# Chapter 8
# Repair Considerations

## 8-1. General

Most damage to hydraulic structures is due to impact of barges and debris, corrosion, or cracking. Many hydraulic structures are riveted and may include damaged or loose rivets that must be replaced. Repairs to hydraulic steel structures must maintain the required structural integrity and should be designed, if possible, to avoid recurrence of the original damage. In all cases, repairs should be designed using industry-approved detailing and fabrication procedures and should be detailed to avoid future corrosion or cracking problems (see paragraph 8-2*a* and paragraph 8-3). Repair of corroded areas is discussed in paragraph 8-2*b*, repair of cracks is discussed in paragraph 8-4, and rivet replacement is discussed in paragraph 8-5. Paragraph 8-6 discusses several repair examples. The type of repair details selected will be determined considering the following factors:

*a. Cause of damage*. If the cause of original damage is not accounted for, it is likely that the damage will reoccur. If possible, the cause of damage should be eliminated or minimized.

*b. Remaining service life of the structure*. A repair of a structure that is intended to be in service for only a short time might obviously be less extensive than for a structure intended for longer service.

*c. Frequency and type of future inspections*. Due to cost or construction constraints, it may be prohibitive to provide an ideal repair. In such cases, a less than ideal repair might be adequate provided a strict inspection plan is developed. Development of inspection schedules for fatigue cracking is discussed in paragraph 6-11.

*d. Construction constraints*. In general, repairs must be completed in a field environment that will include less than ideal conditions. For example, access to the repaired area may be restricted. Conditions may not be appropriate for welding (i.e., temperature, water, or access may inhibit proper welding). Certain situations might involve decrease in structural strength resulting from temporary removal of rivets, cover plates, or other parts. Distribution of dead and live load stresses must be considered. Repair components are generally effective only in resisting live load unless dead load is removed during repair. Each of these conditions will influence the design of the repair detail.

## 8-2. Corrosion Considerations

*a. New repair details*. The primary means to avoid corrosion is by providing a protective coating system. The coating system applied to repair plates or components must be compatible with the protective system of adjacent steel. EM 1110-2-3400, CWGS 09940 and CWGS 05036 provide detailed information on selection, application, and specifications of coating systems. Structural detailing also has a significant impact on susceptibility to corrosion. Repairs should be detailed as much as possible to compensate for conditions that contribute to corrosion (paragraph 3-3*b*). The following items should be considered in the design process:

(1) Detail components such that all exposed portions of the repair detail can be painted properly. Break sharp corners or edges to allow paint to adhere properly.

(2) Where repair plates or components are horizontal, provide drain holes to prevent entrapment of water. Drain holes should be located at the lowest position with the size generally ranging from 25 mm (1 in.) to 75 mm (3 in.) in diameter. The cut edges of holes should be smooth and free of notches especially in areas subject to tensile forces.

(3) Grind weld ends, slag, weld splatter, or any other deposits off the steel. These are areas that form crevices that can trap water. Use continuous welds.

(4) Where dissimilar metals are in contact (generally carbon steel and either stainless steel or bronze), provide an electric insulator between the two metals and avoid large ratios of cathode (stainless steel) to anode (carbon steel) area. Surfaces of both metals should be painted.

(5) Welded connections are generally more resistant to corrosion than bolted connections. In bolted connections, small volumes of water can be trapped under fasteners and between plies that are not sealed. Where possible, use welds in lieu of bolts considering the effect on fracture resistance.

*b. Existing corroded components.* Where significant corrosion exists but strengthening is not required, the area should be cleaned appropriately and a new protective coating system applied. This will inhibit further corrosion, and future repairs might be avoided. In many cases, gate components such as skin plates include pitting corrosion that reduces component thickness where pitting exists. In certain cases, pits may be repaired by filling with weld metal. If this is done, strict weld procedures must be specified so the process is compatible with the existing base metal. This method is not recommended for fracture-critical components.

## 8-3. Detailing to Avoid Fracture

*a. General considerations.* Regarding fracture resistance and fatigue strength, bolted repairs are often preferable to welded repairs. However, bolted repairs typically are more expensive and require more time to design and install. Dimensional constraints can also restrict the use of bolted splice plates. Sound welding, particularly under field conditions encountered during repair operations, can be difficult, increasing the possibility of poor quality welds. Moisture, paint, and other foreign material that can produce weld defects and cracking are often present. Welding residual stresses and degradation of material toughness in the heat-affected zone can also contribute to cracking of the repair. Weld intersections, intermittent welds, and tack welds on tension members should be avoided.

*b. Distortion*. Most of the fatigue damage detected in U.S. bridges is due to distortion, mainly at unstiffened web gaps at the ends of diaphragms or floor beam connection plates (Keating 1994: Fisher 1984). An excellent summary of case studies on bridge failures due to distortion is presented by Fisher (1984). Out-of-plane behavior has been measured in field testing of lift gates (Commander et al. 1994). Unintended distortion can result from unanticipated forces such as those occurring at a semirigid connection designed to be a simple connection. Unintended distortion is generally due to out-of-plane displacement of structural components that is not accounted for in design. Details that are known to be predisposed to distortion damage should be avoided.

*c. Better details*.

(1) Most fractures of structural elements are attributed to adverse stress concentration conditions, unintended distortion, and inferior fabrication. Regardless of the primary contributing factor, cracking is generally associated with or assisted by conditions of adverse stress concentration. Therefore, detailing to minimize the effect of stress concentrations will prevent most fractures or at least will provide a more durable condition. If fracture is a concern, the detail that provides the least critical stress concentration condition should be used. In the design of structural details for new or repair applications, utilization of fatigue design criteria is a very simple means to ensure high fracture resistance. Even without fatigue loading, susceptibility to fracture is reflected by the level of stress and the stress concentration condition as discussed in paragraph 3-3*a*.

(2) Fatigue strength relationships ($S_r$-$N$ curves) for welded details are described in paragraph 2-3*b*. All bolted details provide a lower bound strength equivalent to a Category B detail. Due to a lower clamping force in rivets, riveted details have lower fatigue strength compatible with Category C or Category D as described in paragraph 2-3*c*.

(3) A designer has some flexibility in selecting a detail to minimize likelihood of cracking. For a given condition, various details would serve the same purpose but have different fatigue strength. If budget and other constraints permit, a designer should generally choose the detail with the highest fatigue strength (the least likely to have cracking problems) regardless of loading. In cases of repair, the goal should be to provide a condition with an improved fatigue resistance compared to the original condition. Figure 8-1 shows several situations where a detail can be improved.

(4) If possible, all Category E details should be avoided. Figures 8-1*a* and 8-1*b* demonstrate that other details with higher fatigue strength may be substituted for Category E details. The gusset plate attachments on the left sketch in each figure produce a Category E in the girder flange at the termination of the longitudinal welds or where there is a transverse weld. The Category E situation can be avoided by using a bolted connection (category B) or a gusset plate with a full-penetration weld ground smooth and a generous radius. In both cases, the stress concentration condition has been improved dramatically. Another way to avoid the adverse effects of Category E details is to locate the detail in a region of low stress. Cover plates can be extended to a region of low flexure, and attachments to flanges can be moved to the web where the flexural stress is low.

(5) Fatigue strength can be improved significantly by providing a smooth transition between connected elements as shown in Figures 8-1b and 8-1c. A flange attachment can be improved from a Category E to a Category B detail by providing a radius transition and grinding the weld smooth (Figure 8-1b). The fatigue strength of a transverse groove weld is improved from a Category C to a Category B by removing the weld reinforcement and grinding the weld smooth (Figure 8-1c) (see groove welded connections of Table 2-1). Other important considerations are to avoid intermittent welds on backup bars and discontinuous backup bars. A category E situation exists at the termination of each intermittent weld, and a built-in crack exists where a backup bar is discontinuous.

## 8-4. Repair of Cracks

Effective methods for repairing cracks or improving a detail include weld-toe grinding, peening, remelting, and hole drilling. The appropriate repair method for a given situation is dependent on the size and location of the crack and the type of detail at which the cracking occurred. Small through-thickness cracks subject to low stress range can be arrested by drilling a hole at the crack tip. For large cracks and/or higher stress range, repair can be accomplished by removing the crack tip by drilling a hole and repairing the remaining length of the crack by welding or with bolted splice plates. Simply welding the crack closed, even with a full penetration weld, should never be done without removing the crack tip with a hole. Such a repair generally worsens the condition due to the added residual stresses and deleterious thermal effects of welding (see paragraph 2-2*c*). Shallow surface cracks that typically occur at the toe of fillet welds can be repaired by grinding, air hammer peening, or gas tungsten arc (GTA) remelting. Surface cracks with depths that exceed the penetration capability of GTA remelting and the effectiveness of peening cannot be repaired by these procedures. Such cracks can be repaired by installing bolted splice plates that transfer the stress around the crack.

*a. Hole drilling.* Hole drilling is the most commonly applied means of arresting fatigue cracks. A hole drilled at the tip of a crack essentially blunts the crack tip and the local stress concentration is greatly reduced compared to that for a sharp crack. It has been successfully applied to various types of structures, including navigation lock gates and several bridges (Fisher 1984). Hole drilling is effective for through-thickness cracks in plates or plate components of structural members.

