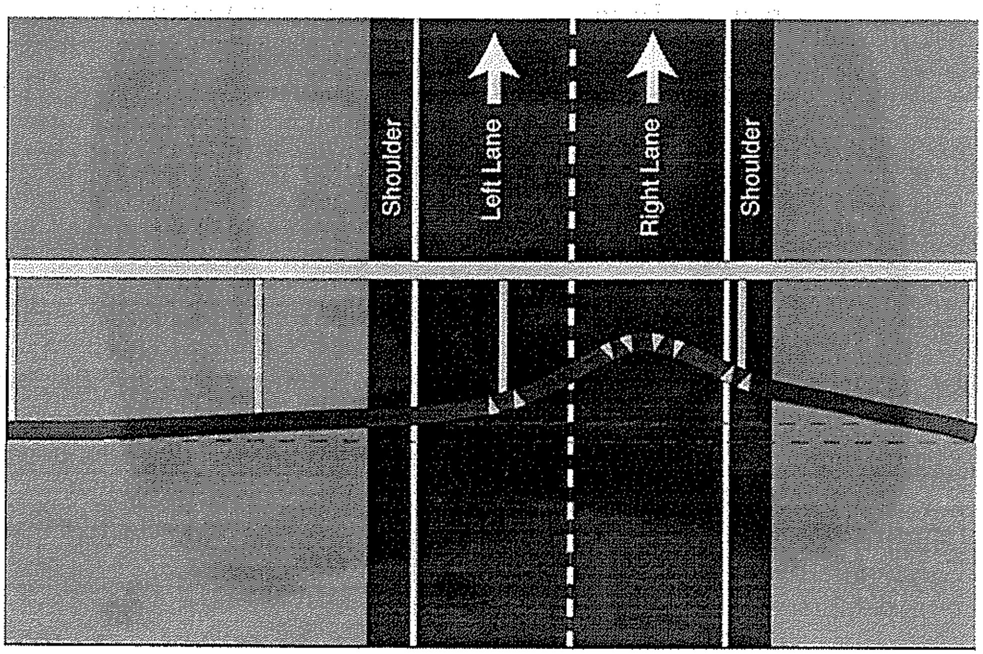


Figure 12
Lower flange heating pattern if both lanes of I-10 could be closed

vee heat pattern and sequence: the direction of flange bending, the sequence of heating so that one lane of I-10 remains open at all times, and the sequence for removal of the damaged diaphragms. The general principle is to begin heating at the zone of greatest damage (in this case the point of impact) which requires closing the right lane. The schematic drawing of figure 8 depicts the lower flange deflections to an exaggerated scale. It is obvious that the zone at impact has the greatest curvature. The orientation of the vee is such that the apex should always be at the edge damaged in compression. Multiple vees may be used if the spacing is equal to or greater than the flange width. If the diaphragms were kept in place, vees could also be simultaneously heated at diaphragms 2 and 3 giving the heating pattern shown in figure 12. However, heating at diaphragm 3 would require closing the left lane also. Since one lane had to be kept open, this approach was not an option. If the flange at diaphragm 3 is not heated simultaneously with the impact point and diaphragm 2, straightening will be constrained by flexural resistance at diaphragm 3. Therefore, it was decided to remove diaphragms 2 and 3. The vee heats could then be applied at the impact point and at the reverse curvature at diaphragm 4 as shown in figure 13. Since this diaphragm was over the median, traffic would not be hindered. By using this heating pattern along with web line heats as described in another section, movement will progress as illustrated in figure 14. As the curvature at the heated zone straightens, the curvature at diaphragms 2 and 3 will remain unchanged, since these locations undergo rigid body motion. The flange at the diaphragms will tend to move past its original location. As a result, this heating pattern will become proportionally less effective since the unheated webs at diaphragms 2 and 3 will tend to progressively restrain movement. Because the degree of damage at diaphragm 4 is small, the flange at this point should straighten sooner than the flange at the impact point. Therefore, after each heating cycle, the flange straightness at diaphragm 4 should be checked. Once it is straight, the vee heats at that point should be eliminated and diaphragm 4 removed. The vee heats at the impact point can be continued. When the flange at diaphragm 3 moves past its original position, a different flange-heating pattern is required. With diaphragm 4 removed, the vee heats are applied at diaphragm 3 (fig. 15) until that zone is straightened. This pattern requires that the left lane be closed and the right lane re-opened. Again, as straightening progresses, the web tends to offer increasing resistance to movement. Due to rigid body rotations, the unheated zone at the impact point increasingly deforms as shown. The next step is to vee heat the flange at diaphragm 2 (fig. 16), which means re-opening the left lane and closing the right lane. As the zone at diaphragm 2 straightens, additional rigid body motion increases the deflection at the zone of impact. Finally, the impact point is again vee heated to complete the lower flange straightening (fig. 17). The deflections at the yield zone between diaphragms 1 and 2 are so small that the recommended tolerance of _ inch in 20 ft. is not exceeded. Therefore, no heats were applied to this section. Due to the web-flange juncture, the web will restrain the flange movement unless heated. Therefore, after any vee heat a strip heat will follow. The strip should begin at the web-flange juncture and extend 12 inches up the web. Its width will be one-half the open end of the vee. The strip heat should be located directly above the vee.

