REPAIR OF POPLAR STREET COMPLEX BRIDGES IN EAST ST. LOUIS

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The web cracks found in the Poplar Street Complex Bridges were located at the top of the web-to-bottom flange fillet weld near the end floor beams. The buckled web was observed at the end of the girders behind the bearing stiffener. This report summarizes the results of the study which intends to determine the proper causes of the distress. It is believed that the main cause of the web crack was due to the out-of-plane movement of the web; and that the cause of the web buckling was from the eccentric reaction induced by the seized bearing pin. The repair method was developed mainly to stiffen the section and to carry the secondary stress induced from the out-of-plane movement of the web and to resist the distortion of the girder due to differential deflection of the main girders. Suggested details for future design are also included.

Introduction

The Poplar Street Complex, located on the east bank of the Mississippi River in East St. Louis, Illinois, is a focal point where Interstate Highways I-55, I-70 and U.S. Route 40 join to cross the Mississippi River. The system was built in stages with the first stage opened to traffic in 1967.

The Complex is one of the largest and busiest interchange system in the State of Illinois (see Fig. 1). It extends from the Poplar Street Bridge over the Mississippi River on the west, northeast to Broadway in East St. Louis for the main line routes with additional ramps to the south and southeast to connect with State routes and East St. Louis Street. It consists of many vaiducts with series of three and four span continuous two girder type bridges.

The majority of the two girder type bridges are on horizontal curves with radii of approximately 550 meters (1800 feet). The torsional rigidity of the open frame system is provided by the closely spaced floor beams which are rigidly connected to the main girders. The floor beams support the stringers and the reinforced concrete deck which carry the traffic loads. The floor beams, then, transfer the loads from the stringers to the main griders.

In late 1973, the Bridge Inspection Team of the Illinois Department of Transportation made their first in-depth field inspection of this bridge. They discovered many structural problems in the main supporting members of the bridges. These problems consisted of web cracking, web buckling and separation between the bottom flange of the girder and the top bearing plate. The major areas of distress were predominantly located at the ends of the continuous girders.

This report summarizes the findings from a series of studies. These studies were intended to determine the causes of the distress. From these studies, corrective measures to restore the structural integrity have been developed. Recommendations for future design are also presented.

Description of Structural Problems

The distressed areas found in these bridges can be categorically divided into three groups.

Web Cracking

Web cracks were first observed at the end of the girder under the end floor beam connecting plate which is positioned 18 cm. (7 inches) toward the center of the span from the center line of the bearing stiffeners. Most of these cracks started near the lower end of the vertical connecting plate and extended in both directions in the girder web as shown in Fig. 2. The longest crack observed was 48 cm. (19 inches) long. Some had two cracks at the same location, one was immediately under the lower end of connecting plate; the other, just above the web-to-flange weld toe. The former was shorter in length. In a later inspection, it was found that the web cracks had also developed at the upper end of the connecting plate in the negative moment region.

Web Buckling

Web buckling was observed at the end of the girder. This buckling of the web occurred a few inches above the bottom flange as shown in Fig. 3 and was often associated with the separation of the top bearing plate from the bottom flange of the girder (see Fig. 4). In some cases, web cracking above the web-to-bottom-flange weld toe was also observed. This crack started at the end of the girder and progressed horizontally toward the bearing stiffeners.

Separation Between Bottom Flange and Bearing Plate

The front part (span side) of the top bearing plate separated from the bottom flange of the girder. In some locations the separation started at the front edge of bearing plate and extended horizontally to a point below the end bearing stiffeners. In other locations, the separation was wider at the outside edge of the flange than on the inside edge of the flange. Figure 4 shows a general view of the separation.

Analytical Study

Analytical Study was initiated in December 1973 by the Bridge and Traffic Structures Section of the Illinois State Department of Transportation to determine the probable causes of the structural problems. The following is a discussion of the study:

Web Cracking

These cracks were found near the end of the girders. As shown in Figure 5, the end floor beam is rigidly connected to a connecting plate on the inside face of the girder web. The connecting plate located 18 cm. (7 inches) from the centerline of the end bearing stiffeners was welded to the top flange and the web of the girder, but had a tight fit at the bottom flange of the girder. Since the end floor beam is rigidly connected to the connecting plate, the rigid connection transmits the rotation of the floor beam to the supporting girder. The rotation tends to pull the top half of the main girder inwards and push the bottom half outwards. The girder flanges at this location are restrained from movement by the concrete slab at the top and by the bearing assembly at the bottom. This restraint induces a moment at the junction of the girder web and the girder flange. The moment at bottom of the girder web produces tension stress on the inside face of the girder web and compression stress on the outside face of the girder web. The unconnected but tight fitted lower end of the connecting plate cannot resist this tensile stress and this additional force is transmitted into the web. The stress produced by this force on the web approaches the yield strength of the material every time when the end floor beam is subject to the designed live load. The fatigue resistance of the web at the end of the welded connection plate is classified as categoty C in AASHTO Specifications. It is apparent that the high cyclic tensile stress in the web will initiate the fatigue crack.

If the connecting plates had been welded to the flanges, the additional strength of the T-section formed by the connecting plate and the web would have reduced the stress in the web due to moment to within the allowable stress range. It appears to us that this is the reason why there were no cracks in the web where the connection plates were welded to the flange. Cracking did not occur in the lower web of the girder at the piers or at end of the girder where the floor beams were connected to the bearing stiffeners. Since the bearing stiffeners were milled to bear on the bottom flange and were placed on both sides of web, the compression stress in the stiffeners due to reaction at the bearing can offset the tensile stress produced by the movement of the web as mentioned previously; besides, the frictional restraint at the contact surfaces between mill-to-bearing end of the stiffeners and the top face of the bottom flange can prevent the web from moving.