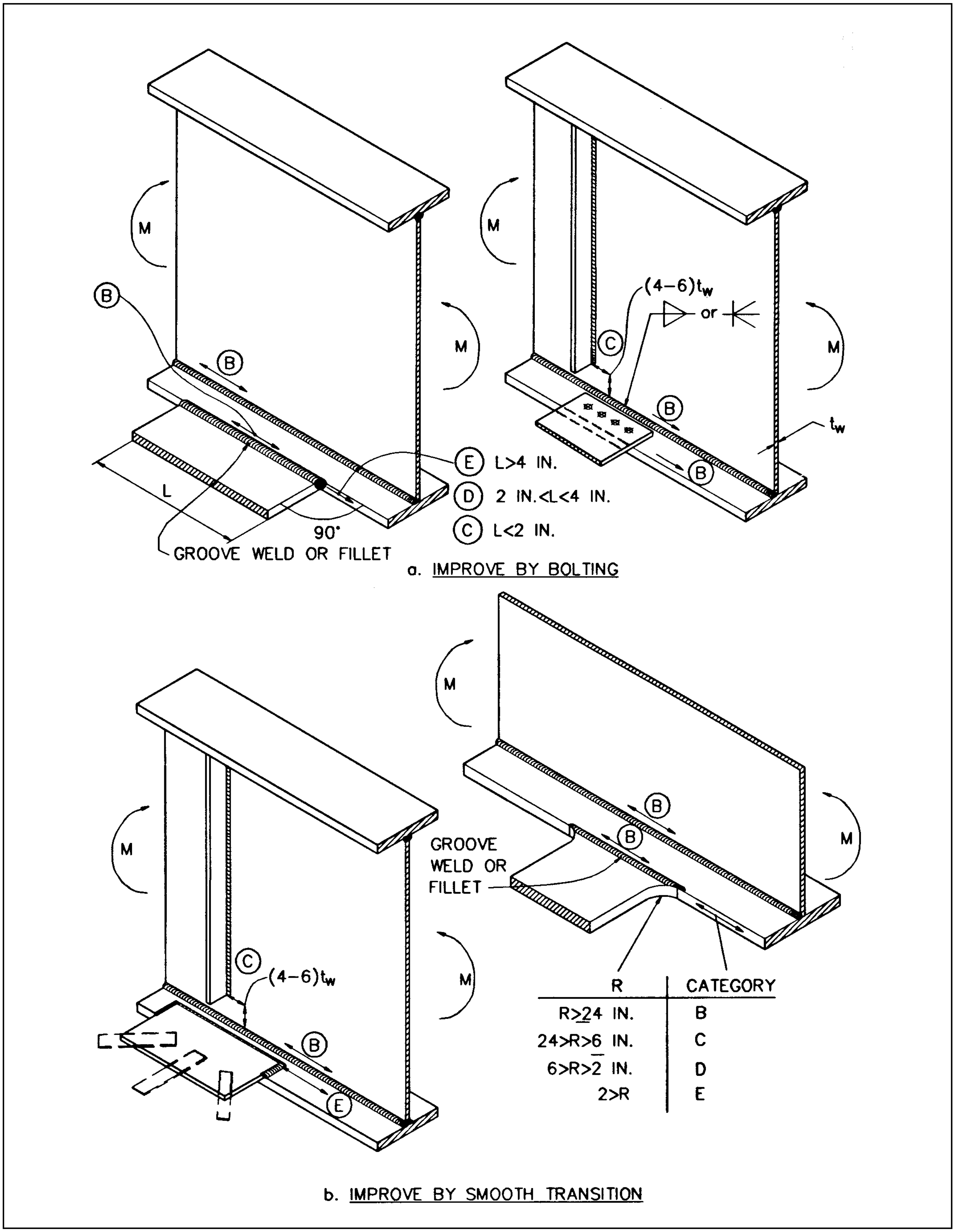


**Figure 8-1. Better fatigue details (1 in. = 2.54 cm) (after Fisher 1977) where $t_w$ is the web thickness, *M* is the bending moment, *L* is the length of weld considered, and *R* is the radius on attached component (Continued)**

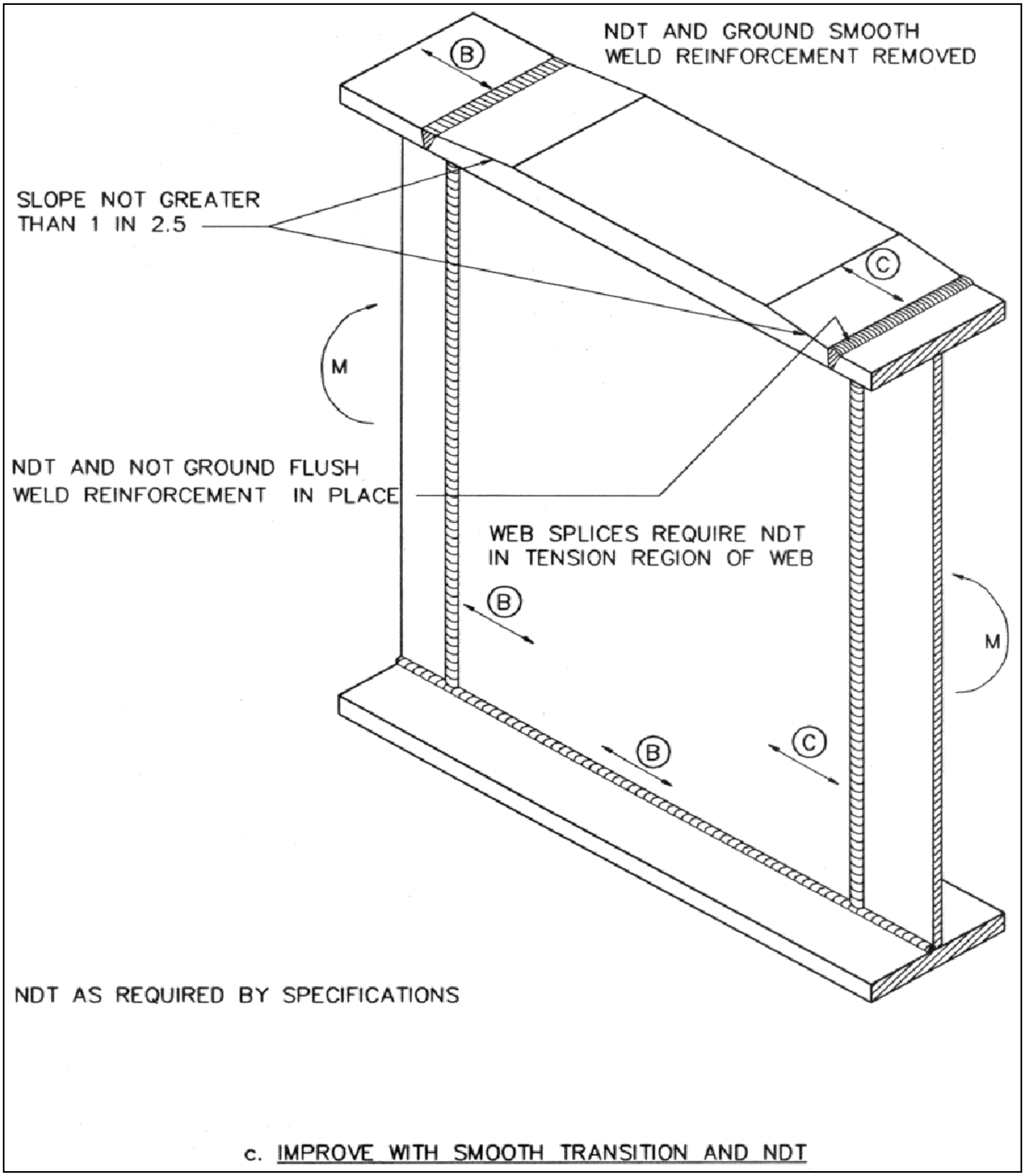


**Figure 8-1. (Concluded)**

(1) The minimum hole size required to prevent crack initiation can be estimated with the relationship

$$\frac{\Delta K}{\sqrt{r}} = 26.7\sqrt{\sigma_y} \tag{8-1}$$

where

$\Delta K$ = stress intensity factor range, MPa-$\sqrt{\text{m}}$

$r$ = radius of the hole, m

$\sigma_y$ = yield stress, MPa

(For non-SI units,

$$\frac{\Delta K}{\sqrt{r}} = 10\sqrt{\sigma_y}$$

where $r$ is in in., $\sigma_y$ is in ksi, and $\Delta K$ is in ksi-$\sqrt{\text{in.}}$ )

(2) $\Delta K$ is calculated considering the entire stress range (algebraic sum of the tensile and compressive stress), and the crack size $a$ (see Equation 6-1) includes the extent of the hole. Equation 8-1 is valid for structural steel and provides reasonable results for moderate stress ranges (less than 40 MPa (6 ksi)) and crack sizes. For most practical cases regarding moderate crack size and stress range less than 40 MPa (6 ksi), a crack will not reinitiate from a hole if the hole diameter is at least one-fifth the total crack length (Keating 1994). Hole diameters of 20 mm (13/16 in.) and 27 mm (1-1/16 in.) are practical since these sizes are commonly used for installation of high-strength bolts. The following are appropriate steps to arrest a small crack in structural steel subject to moderate stress range:

(a) Determine the appropriate hole size (Equation 8-1).

(b) Locate the crack tip with dye penetrant testing.

(c) Drill hole with center at crack tip.

(d) Inspect drilled surface of hole with dye penetrant testing to verify complete removal of crack tip.

(e) In some cases, crack reinitiation may be inhibited by installing tightened bolts in the holes. This introduces local compressive stresses in the through-thickness direction that inhibits crack initiation from the hole.

(3) For larger crack sizes and stress range greater than 40 MPa (6 ksi) (often the case for hydraulic structures), the hole size required by Equation 8-1 is significant and is not practical. In these cases, the crack tip may be removed by drilling a hole and the remaining crack repaired by welding or bolted splice plates. The following are general guidelines for a welded crack repair:

(a) Clean area and determine extent of crack with dye penetrant testing (see paragraph 4-5*b*).

(b) Drill hole at crack tip location.

(c) Gouge out crack and prepare joint as a full-penetration groove weld in accordance with ANSI/AWS D1.1.

(d) Preheat and weld joint using runout tabs and backing as required per American National Standards Institute/American Welding Society (ANSI/AWS) D1.1.

(e) Remove backing and runout tabs.

(f) Grind weld smooth.

(g) Ream hole to remove weld metal and smooth edges.

(h) Verify removal of crack tip with dye penetrant testing.

(i) Inspect weld with appropriate nondestructive testing (ultrasonic testing or radiographic testing (paragraph 4-5)).

(4) Alternatively, a bolted repair of the fatigue crack can be installed after a hole is drilled to arrest the crack:

(a) Determine extent of crack with dye penetrant testing.

(b) Drill hole at crack tip location.