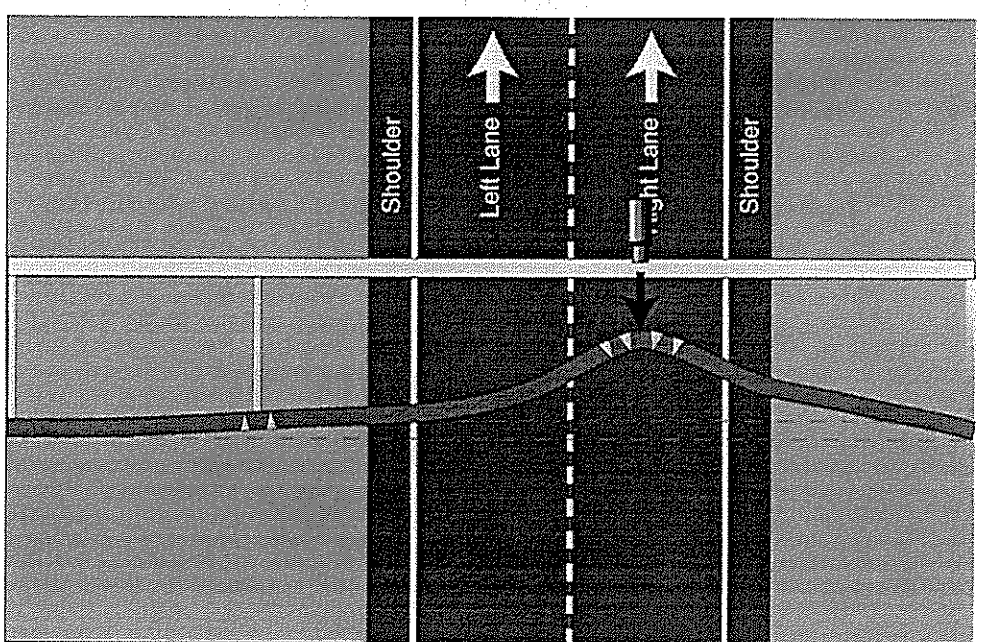


Figure 13
Lower flange heating pattern with left lane remaining open

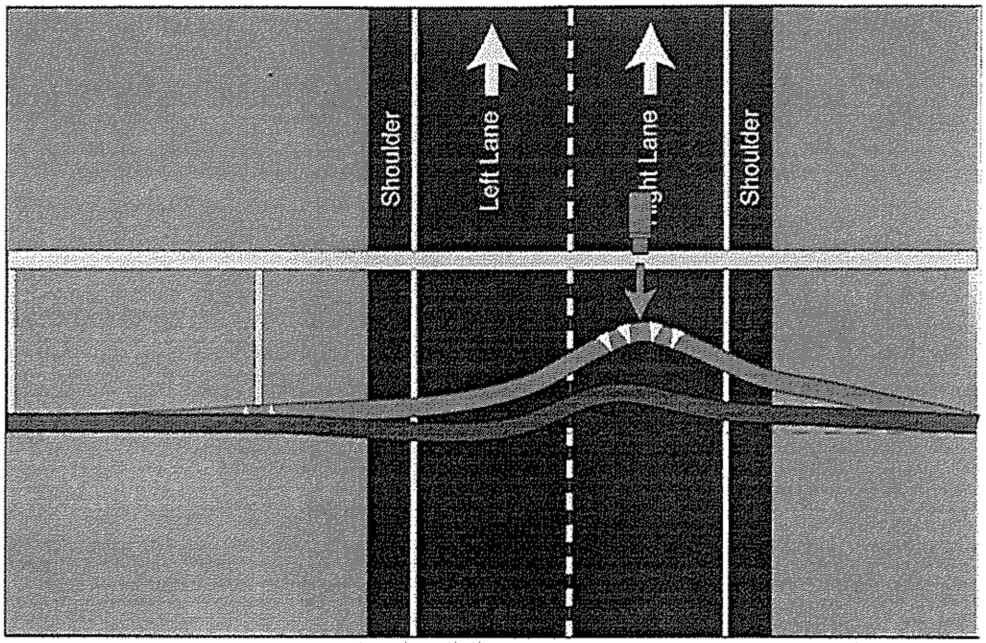


Figure 14
Lower flange movement after the initial heating phase

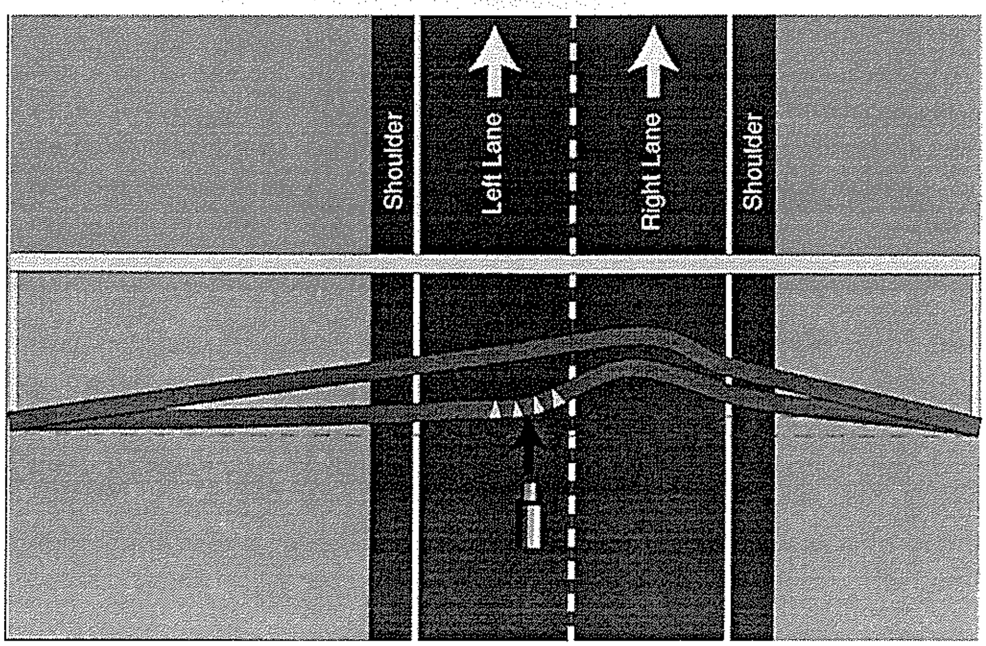


Figure 15
Heating pattern at diaphragm three and expected movement in second stage of repair.