(c) Verify removal of crack tip with dye penetrant testing.

(d) Prepare and install bolted repair over the crack.

*b. Weld toe grinding*. Weld-toe grinding reduces the geometrical stress concentration and extends the fatigue life of undamaged details (Keating 1994). Grinding can be used to remove shallow fatigue cracks that may exist in the weld toe. Grinding should always be done in the direction of applied stress. A pencil or rotary burr grinder can be used. Magnetic particle inspection of the ground area should be conducted after grinding to ensure that embedded flaws are not exposed. (Penetrant inspection may reveal false indications due to grinding marks.)

*c. Peening*.

(1) Peening is effective as a retrofit for shallow surface cracks that commonly occur at fillet weld toes. Peening imposes compressive residual stresses resulting from the plastic deformation induced by the peening hammer and reduces the geometrical stress concentration similar to that with grinding. Air hammer peening is effective in arresting fillet weld toe surface cracks with a depth of up to 3 mm (1/8 in.) if the tensile stress range does not exceed 40 MPa (6 ksi). Peening can also be applied to uncracked fillet welds to improve the fatigue resistance of the detail. The expected benefit of peening under favorable conditions (low stress range, low minimum stress) is an increase in fatigue life approximately equivalent to one fatigue design category (Fisher et al. 1979).

(2) Peening should be done using a small pneumatic air hammer with all sharp edges of the peening tool ground smooth. Although peening intensity can be easily varied by changing air pressure, multiple-pass peening at lower air pressures is most effective. Initial passes of the peening hammer may reveal some cracks that were not initially visible, and peening should be continued until the weld toe is smooth and no cracks are apparent. Penetrant inspection of the peened area should be conducted after peening to ensure that embedded flaws are not exposed. Peening is most effective when performed under dead load so that the imposed compressive residual stress has to be effective only against the live load.

*d. Gas tungsten arc remelting.*

(1) The GTA remelting process is also an effective procedure for repair of shallow surface cracks that occur at fillet weld toes. This procedure is generally effective for surface cracks with a depth of up to

5 mm (3/16 in.) (slightly greater depths than peening) and is not limited to small stress ranges and minimum stress levels. Like peening, GTA remelting can also be used to improve the performance of uncracked fillet welds, approximately doubling the fatigue life. However, it is not as easily performed in the field, and it requires highly skilled welders and good accessibility.

(2) With the GTA remelting procedure, a small volume of the weld toe and base metal is remelted with a gas-shielded tungsten electrode. After the area cools, the geometric stress concentration is improved and nonmetallic inclusions that might exist along the weld toe are eliminated. When the procedure is applied to crack repair, sufficient volume of the metal surrounding the crack must be melted so that upon solidification, the crack is eliminated. The effectiveness of the procedure is dependent on the depth of the remelted zone, since insufficient penetration would leave a crack buried below the surface. Such a crack would simply continue to propagate, resulting in premature failure. Proper selection of shielding gas and electrode cone angle is crucial in obtaining maximum penetration of the remelted zone. Argon-helium shielding and an electrode cone angle of 60 deg were found to be most effective (Fisher et al. 1979). For any retrofit procedure, the depth of penetration should be verified by metallographic examination of test plates before the procedure is applied in the field.

## 8-5. Rivet Replacement

*a.* Missing, loose, or headless rivets and rivets with rosette heads should be replaced (Fazio and Fazio 1984). Deteriorated rivets missing more than 50 percent of the head should be replaced if the rivet is subject to an applied tensile force or tension resulting from prying action (Fazio and Fazio 1984). Rivet heads with rosettes and deteriorating projections should not be built up using weld metal or other materials (brazing, caulking), since these could aggravate rather than improve the condition.

*b.* Rivets that require replacement should be replaced with high-strength bolts. However, removing a deteriorated rivet is sometimes difficult. The most accepted method of rivet removal is to knock off the rivet head using a pneumatic rivet buster and then force the rivet shaft out of its hole using a powered impact tool (Birk 1989). If necessary, the rivet hole should then be drilled out to obtain an aligned hole through the connected parts. Then a high-strength bolt is installed and tightened by an accepted method such as the turn-of-the-nut method. When pneumatic rivet busters are not available, rivet heads can be burned off. This technique can cause thermal metallurgical damage to the adjacent steel, and may result in burn gouges that adversely affect fatigue strength and susceptibility to corrosion.

## 8-6. Repair Examples

*a. Crack repair procedures developed for a cracked miter gate.*

(1) Description of condition. Figure 8-2 shows a crack in a tension flange of a girder on a miter gate (the photograph shows the inside face of the flange). The crack extends from the termination of a weld joining the flange of a diagonal bracing member and flange of the girder. Similar cracking occurred at perpendicular intersecting members (diaphragm and girder). Numerous through-thickness cracks similar to this occurred on the structure.

(2) Cause of cracking. In general, cracking is attributed to high stress fatigue damage of low fatigue strength details. Cyclic loading occurs due to opening and closing of the gate leaves and to variation in hydrostatic pool. Unusually high stress may have occurred due to unintended loading while the gate was opened and closed with silt buildup at the gate bottom. Most of the cracks occurred at terminations of welds that join intersecting members, similar to the condition shown in Figure 8-2. Considering girder flexure, the fatigue strength of such details is Category E.

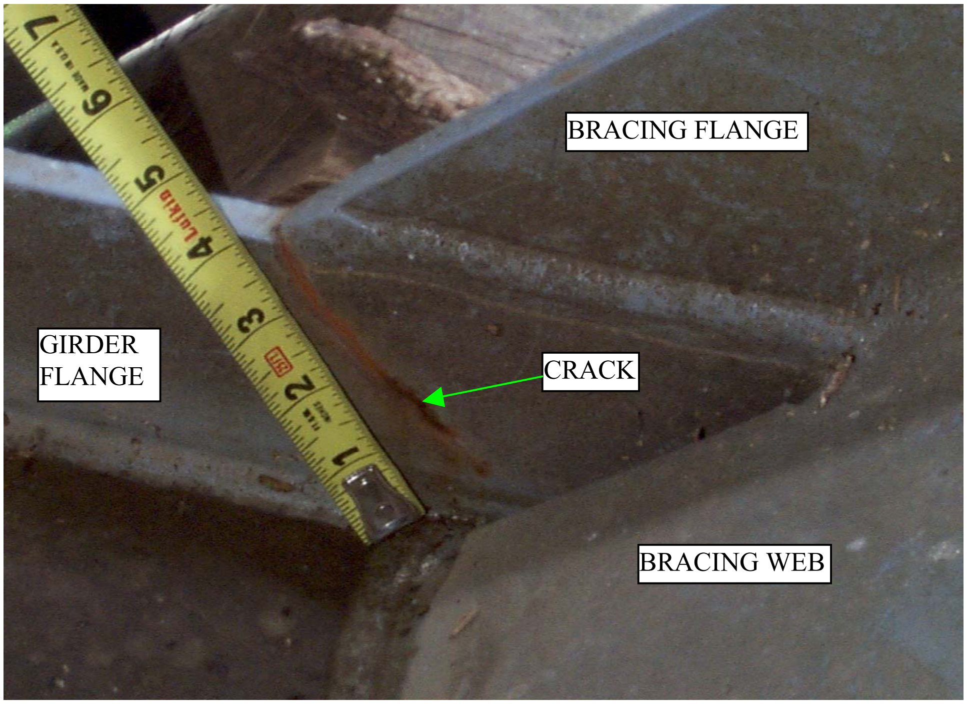


**Figure 8-2. Crack in miter gate girder tension flange**

(3) Repair alternatives. The following repair alternatives were developed for the miter gate. The types of cracks found on this structure are common to hydraulic structures that have experienced cracking. The presented alternatives are generally applicable to similar situations on all gates.

(a) Figure 8-3 shows a repair procedure that was developed for small cracks (less than 12 mm (1/2 in.)) located at re-entrant corners of perpendicular members. The area should be cleaned and prepared as necessary to locate and mark the crack tip using dye penetrant testing. The radius plate should then be installed using a full-penetration weld with welding in accordance with ANSI/AWS D1.1. The plate should be of the same (or similar) thickness as the adjacent plates (flanges). A 25-mm (1-in.) hole should then be drilled to encompass the crack and to remove the weld intersection. Penetrant testing should be conducted to verify removal of the crack tip, and the area should be repainted. Even if cracking has not occurred, this repair could be used to retrofit poor conditions found at intersecting perpendicular members (i.e., diaphragm and girder) on any structure. The retrofit shown (with radius of 15 cm (6 in.)) improves the fatigue strength from Category E to Category C.

(b) Figure 8-4 shows the selected repair for edge cracks greater than 25 mm (1 in.) The repair should be completed following the guidelines for welded crack repair given in paragraph 8-4*a*. Any type of full-penetration weld is acceptable. For edge cracks that extend into the web, a repair similar to that shown in Figure 8-4 is appropriate. However, some additional steps are required. A crack that extends into the web has a crack tip in the flange opposite that where the crack initiated and in the web. Holes should be drilled at both locations. Additionally, a weld access hole should be cut in the web to accommodate the full-penetration flange weld. The access hole should be proportioned in accordance with ANSI/AWS D1.1. Any type of full-penetration weld is acceptable.

*b. Cracked girder, vertically framed miter gate.*

(1) Description of condition. Figure 8-5 shows a connection bracket that is welded to the downstream flange of a vertical girder in a spare vertically framed miter gate. The gate consists of 3-m- (10-ft-) high welded modular sections that are stacked vertically and joined by bolts that extend through the connection

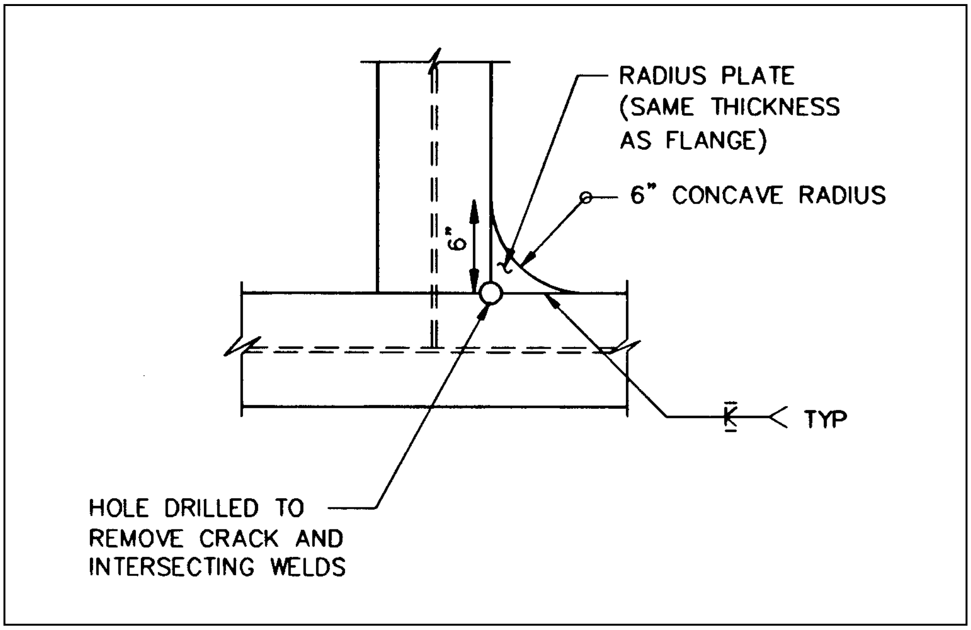


**Figure 8-3. Retrofit to improve fatigue strength at intersecting perpendicular members (1 in. = 2.54 cm; 1 ft = 0.3 m)**

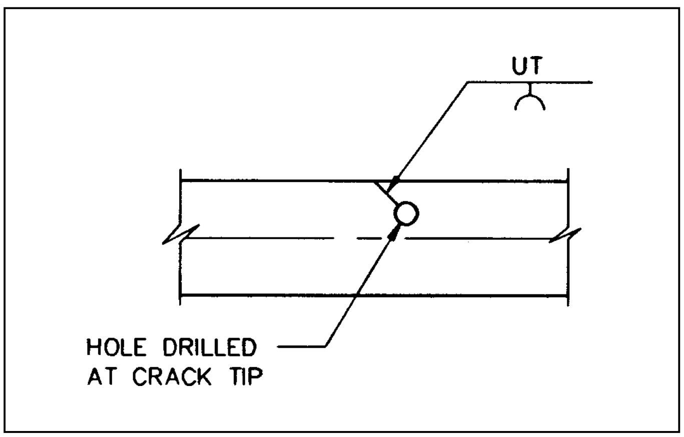


**Figure 8-4. Weld repair for edge crack**

bracket. The gate was fabricated in 1969 and had been installed several times for temporary use. While in service, the gate did not have any loading greater than the design load. In 1989, it was discovered that the downstream flanges on three of seven vertical girders were cracked as shown in Figure 8-5. In each case the crack extended through the 38-mm- (1-1/2-in.-) thick flange and approximately two-thirds of the way through the web.

(2) Cause of cracking. The crack was located in the tension flange of the vertical girder at the intersection of the bracket plate and the flange plate. The weld that joins the bracket plate and flange plate is transverse to the direction of stress flow, and the intersection of the two plates creates a severe stress concentration for stress flow through the flange. This situation is similar to that at the end of a welded cover plate and would be classified as a category E fatigue detail. Considering the quality of weld, the actual condition is worse than a Category E. The general weld profile is rough and undercut, which essentially creates a small initial crack. The cracking in three of seven girders illustrates the adverse effects of this type of stress concentration.

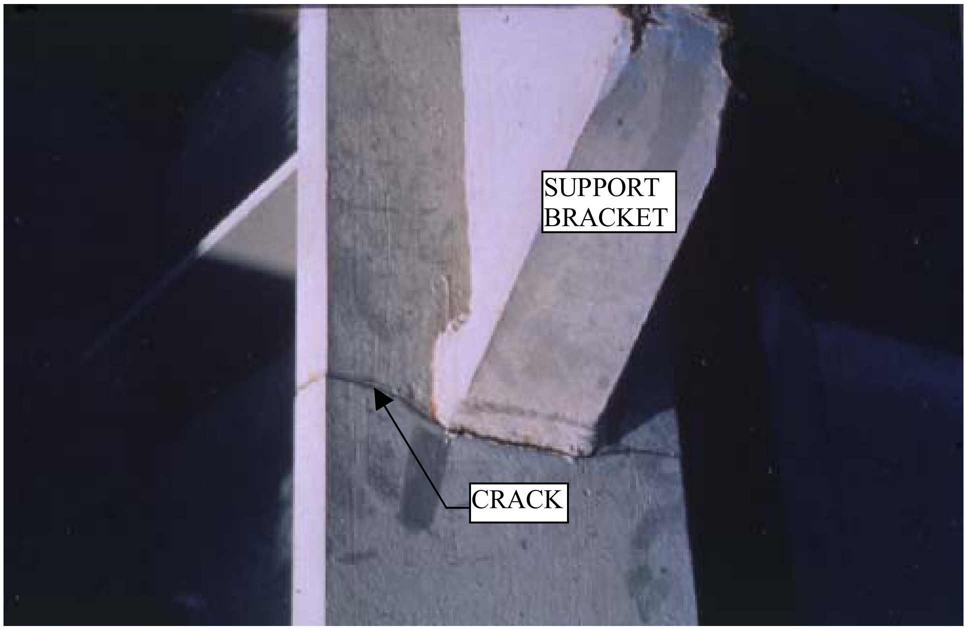


**Figure 8-5. Cracked miter gate vertical girder tension flange**

(3) Repair alternatives. Due to the general configuration and restrained geometry of this connection, a repair that restores the original intended strength may be difficult to achieve. However, the crack can be repaired using splice plates on the flange and web. The splice plates could be welded or bolted. A bolted repair would result in a Category B detail; however, due to the constrained geometry, the effective area considering the required bolts may be a concern. A welded repair would result in a Category E condition at the end of the splice plates. (However, with modern welding practices, the condition would be improved over that of the original connection.) To minimize the effect of the Category E, the splice plates could be extended into a region of low stress. For either a welded or bolted repair, a hole should be drilled at the crack tips. Prior to cracking, the condition could have been improved by grinding the weld profile smooth, or by retrofitting the welds by peening or GTA remelting procedures. A similar modification was undertaken on an extensive retrofit of the Yellow Mill Pond Bridge in the early 1980s (Fisher 1984).

*c. Cracked girder and bracing members on a vertical lift gate.*

(1) Description of condition. Figure 8-6 shows a connection between a vertical diaphragm, diagonal bracing members, and a main horizontal girder on a vertical lift gate. This type of connection (intersection of bracing members, diaphragms, and girders) is a very common occurrence on lift gates, miter gates, tainter gates, and bridges. Flanges of bracing members and the diaphragm were each welded directly to the girder flange. Cracking occurred completely through each bracing member and through the diaphragm flange and girder flange (at various locations on this particular structure). The girder is designed to resist flexural forces imposed by hydrostatic pressure, and under this condition, the downstream flange is subject to tension. The bracing members are designed as members of a truss that resists vertical loads imposed by the gate weight and water pressure. Therefore, the bracing members are presumably subjected to axial tension or compression. Field measurements have shown that out-of-plane displacement and rigidity of end connections may also impose flexure in the bracing members (Commander et al. 1994).

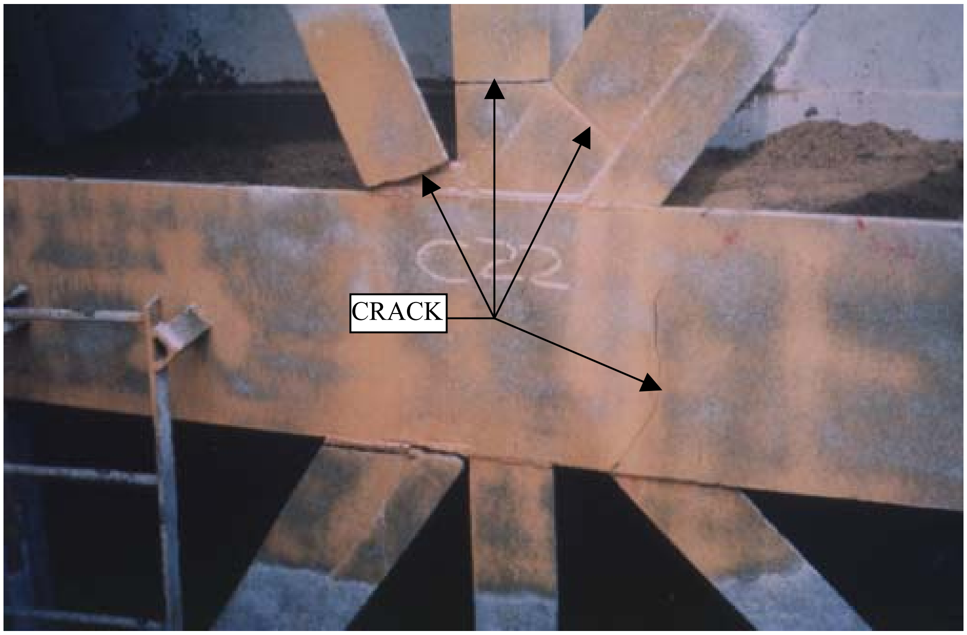


**Figure 8-6. Cracked girder, diaphragm, and bracing in a lift gate**

(2) Cause of cracking. The location and orientation of cracks indicate that cracking initiated at weld terminations and weld intersections. The re-entrant corners between members and the inferior weld geometry (overlapping welds, transverse to stress and not ground smooth) both create a critical stress concentration condition for the stress flow through the girder flange, diaphragm flange, and bracing members. The attachment to the girder tension flange is a Category E, and considering axial behavior of intersecting members, a Category C, D, or E situation exists depending on the thickness of joined elements. (With overlapping welds and poor weld profiles, the strength is likely less than that of a Category E detail.)