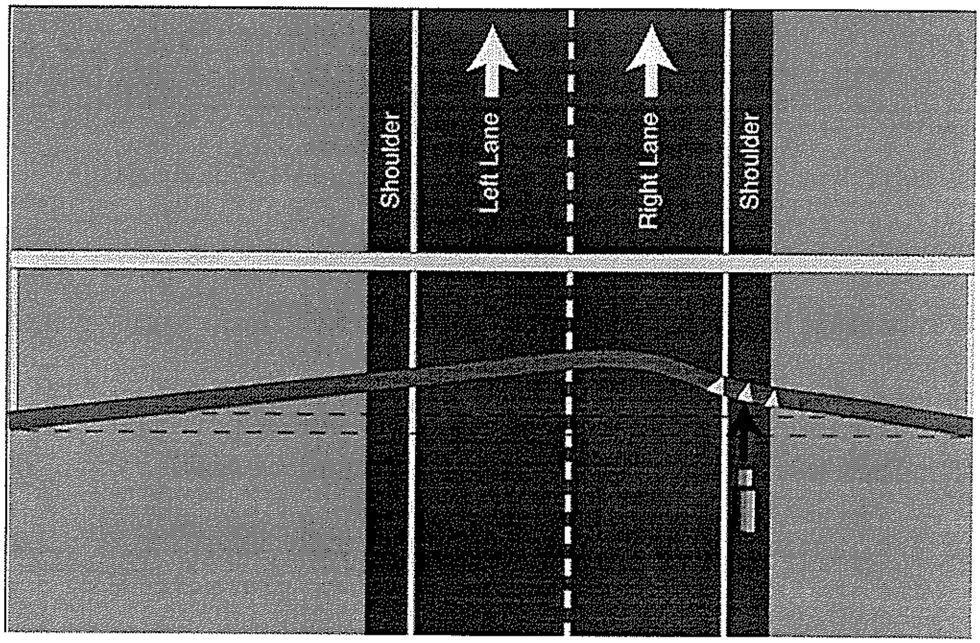


Figure 16
Heating pattern at diaphragm two and expected movement in third stage of repair.

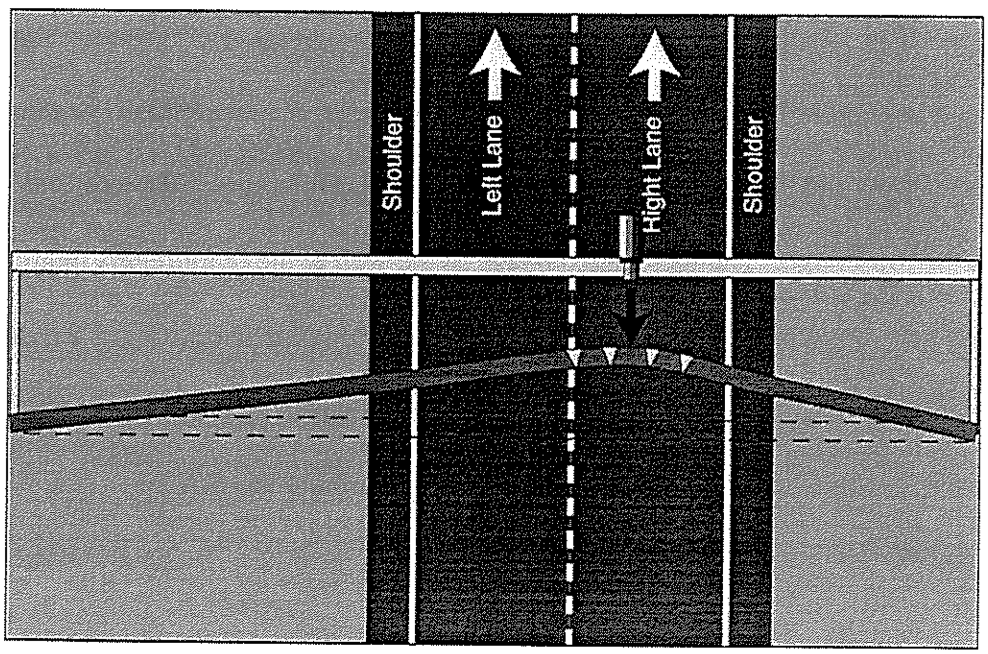


Figure 17
Heating pattern and expected movement in the final stage of vee heats at the impact zone