(3) Repair alternatives. It is necessary to restore the girder strength and to provide adequate connections of the intersecting members. To avoid future fractures, the repair details should improve the original condition if possible. Various alternatives could be used to repair the girder while improving the original condition:

(a) One alternative would be to drill holes at the ends of each existing crack and to add a bolted gusset plate as shown in Figure 8-7. The gusset plate would be sized such that the plate and connected flanges would resist the required forces considering the net area. This alternative would improve the fatigue strength to Category B; however, due to the number of bolts required and the resulting reduction in net area, a very large plate would likely be necessary.

(b) A second alternative would be to use a welded gusset plate. A gusset plate could be placed over the existing flanges and welded to each flange. This would provide a temporary patch; however, the fatigue strength considering bracing and girder stresses would be Category E (although with proper welding procedures and no intersecting welds, the situation would be improved over the original condition).

(c) A better detail is shown in Figure 8-8. This would require removing a specified length of flange from each of the intersecting members and replacing the flanges with a single gusset plate. All of the member flanges would be welded to the gusset plate with full-penetration groove welds, and the member

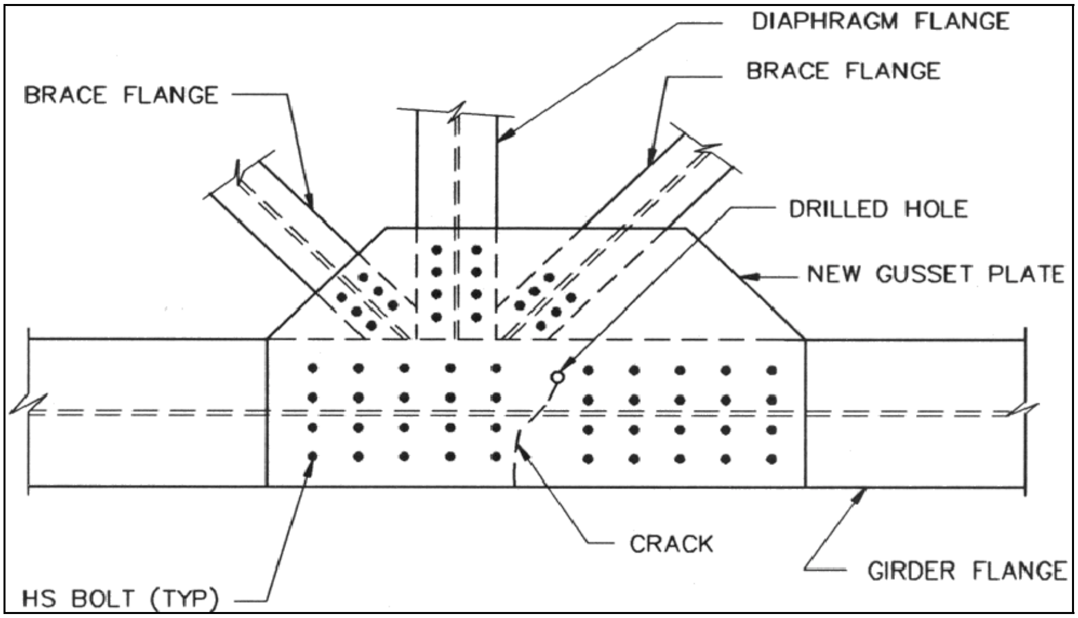


**Figure 8-7. Bolted repair alternative for cracked lift gate**

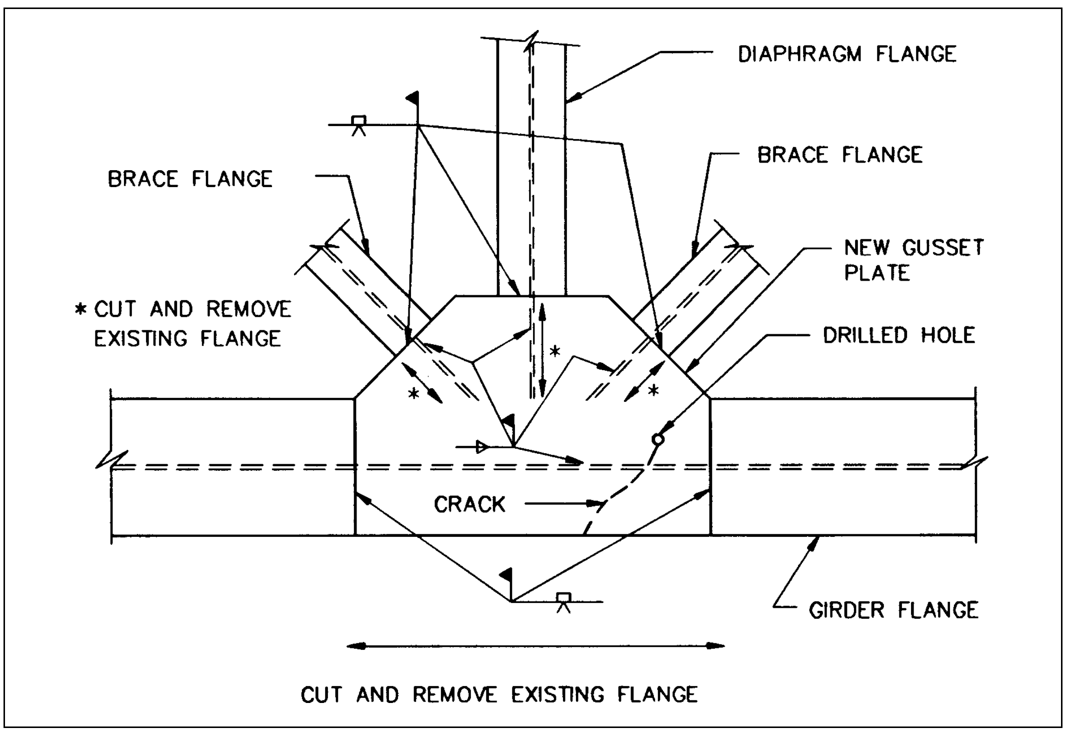


**Figure 8-8. Welded repair alternative for cracked lift gate**

webs would be welded to the gusset plate with full-penetration or fillet welds. Web access holes are required at flange welds and should be prepared in accordance with ANSI/AWS D1.1. The exact configuration should be determined to avoid intersecting welds. With this approach, the detail would improve from a Category E to a Category C or B depending on weld profile and weld inspection requirements (see requirements for groove welded connections in Table 2-1).

*d. Cracked bridge floor beam connection angle.*

(1) Description of condition. Figure 8-9 shows a crack in a connection angle that attaches a floor beam to one web of a box girder in a USACE tied arch bridge. The crack extends from the upper edge of the connection angle downward along the fillet of the angle. The cracks were discovered after approximately 40 years of service. Similar cracks have been found in at least four connections. The cracks were repaired by drilling a hole at the end of the crack approximately 6 years ago. Recently, cracking through the hole was observed in at least one location.

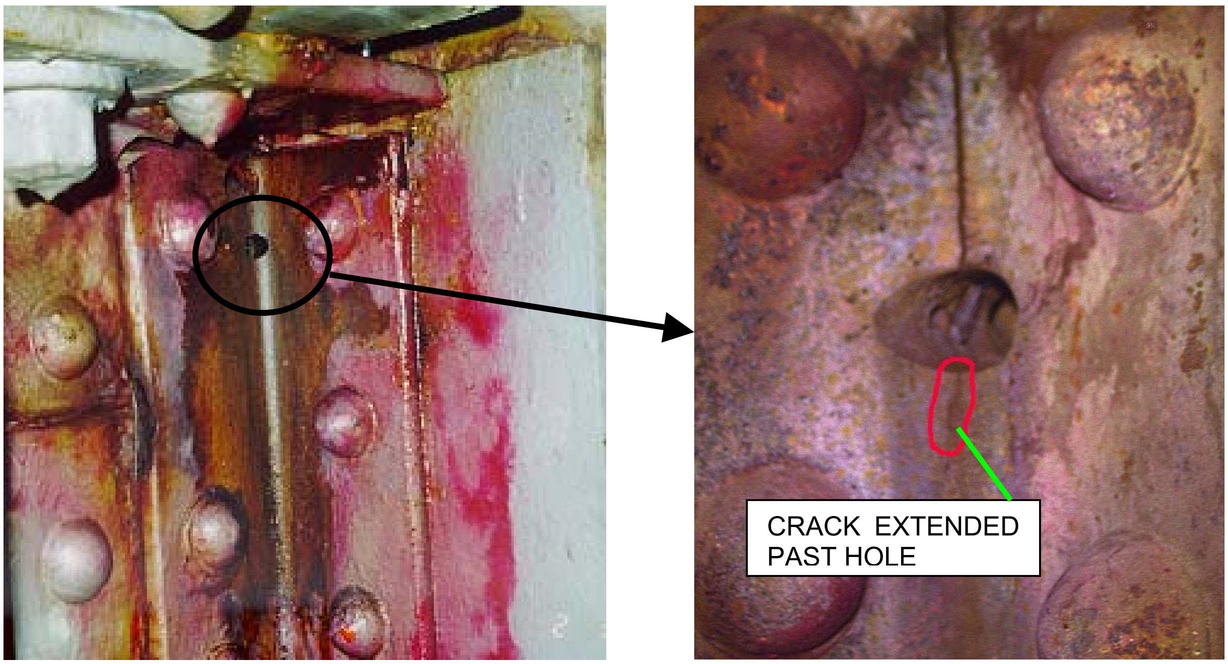


**Figure 8-9. Crack in bridge floorbeam connection angle**

(2) Cause of cracking. For the purposes of this example, it is assumed that floor beam flexural forces cause unintended distortion of the connection angle that was not accounted for in the design. The connection is assumed to be a simple shear connection and was not designed to resist floor beam flexure. However, the angle actually resists out-of-plane forces due to connection rigidity, and the crack driving force is apparently due to the floor beam flexure. The prior repair, which consisted of drilling a hole at the end of the crack, served to arrest the crack temporarily. However, since the out-of-plane displacement is not restrained and the floor beam flexure still exists, the crack has reinitiated from the hole.

(3) Repair alternatives. To eliminate the cause of cracking, the connection must be modified to reduce the inherent rigidity (to minimize bending forces) or to increase the rigidity (to minimize the out-of-plane displacement of the connection angle). Cases similar to this are discussed by Keating (1994) and Fisher (1984).

(a) Simple connection. One alternative is to alter the floor beam connection detail to reduce the connection rigidity such that minimal flexure is imposed at the end of the floor beam. This would eliminate the driving force that causes the out-of-plane distortion of the angle. Although many repair details could be designed to serve this purpose, one possibility would be to remove rivets at the top of the angle and to cut away the corresponding length of angle to reduce the angle length. To account for the lost shear strength, a seat angle could be added at the bottom of the floor beam. This alternative would maintain the required shear strength and would reduce the connection rigidity that causes crack driving force.

(b) Rigid connection. Another alternative would be to reinforce the connection to prevent the distortion. This could be done by attaching the top flange of the floor beam to the box girder web using a tee section with its flanges bolted to the box girder web and its web bolted to the top flange of the floor beam. The top portion of the existing connection angle would have to be removed to provide room for the tee flange. Although the displacement of the original connection angle would be controlled, large flexural forces would develop at the end of the floor beam due to the connection rigidity. This may result in other problems such as distress of the girder web, since the connection was designed as a simple connection.

*e. Fractured bars on a trashrack.*

(1) Description of condition. Figure 8-10 shows a trashrack used at an inlet structure on a dam. The trashrack is composed of a steel outer frame, two support beams, and several screen bars that span the frame across the support beams. The bars were attached on the upstream face of the rack with the edges of the bar welded directly to the support beams and frame with fillet welds. Seventeen out of twenty of the bars fractured completely as shown in Figure 8-10. In each of the fractured bars, the cracks initiated at the end of the weld that joins the bar to the supporting member (on the downstream edge of the bar).

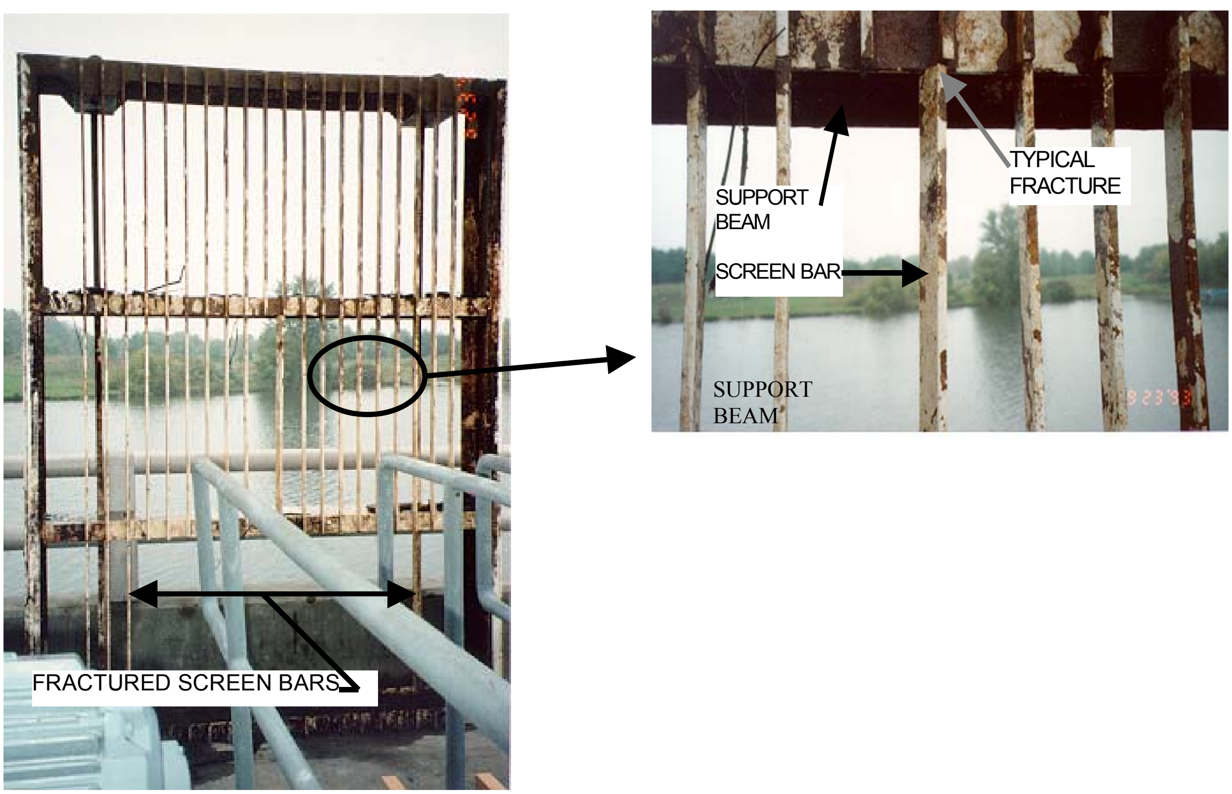


**Figure 8-10. Fractured screen bars on dam intake trashrack**

(2) Cause of cracking. Design loads consisted of lateral hydrostatic loads that induce flexure in the bars. The direction of bending in the bar at the welds is such that the design stress is compressive on the downstream edge of the bar at the crack locations. Therefore, under design assumptions, cracking is not expected. The cracking is attributed to tensile fatigue stresses caused by out-of-plane distortion of the bars

as they are vibrated by passing water. The weld termination and abrupt change in geometry between the bar and supporting member create a severe stress concentration resulting in a detail with low fatigue strength. Even with vibration due to passing water, the cracking might not have occurred given connection details with higher fatigue strength.

(3) Repair alternatives.

(a) The attachment between the screen bars and supporting members creates a severe stress concentration condition that could be avoided by using a different type of connection. Similar trashracks have been designed where the supporting members have carefully sized holes through which the screen bars pass and there is no need for a welded attachment. This eliminates the stress concentration at the weld, and it is likely that the screen bars would have a significantly longer life. The actual repair for this case is shown in Figure 8-11. New screen bar supports with holes (retainer bars) were fabricated and attached to the existing channel support members with bolts. The bars were then threaded through the retainer bar holes and held in place by angles at the bar ends oriented perpendicular to the bars and attached to the existing frame with bolts.

(b) The selected repair eliminated the stress concentration and may have reduced the future number of load cycles. The fatigue strength has been improved from a detail similar to Category E to Category A. The repair may also decrease the vibration of the bars with passing water since the new screen bar edges were rounded on the upstream edge to minimize hydraulic disturbance. Additionally, the overall flexural stiffness of the bars has been reduced significantly since the bars are now free to rotate at the connection points. This affects the natural frequency of vibration of the bars and may reduce vibration as water passes.

*f. Crack at diaphragm flange to girder flange intersection in a lift gate*.

(1) Description of condition. Figure 8-12 shows a crack in the downstream girder flange of a vertical lift gate. The crack initiated at the end of the weld between a diaphragm flange and downstream girder flange and propagated into the girder flange. The fatigue strength of the girder flange at the weld termination is analogous to Category E. Under typical design assumptions, the girder is in flexure due to lateral hydrostatic forces and the downstream flange is subject to tensile stress. If cracking were to occur considering design assumptions, the expected direction of cracking in the girder flange would be transverse to the flange (perpendicular to flexural tensile stress). However, the crack is oriented at approximately 45 degrees to the horizontal girder flange.

(2) Cause of cracking. The crack is located at the re-entrant corner between flanges (a severe stress concentration condition), and tensile cyclic stress exists in the flange at this location. The cracking is attributed to fatigue cracking of a detail with low fatigue strength. It is also presumed that the condition was exasperated by out-of-plane distortion of the girder flange. Under vertical hydrostatic loading on the lift gate, the horizontal girder flanges displace in a vertical plane similar to a uniformly loaded simple beam as shown in Figure 3-5. The figure illustrates displacement of downstream girder and diaphragm flanges due to vertical loading. The ends of diaphragm flanges are forced to rotate with the displaced girder flanges causing out-of-plane flexure in the diaphragm flanges. This induces stresses acting parallel to the diaphragm flange with tension on one edge and compression on the other as shown in Figure 3-5. Experimental measurements of lift gate stresses verify this behavior (Commander et al. 1994). At the point of crack initiation, longitudinal tension stresses exist in both the girder flange (due to lateral hydrostatic loading) and diaphragm flange (due to out-of-plane distortion). The combined effect of these perpendicular tensile stresses results in a primary tensile stress that acts perpendicular to the direction of the existing crack.