This overview of the flange movement due to vee heats is incomplete without a discussion of the accompanying line heats and jacking forces. Web line heats in conjunction with the vee heats are necessary to insure that the web straightens with the flange. A pair of line heats is appropriate for each cycle. The use of more line heats per cycle would require too much cooling time prior to the lower flange vee heats. During successive cycles, the pair of lines should be shifted to the region of the web with the largest remaining curvature. The contour gauge measurements, taken at the web-diaphragm intersections, were used to compute the maximum strain ratio values by the offset method. Part of this yielding pattern was local bulging and part was bending due to lower flange movement. The maximum strain ratios are shown at each diaphragm in figures 10 and 11 with the line indicating the axis of bending for each value. During heat straightening of the damage in the lower flange and web, some elastic rebound will occur in the top flange. It was decided not to heat the top flange until the remainder of the repair was complete. If the final lateral deflection of the top flange meets tolerance requirements, no heating would be required. This behavior did in fact occur, so that using the tolerance standards of _ inch over 20 ft., the final deflection rebounded to within tolerance. Therefore, no heats were required on the top flange. The localized damage in the web at the diaphragms requires a series of line heats spaced over the bulge areas. Since the magnitudes of these bulges are small, the bulge heat straightening should occur last. Because the bulges extend over the depth of the web and are narrow, the line heating pattern will be an ellipse around the perimeter and a series of horizontal and vertical lines across the bulge as shown in figure 18. The extent of the yield zone was identified visually. The localized flange damage at the impact point should only be partially straightened. Line heats can be used to straighten the flange except at the notch itself. As shown, the strain ratio is greatly in excess of 100. It was decided to leave this notch and grind any discontinuities smooth. The line heat pattern is shown in fig. 19.

Determination length and location of line heats. The procedure for straightening general flexure of the web is to place the two line heats at the locations of largest curvature. The lines should extend over the length of the web yield zones. The length of the web yield zones varied as previously described. The line heats are shifted over the yield zone on successive cycles. In addition, as the web straightens progressively from the lessor-damaged ends toward the center, the line heats can be shortened.

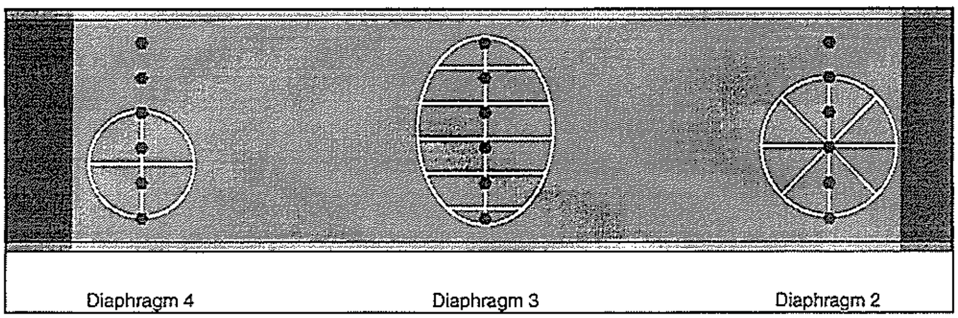


Figure 18
Typical heating patterns for web bulge at diaphragms

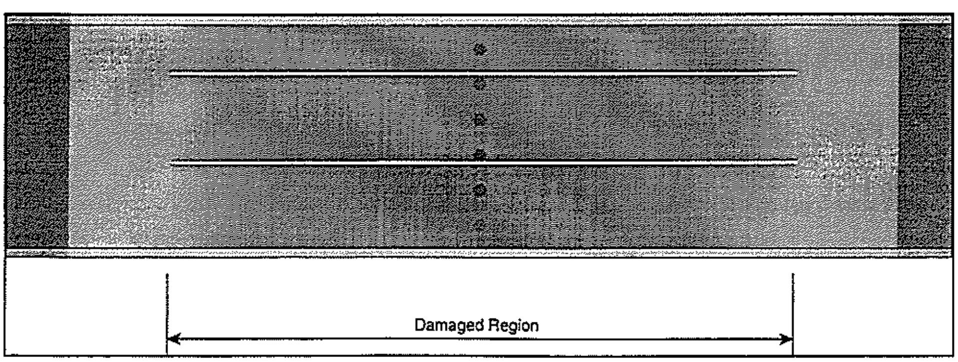


Figure 19
Line heat pattern for local damage at lower flange impact zone

Top flange. The top flange had small lateral displacements in comparison to the bottom flange. There was small positive curvature yielding in the vicinity of diaphragm 4 and at the impact zone. Likewise, reverse curvature bending and yielding occurred at diaphragm 3. Most of the upper flange movement was elastic and the three yield zones had modest strains above the yield values. Once the lower flange was straightened, it was expected that the top flange would be with in tolerance and no heating would be required. In fact, this event did occur. Prior to deciding on heating patterns, the vertical movement should also be evaluated since the beam is noncomposite with the deck. The maximum vertical displacement at the centerline was slightly less than three inches. The top flange pulled out of the deck slot between diaphragms 1 and 4. Four yield zones occurred with relatively small strains in excess of yield. In order to remove this vertical deflection by heat straightening, upward jacking forces would be required to compensate for the weight of the beam acting downward. The application of jacking forces was not practical due to traffic and cost considerations. It was therefore decided not to repair this vertical displacement but instead to grout the void between beam and deck after other heat straightening was completed. This alternative was viable because the roadway clearance was larger than required by standards for interstate highways.

Determine vee angles. Since the flange is fairly thick (1.5 inches), relatively narrow vees will allow for heating of the entire vee area before significant cooling occurs. Full depth vees were chosen with the vee width equal to four inches. This geometry produces a vee angle of 13.8 degrees.

Development of constraint plan. The next phase was to develop the constraint plan. As previously described, the heat straightening of the lower flange requires a four step process. Different sets of jacking restraints are required at each location. Jacking forces at each step should be applied in a direction that tends to straighten the beam. The magnitude of the jacking forces should be limited so that the moment in the heated flange region does not exceed a moment of one-half the capacity, M_p. For the first step, vee heats are to be applied at the impact point and diaphragm 4. The appropriate location for the jacking force is at the impact point as shown in figure 13. The determination of the magnitude of the jacking force is complicated by several factors including the load application at the lower flange rather than at the center; the large deflections associated with the deformed shape; part of the upper flange between diaphragms 4 and 5 remaining in the concrete deck slot and thus being restrained; and stiffness of the supports. For lateral loads, the beam was modeled as simply supported at the ends and continuous over one interior support at diaphragm 4. To account for the interaction of the various complicating factors, an equivalent moment of inertia was obtained. First, the jacks were placed on the beam and the load-deformation response was measured at the jacking location prior to heat straightening. These measurements were then compared to theoretical values based on the beam model in which the full moment of inertia about the y-axis was used. The comparison gave an equivalent moment of inertia of $1.15I_y$. This same factor can be used to determine the maximum jacking force limit. The plastic moment capacity of the section about the y-axis equals the plastic section modulus times the yield stress, or 675 ft-kips. Taking one-half this value and proportioning to the theoretical moment diagram (fig. 20), the load to produce this moment is 31.7 kips. However, the experimental load-deflection measurements indicate that a portion of the load is not effective in creating the expected deflection and, consequently, moment. The maximum effective jacking force can thus be estimated by increasing the theoretical jacking force by the factor 1.15. The jacking force limit can therefore be calculated to be 36.5 kips. The use of a rational model correlated to a few field measurements is an effective way to establish realistic jacking force limits. A similar procedure was used to determine the equivalent stiffness and jacking force limits after the removal of the only remaining interior diaphragm, Number 4. For this case, field load-deformation measurements were taken at the center of the beam (diaphragm 3). The theoretical stiffness was computed to be 1.8 kips/inch and the measured stiffness was 3.04 kips/inch. Obviously, internal restraints, such as part of the upper flange remaining in the slot, resulted in a stiffer beam than the model indicated. An equivalent moment of inertia was computed to be 1.69 I_y. The theoretical jacking force to produce a moment of $M_p/2$ at diaphragm 3 was 18 kips. Using the equivalent stiffness, the actual maximum jacking force limit can be approximated to be 30.4 kips when applied at diaphragm 3 with all interior diaphragms removed. Depending on the heating pattern, jacking forces will be required at the impact point, diaphragm 2 (fig. 16) and diaphragm 3 (fig. 15), with all interior diaphragms removed. Using a simply supported beam as the model and an equivalent moment of inertia of 1.69, the maximum jacking force at each location can be computed as

P_{max} = 40.6 kips (diaphragm 2)

P_{max} = 36.5 kips (impact point)

P_{max} = 30.4 kips (diaphragm 3)

In summary, the sequential heating patterns and accompanying jacking forces are:

1. Jack at impact with diaphragms 2 and 3 removed.
2. Jack at impact with diaphragm 4 also removed. For both cases, the jacking force acts outward from the bridge.
3. Jack at diaphragm 3 with all interior diaphragms removed. The force is applied inward toward the bridge.
4. Jack at diaphragm 2 with all interior diaphragms removed.
5. Jack again at the impact point with all interior diaphragms removed.