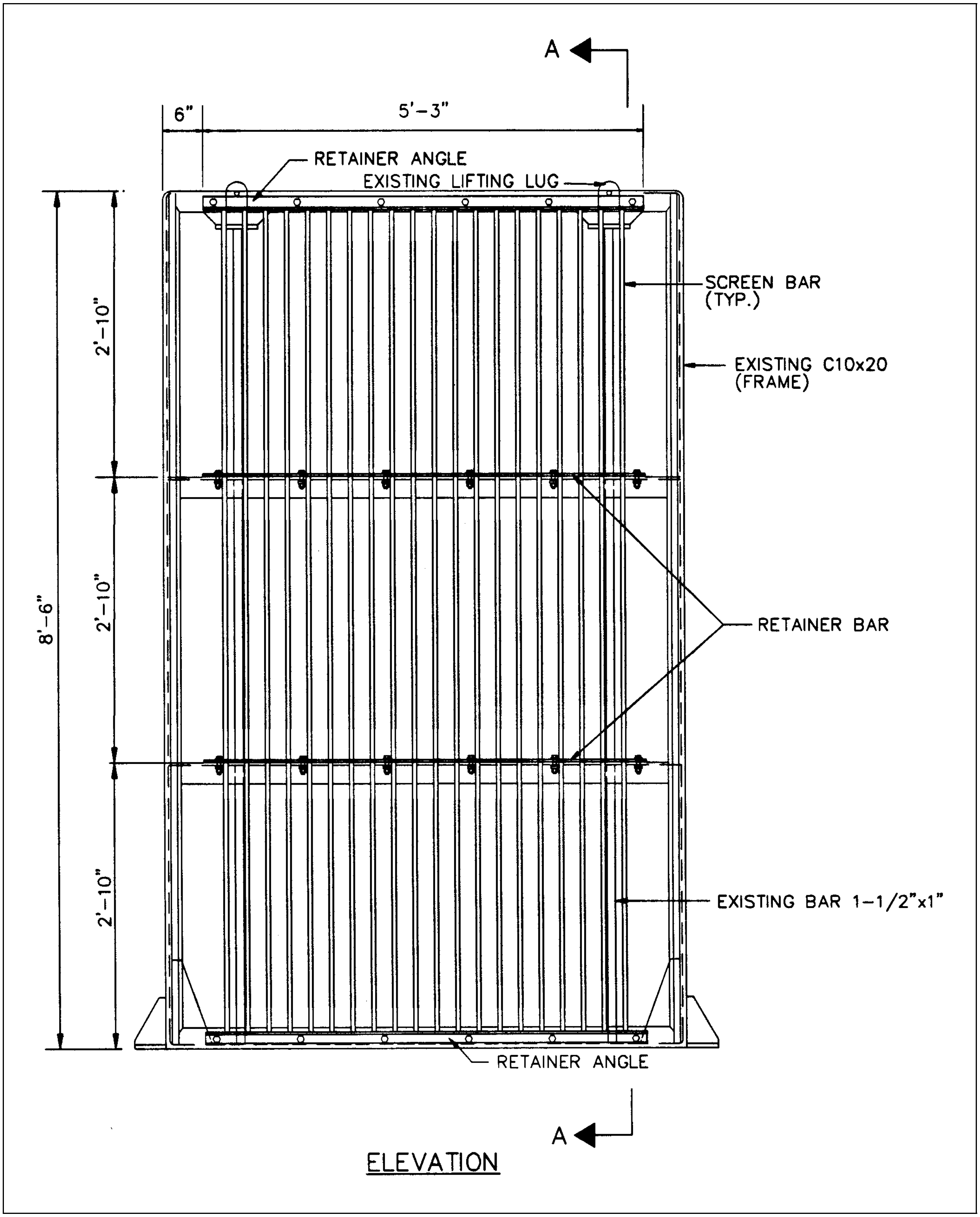


**Figure 8-11. Trashrack repair details (1 in. = 2.54 cm; 1 ft = 0.3 m) (Continued)**

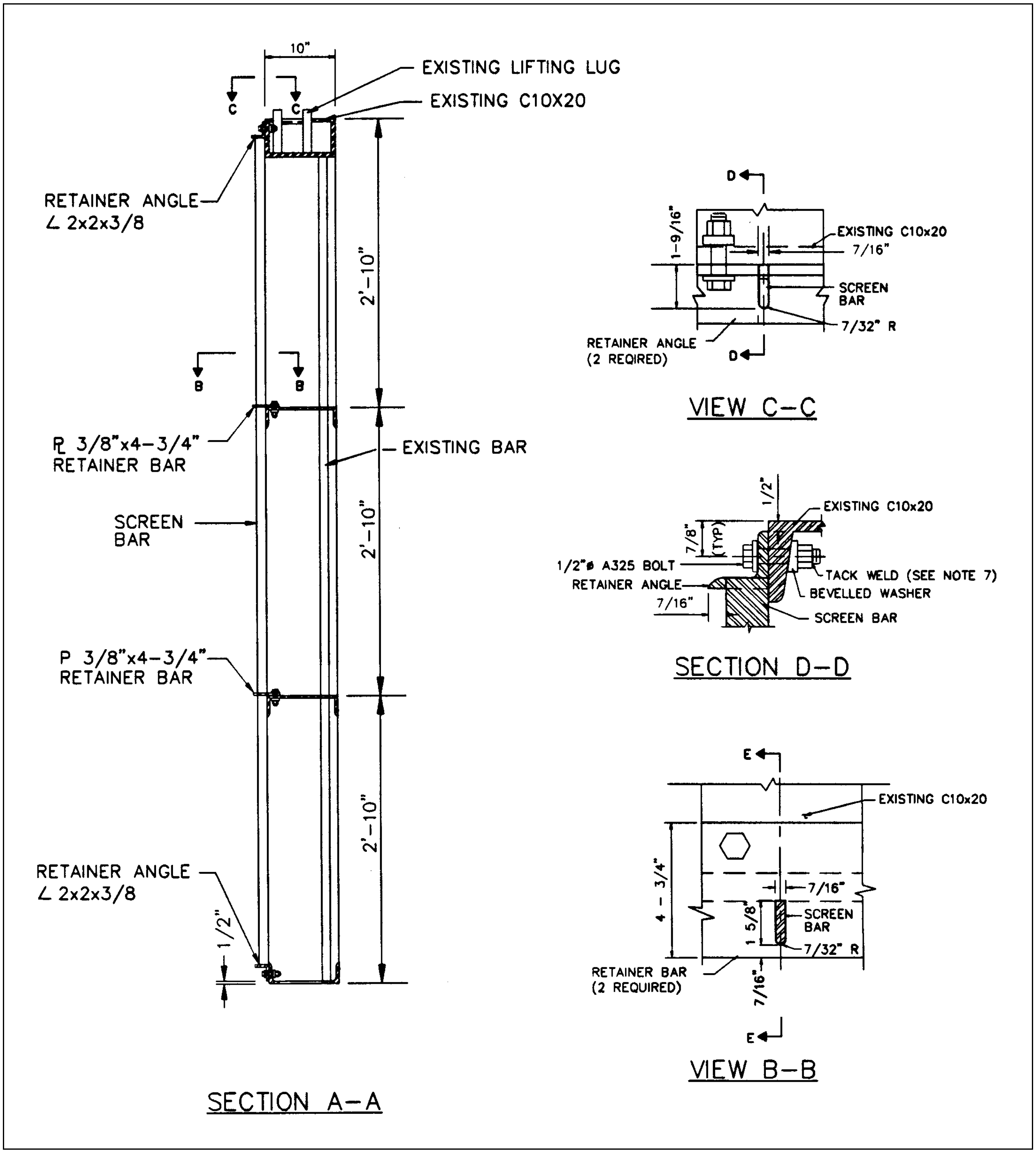


Figure 8-11. (Concluded)

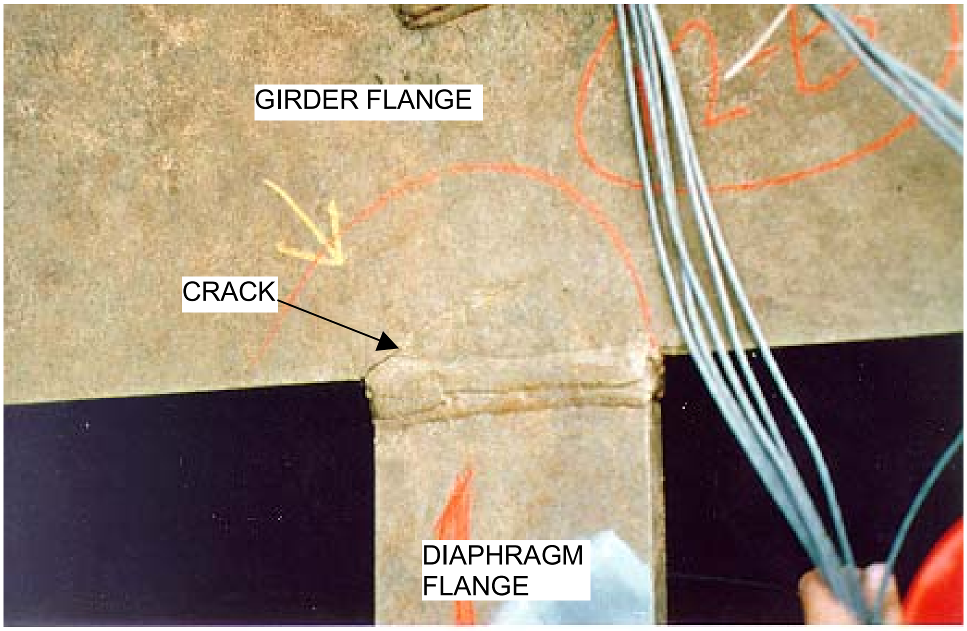


**Figure 8-12. Cracked girder tension flange at diaphragm of a lift gate**

(3) Repair alternatives.

(a) The ideal crack repair would also improve the fatigue strength of the detail and would eliminate the out-of-plane distortion. However, to eliminate the displacement shown in Figure 3-5 would require significant structural modification, and the cracking might not have occurred given connection details with higher fatigue strength. The fatigue strength of the detail would be improved by providing a smooth radius between the diaphragm flange and girder flange. This would improve the stress concentration condition and could theoretically improve the fatigue strength from Category E to Category B (see condition 16 of Table 2-1). The recommended repair is a combination of crack repair procedures shown in Figures 8-3 and 8-4. First, repair the crack according to Figure 8-4 while following the guidelines for welded crack repair given in paragraph 8-4*a*. Then add the radius plate and drill the hole as shown in Figure 8-3 and as described in paragraph 8-6*a*(3).

(b) Another possible alternative would be to install a bolted repair similar to that shown in Figure 8-7 (a similar repair is described in paragraph 8-6*c*(3)). Before the bolted repair is installed, the crack tip should be drilled and the diaphragm-flange-to-girder-flange weld should be removed to eliminate the stress concentration.

(c) In the design of new gates, the low fatigue strength details could be eliminated by installing a skin plate on the downstream face of the gate. This was done in a recent design of a vertical lift gate. Instead of downstream bracing members, the new design called for a skin plate on the downstream face of the gate.

*g. Crack in vertical lift gate at uncoped web stiffener.*

(1) Description of condition. A through-thickness crack that extends through the tension flange of a built-up girder on a vertical lift gate is shown in Figure 8-13. The structure had been in service for less than 2 years at the time the crack was discovered. The crack is located where an uncoped transverse web stiffener is attached. The crack apparently initiated at the intersection of the three welds (web-to-flange,


**Figure 8-13. Cracked girder tension flange of a lift gate**

stiffener-to-web, and stiffener-to-flange). Figure 8-14 shows the intersection of welds where the girder web, girder flange, and stiffener are joined.