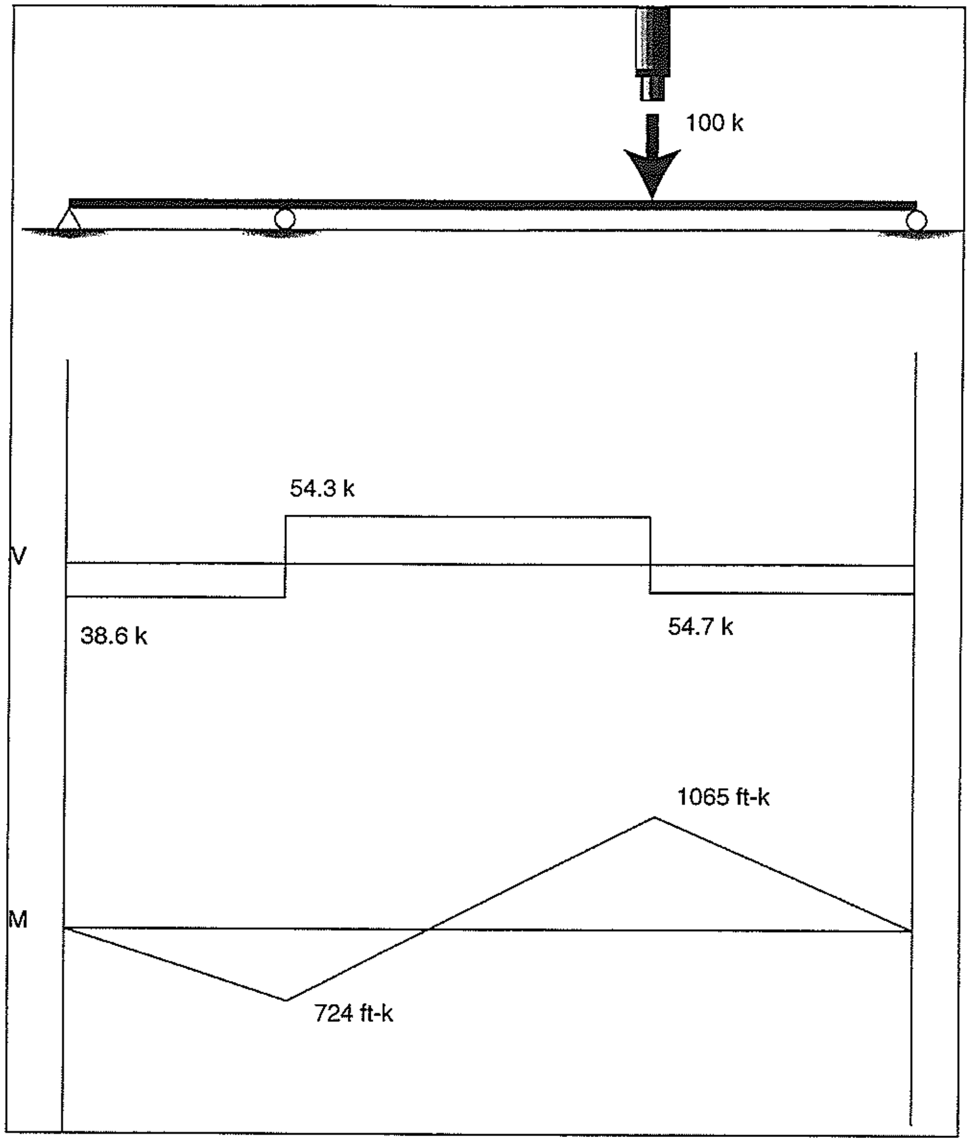


Figure 20
Moment diagram for a 100 kip jacking force applied at impact point

Estimate number of heat required. An estimate of the number of vee heats required to straighten the lower flange at impact can be obtained. However, available formulas do not specifically fit this case. An upper bound can be obtained by considering the lower flange as a plate and using the plate formula.

$$\varphi_p = F_\ell \varphi \quad (3)$$

where

$$\varphi = 0.0147 \sin\frac{\theta}{3} \quad (4)$$

$$F_\ell = 0.6 + 2\frac{M_j}{M_P} \quad (5)$$

Assuming a jacking ratio of 50 percent and a vee angle of 13.8 degrees, the number of vee heats required is 108. Assuming five simultaneous vees, 22 cycles of heating and cooling would be required. Another estimate can be obtained by considering the beam as a category W wide flange, symmetrically damaged about its weak axis. The equations for this case are given by

$$\varphi_p = F_\ell F_s F_a \varphi_b \quad (6)$$

where

$$\varphi_b = 0.0147 \sin\frac{\theta}{3} \quad (7)$$

$$F_\ell = 0.6 + 2\frac{M_j}{M_p} \quad (8)$$

$$F_s = 1 + \frac{1}{2}\left(\frac{b_s d_s}{d^2}\right) \quad (9)$$

$$F_a = 1 - 2\left[1 - \left(\frac{2}{3}\right)\left(\frac{Z}{S}\right)\right]\frac{M_j}{M_p} \quad (10)$$

Using these equations, the number of heats required is 68. Using five simultaneous vee heats, 14 cycles of heating and cooling would be required. The total number of heating cycles actually used at the impact point was 24 although a jacking ratio of approximately 40 percent was used during most heats. The maximum jacking ratios used at diaphragms 2 and 3 were 22 percent and

30 percent, respectively. Using the category W formula, the estimated number of heats at diaphragm 2 is 34. However, only 12 were required. At diaphragm 3, the estimate was 32 heats while 23 were used. The use of the plate formula gave an even higher estimate. These values suggest that during heating at the impact point, some residual moments were built up in the flange at diaphragms 2 and 3. The over-deflected deformed shape prior to heating at diaphragm confirms this probability. If the combined jacking force and residual moment effect was equivalent to a 50 percent jacking ratio, the predicted number of heats would be:

- 22 at diaphragm 2
- 24 at diaphragm 3

which are more consistent with the actual results. This behavior emphasizes the need to be sensitive to the buildup of residual moments during heating and to compensate with reduced jacking forces.

Steps in Conducting the Repair

Traffic control. The first step was to close one lane to provide a safe working area.

Equipment and safety precautions. The safety precautions and equipment will vary with each case. Of special interest here is that the damaged beam is noncomposite and that all interior diaphragms will be removed during the repair. This procedure produces a safety hazard in that beams have been known to fracture during heat straightening. The primary reason for such fractures is over-jacking. However, discontinuities and microscopic damage may be contributing factors. Should a fracture occur on a noncomposite beam without supporting diaphragms, the beam could fall into the traffic lanes. In order to preclude the possibility of an unstable beam after fracture, safety cables were attached on either side of the impact zone. The procedure began by closing the bridge to all traffic. The closure was possible because the overpass was lightly traveled and an alternate route was available. Two steel beams were placed transversely across the bridge to serve as strong-backs to support the cable attachments. 1_-inch diameter holes were drilled in the deck such that a cable could be looped around the damaged beam, passed through the deck, and looped around the strong back. A similar procedure was performed at the other end of the strong-backs and cables attached to an undamaged beam. Shims were placed under the strong-backs at the crown of the deck so that the strong back did not bear on the deck above the damaged beam. The cables attached to the undamaged bridge beam and strong back were tightened. The cables around the damaged beam were adjusted with enough slack to allow the damaged beam to straighten but tight enough to prevent the beam from dropping more than about six inches should a fracture occur (fig. 21). Since the overpass was closed, the fuel tanks were placed on the bridge and fuel lines dropped to the areas to be heated. Two trucks with lift platforms were used for access to the damaged girder. A series of jacks and pumps with calibrated gauges were used to apply jacking forces.

Initial heating at point of impact. Two rods, with a tape measure attached, were set on either side of the impact point so that the progression of movement during heat straightening could be measured. In addition, measurements were taken at the impact point after each heat. Prior to heating, jacks were set on each side of the impact point. Compression jacks with steel tube extensions were used with the upper fillet of the adjacent beam as a reaction. During the first heat, relatively low jacking forces were used. The ratio of M/M_p was initially 11 percent. After this heating cycle, the jacking ratio was increased to 22 percent. Prior to each heat, chalk was used to lay out the vee and line heat pattern. Typically, four simultaneous, full depth vees were used with a vee angle of 13.8 degrees. Note that the apex of the vee was located at the edge of the flange that had been damaged in compression. In addition, two line heats were used on the of the flange that had been damaged in compression. In addition, two line heats were used on the web. The location was initially taken at the zone of largest curvature and the heat applied to the convex side. The line heats were conducted first, starting with two torches at the ends and working toward the middle. Temperature sensing crayons were used to check the temperature level during heating. Once the line heats were completed, the vees were heated on the bottom flange. Starting the apex of the vee, heat was applied progressively across the vee. Again, the

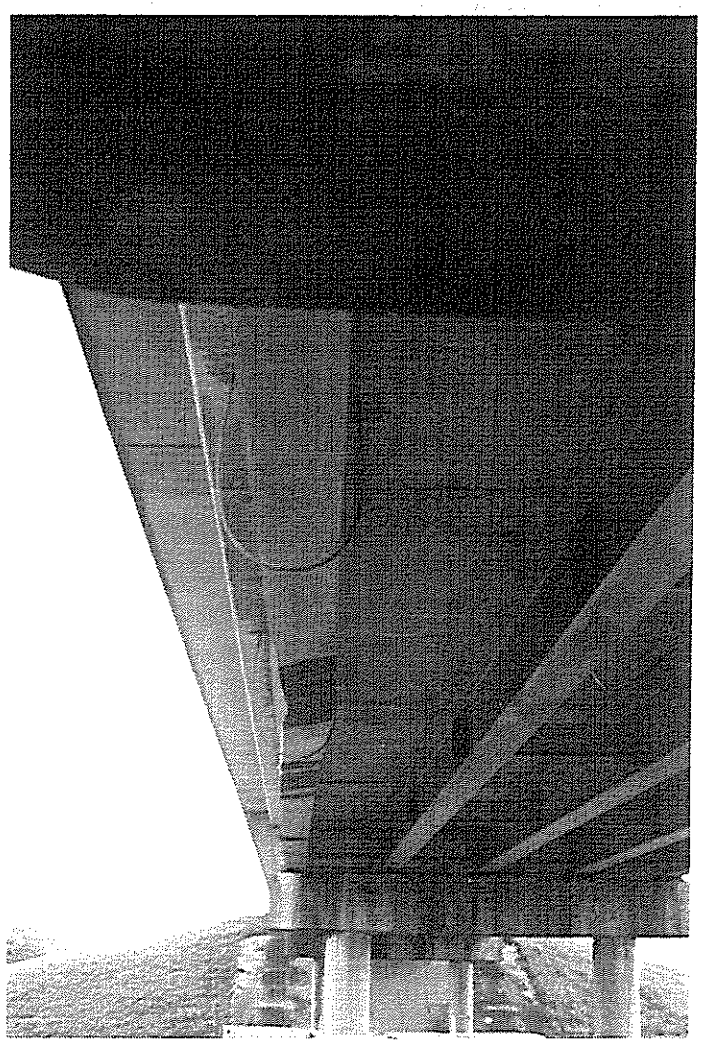


Figure 21
Safety cables around damaged beam during repair

temperature was checked with crayons. The web strip heat was then applied. At the same time, two simultaneous vee heats were applied to the lower flange at diaphragm 4. The vees were reversed in direction to reflect the reverse curvature bending. Successive cycles of heating were conducted using a jacking ratio of 22 percent. These vees were spaced with at least a distance equal to the flange width.

Heating at impact point after removal of diaphragm 4. After the sixth of these seven heat cycles, the flange at diaphragm 4 was straight. Diaphragm 4 was removed and heating continued. The jacking force was then increased to 44 percent and nine heating cycles were conducted. During this heating series, two jacks were placed between the top and bottom flange to provide assistance in the straightening of the localized flange damage. Short web line heats near the local flange damage were also used in this series. At the completion of this heating series the degree of damage at the impact zone had been decreased to approximately 4 degrees. The position of the lower flange at this stage is shown in figure 14. Note that the flange at diaphragms 3 and 4 has passed across its original position and now has deflected in the opposite direction.

Heating at diaphragm 3. At this point the heating equipment was moved to diaphragm 3. The jacking forces had to be applied inward toward the bridge, requiring the use of tension jacks. Two hydraulic jacks capable of exerting tension forces were used. These jacks had a center hole through which a rod could be inserted and a tension device rigged. Chains were hooked to each end of the jack and attached to the lower flange of both the damaged flange and the adjacent undamaged flange. Since the diaphragms of the undamaged beams were still in place, they provided a reaction by distributing the force over all the undamaged beams. The maximum jacking force exerted by each jack was limited to nine kips. Thus, a jacking ratio of

30 percent was used. Five cycles of heating were conducted. For each cycle, five simultaneous vees were used. The vees were distributed over the yield zone and spaced at least a flange width apart. Line heats were not applied to the web in this case. The flexural bending of the web was negligible and only the bulge remained. After five heating cycles, this section of the flange was straight. The configuration of the flange after this stage is shown in figure 15.