(2) Cause of cracking. The three intersecting welds (web-to-flange, stiffener-to-web, and stiffener-to-flange) each contract during cooling and contain tensile residual stresses creating a state of triaxial tension stress. Under the condition of triaxial tensile stress, steel cannot yield and an extremely brittle condition exists. Additionally, at locations of intersecting welds, there is often a lack of fusion at the end of one or both stiffener welds. This results in an embedded discontinuity. The fatigue category considering girder flexure is a Category C for a stiffener coped per American Association of State Highway and Transportation Officials (AASHTO) requirements (minimum cope dimension is required to be at least 4 times the thickness of the web). However, the described condition has much lower fatigue strength due to the increased brittleness and likelihood of embedded discontinuities. The use of uncoped stiffeners should always be avoided; however, there are many such cases in existing USACE structures. A similar condition exists in many vertical lift gates and miter gates where built-up girders and diaphragms intersect. If the diaphragm web is not coped, intersecting welds exist (girder-web-to-girder-flange weld, diaphragm-web-to-girder-web weld, and the diaphragm- web-to-girder-flange weld).

(3) Repair alternatives. Prior to cracking, a general retrofit for uncoped stiffeners is to drill a hole in the stiffener adjacent to the intersection and grind all surfaces smooth. The drilled hole removes the weld intersection and effectively serves as a cope. A similar type repair has been completed on web connection plates that intersect with transverse web stiffeners (Fisher 1984). The actual repair of this condition consisted of a bolted splice plate (Figure 8-15). Ideally, the stiffener should have been drilled near the intersection (as previously described) before the splice plate was installed. Additionally, the crack tip should have been located and drilled out. With this repair, the crack is isolated and the fatigue strength is improved to Category B. It is possible that a welded repair (similar to that described in paragraph 8-6*a*(3) for a crack that extends into the web), could have been completed. However, such a weld repair would have been difficult or impossible with the existing stiffener located adjacent to the crack.

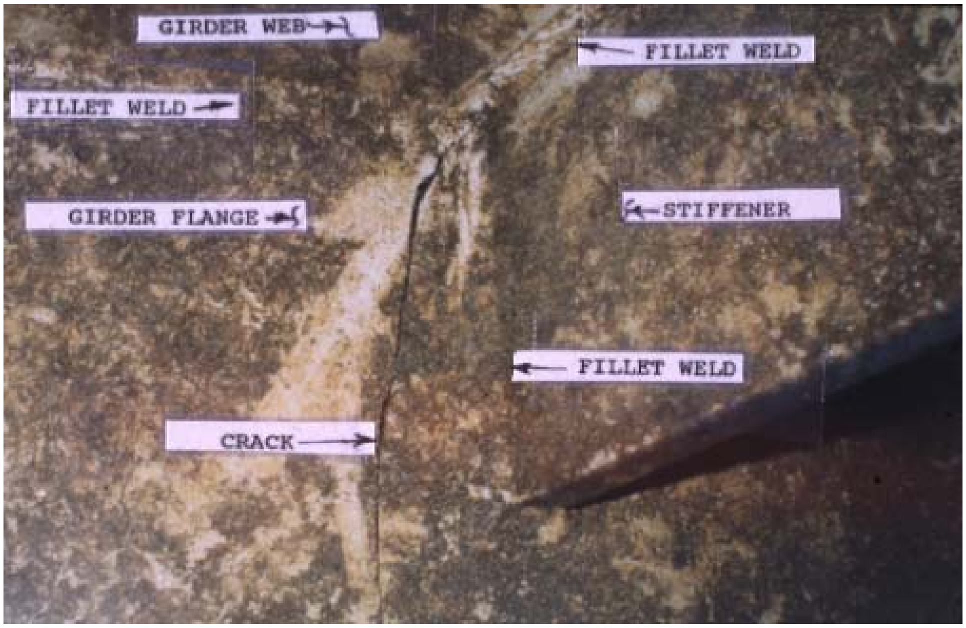


**Figure 8-14. Intersecting welds at web stiffener of the girder shown in Figure 8-13**

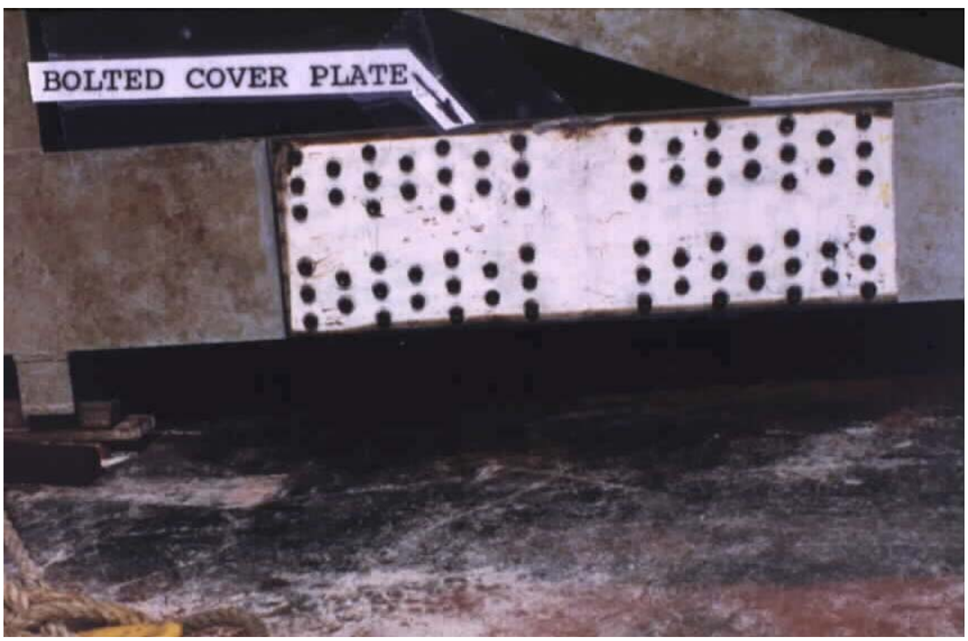


**Figure 8-15. Bolted repair splice for the girder shown in Figure 8-13**

*h. Cracked handrails.*

(1) Description of condition. After less than 2 years of service, severe cracking occurred at numerous locations on a welded steel handrail (Figure 8-16). The basic railing configuration is shown in Figure 8-17. All railing consists of 38-mm (1-1/2-in.) stainless steel pipe. The top rails are continuous and are fillet welded to the top of vertical posts. The bottom rails consist of segments of pipe fillet welded at each end to the vertical posts. Considering flexure in the rails, the fatigue strength of the rails at


**Figure 8-16. Cracked steel handrail**

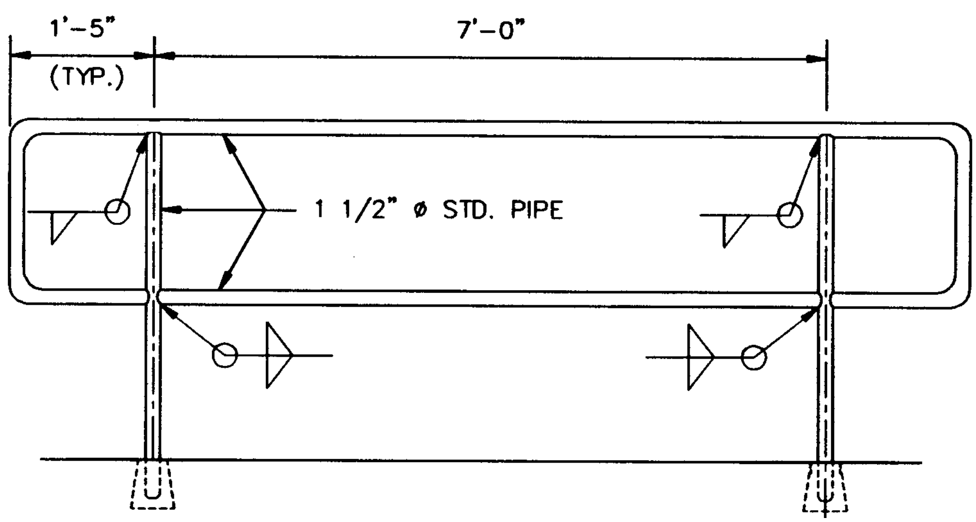


**Figure 8-17. Steel handrail schematic (1 in. = 2.54 cm; 1 ft = 0.3 m)**

the post is similar to Category C. Vertical cracks (perpendicular to the rails) located at the outer edges of the posts occurred in the top and bottom rails at numerous locations. Several of the cracks propagated through the pipe.

(2) Cause of cracking. Cracking is attributed to high cycle fatigue. A laboratory analysis was conducted on one of the failed pipes to determine the cause of cracking. The analysis showed that the crack

initiated at the weld toe and propagated to failure under high cycle vibration loading. Field observations confirmed that the rails vibrated with significant midspan displacement when subjected to wind loading.

(3) Repair. The handrails were repaired with bolted tee and cross fittings fabricated to fit snugly around the intersecting pipes (Figure 8-18). The fittings consist of two pieces that sandwich the pipe like two halves of a sleeve to form a bolted splice. The first repair fittings were aluminum because steel fittings were not available. Therefore, corrosion was also a consideration since stainless steel and aluminum are dissimilar metals. To protect the aluminum from corroding, an electric isolater that consisted of a thick epoxy-based paint was applied to the inside surface of the fittings. After 2 to 3 years, the aluminum fittings had corroded significantly. The fittings have since been replaced with custom-manufactured stainless steel fittings. This repair improved the original fatigue strength from Category C to Category B. In addition, the rails are now more flexible since their end connections are no longer rigid. This may improve the vibration problem (similar to the discussion of repair of the trashrack bars in paragraph 8-6*e*).

**Figure 8-18. Bolted tee connection retrofit of fractured hand rail**