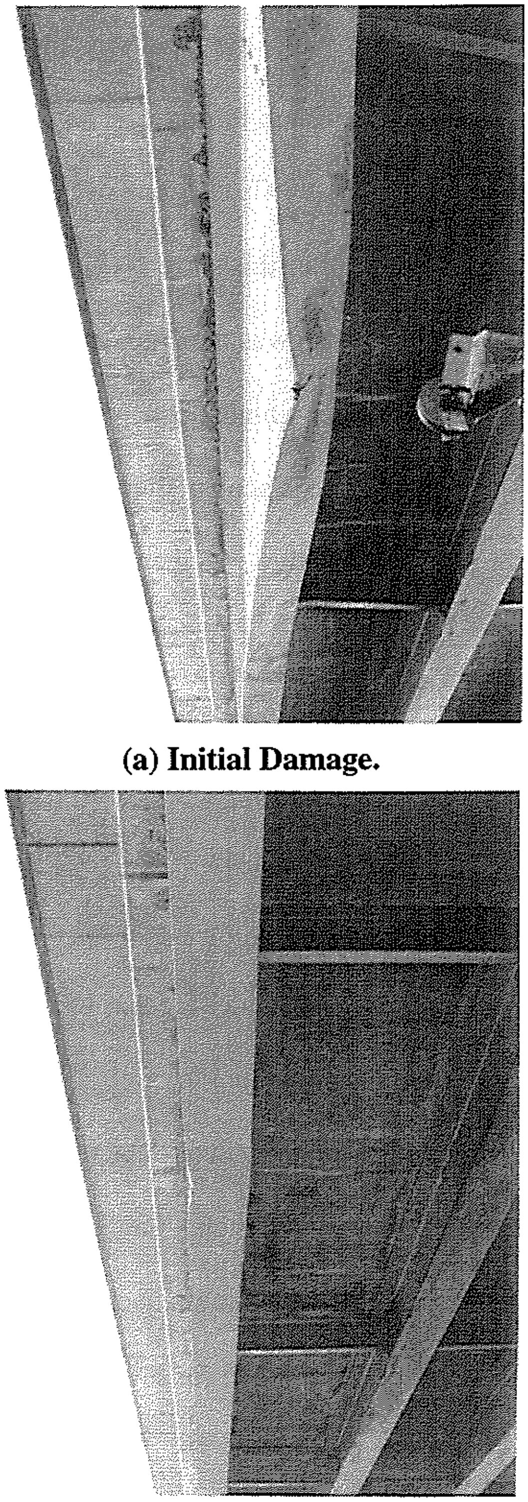
Heating at diaphragm 2. The set-up was then moved to diaphragm 2 where the tension jacks were again used. Three cycles of four simultaneous vee heats were used. In addition, web line heats were also used. The lower flange is shown after the three heating cycles in figure 16.

Re-heating at impact point. The set-up was then moved back to the impact zone. Compression jacks were used for seven heating cycles similar to those conducted previously. After seven cycles, the lower flange was essentially straight. The tolerance limit of 0.5 inch over 20 ft. was satisfied.

Heating of web bulges. With the flange and web straight, only the local web bulges at the diaphragms and flange bulge at the impact point remained. The maximum web deformation was less than 1_ inches. The approach to straightening was to first replace a diaphragm. Then the bolts were tightened which tended to straighten the web. Finally, the line heat pattern was applied to the convex side. The process was repeated three or four times until the bulge reached a tolerance level of d/100 or approximately 3/8 inch.

Heating of flange bulge. A C-clamp hydraulic jack was used to apply a force to the local flange damage. A series of line heats was applied for several cycles. The notch was not straightened.

Final configuration. A view of the beam, before and after repair is shown in figure 22.



(a) Initial Damage.

(b) Beam After Repair.

Figure 22
Beam before and after repair.

DISCUSSION OF RESULTS

The fascia beam was successfully straightened with the exception of two aspects. First, the dimple at the impact point was not straightened because the localized damage at the impact point exceeds the recommended repair limits. Additionally, this damage was quit localized and did not significantly jeopardize the strength or function of the beam. Second, the top flange of the beam did not return completely into the deck slot. Grout is to be used to fill the remaining void areas.

CONCLUSIONS

This repair project illustrates that complex damage can be repaired by heat straightening. The damage was relatively severe and required the equivalent of five working days to complete (rain delays extended the actual time to seven days). The step-by-step documentation of repairing a noncomposite steel girder is given in this report. This methodology is applicable for typical noncomposite girder repairs. The material obtained during this project has been developed into a case study. An interactive CD-ROM has been developed and is included as a part of this report.

RECOMMENDATIONS

This project illustrates the practicality of implementing heat-straightening repairs for Louisiana bridges. It is recommended that steps be taken to develop capabilities of DOTD. The necessary steps include.

1. Selecting a bridge maintenance engineer to serve as team leader.
2. Selecting a team for conducting heat-straightening repairs.
3. Identifying a series of bridges for heat straightening.
4. Designing and implementing the repair of these bridges as part of a training program for the repair team

LIST OF SYMBOLS

b_s = Width of stiffening element
C = Temperature in degrees Celsius
d = Depth of wide flange beam or primary plate element
d_s = Distance between the vee apex edge of the primary plate element and the stiffening element
E = Modulus of elasticity
F_a = Stress factor for calculating plastic rotation in rolled shapes
$F_\ell(M)$ = Jacking load factor
F_s = Shape factor for calculating plastic rotation in rolled shapes
F_y = Yield stress
L, L_r = Lengths between offsets
M_j = Moment produced by jacking forces
M_p = Plastic moment capacity of a member
R = Actual radius of curvature
S = Shortening of member after heat straightening or section modulus
y_r = Measured offsets at point r
y_{max} = Distance from centroid to extreme fiber
Z = Plastic section modulus
μ = Ratio of maximum strain to yield strain, ε
φ_b = Basic plate rotation factor
φ_d = Degree of damage
φ_p = Plastic rotation resulting from a single vee heat on a plate or rolled shape
θ = Vee angle

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