The floor beams located in the positive moment regions which are connected to a single connecting plate as previously discussed showed no distress because the bottom flange of the girder was free to displace and rotate. The freedom to move released the stress in the web and prevented the cracks in the web near the bottom flange from developing.

Buckling of Web Behind End Bearing Stiffener

The cause of the web buckling was due to the eccentricity of the reaction between the bearing shoe and the bearing stiffener. This eccentricity of the reaction resulted from the following two existing conditions: (a) Misalignment of the centerline of the bearing stiffener with the centerline of bearing assembly during construction of the structure (b) The transverse separation of the bottom flange of the girder from the top plate of the bearing due to a seized bearing pin in the bearing assembly.

The misalignment of the bearing was apparently the result of the substructure being built out of alignment and/or incorrect fabrication of the curved girders. It was noted that some of the bearing shoes (see Figs. 3 and 4) were not bolted to the bottom flange as specified in the plans, but were welded to the bottom flange in the field.

The seized bearing pin forced the girder to bend in order to accommodate the thermal movement and rotation. This additional bending pulled the bottom flange and top bearing shoe apart and resulted in the eccentricity of reaction between the effected area of the bearing shoe and the bearing stiffener.

The eccentric position of the bearing shifted part of the load from the bearing stiffener to the web behind the stiffener and can cause the web to buckle. It should be kept in mind that since the reactions are very large, a small eccentricity of the reaction from the bearing will result in a very high stress on the end of the web plates.

Separation Between Bottom Flange and Bearings

The separation of the bottom flange from the top bearing plate occurred at locations where the bearing pin seized and ceased to rotate. It appears from the unscraped painted surface on the pin that many of the bearing pins have never functioned properly. This painted surface referred to is between the center support plates of the top and the bottom bearing shoes on the bearing pin. Since these support plates are in contact with the painted surface on the pin, any movement of the bearing will scrape paint from the pin.

At several locations, separation between the bottom flange and the bearing shoe along the outside edge of the flange was observed. In some cases, this longitudinal separation was associated with the broken connecting bolts. These bolts held the bottom flange to the bearing shoe. The cause for this type of separation seems to be due to the moment at the floor beam connection which has a tendency to push the bottom of the girder outwards and the additional bending of the girder from the seized bearing pin as discussed previously. The twist of the bottom flange induced a tension force in the bolt. This is a tensile fatigue loading. After enough cycles, fatigue cracks in the bolt will result.

Field Tests

It had been reported from visual field inspection that most of the expansion bearings were seized. In order to verify the visual observation, field tests were planned and carried out by the Research Team of the Department of Transportation, State of Illinois, from December, 1973 through February, 1974.

Two sets of measuring devices were developed and installed at six different locations (Fig. 6). One measuring device consisted of two steel bars attached to the top and the bottom shoes of the pin supported type bearing assemblies to measure the rotation. Another measuring device consisted of a scale fastened to the bottom flange of the girder and a point indicator attached to the substructure to measure the relative movement. Test readings indicated no movement on half of the bearings tested, and less movement than expected on the other half.

The seized bearings at the east abutment of ramp B were removed and replaced with elastomeric bearings reinforced by steel laminas (see Fig. 7). These elastomeric bearings were set tangent to the radius at the center line of the bearing. An instrument was installed on the bottom of the girder flange to measure the thermal movement of the girder. Theoretically, the thermal movement of a curved girder is along the chord line between the fixed bearing and the expansion bearing. The measured direction of the movement at the east abutment of ramp B for the temperature differential of 28° C(50° F) was about 4° shown on Fig. 8. The angle between the tangent at center line of bearing and the chord line through the fixed bearing is about 1° 30' according to plan dimensions. The measure angle was approximately 2.7 times the theoretical angle. The discrepancy may be due to the following reasons:

1. The rotation of the end floor beam pushed the girder outward.
2. The distortion of the structure by restraining force developed within the system of steel bearings used.
3. The substructure was built out of alignment and/or incorrect fabrication of the curved girder.

This field test supported the visual observation reported by the Inspection Team that a majority of the expansion bearings were seized. The seized bearing pin forced the girder to bend in order to accommodate the expansion and rotation. The bending of the girder had contributed to the separation between the bottom flange and the top bearing plate. The separation created an eccentric load on the bearing stiffeners. A small eccentricity of the reaction from the bearing results in a very large stress on the end of the web plate. When this stress is larger than the critical stress of the web plate, the web will buckle.

A second field test was planned and performed by Professor John Fisher in the Summer of 1975. The purpose of the test was to ascertain what caused the web cracking.

Strain gauges were installed on the web at the pre-selected locations for strain measurement. The complete results were presented in Professor Fisher's Report (3).

Following is a discussion relative to the test results:

At the End Floor Beams

Most of the end floor beams are set near the top of the girder and are rigidly connected to a vertical connecting plate. This plate was welded to the top flange and the web of the girder, but had a tight fit at the bottom flange. This plate is located 18 cm. (7 inches) from the centerline of the end bearing stiffeners. The connecting plate was clipped 25x25 mm. (1x1 inches) top and bottom at the inside corners to clear the web-to-flange weld. The gap between the clipped edge of the plate and the web-to-flange weld was created in the web. See Fig. 5.

Two strain gauges were installed in the lower gap region at the northwest bearing of pier 26, ramp C, identified as C-26NW. See Fig. 9. Gauge readings indicated very little out-of-plane movement of the web at this location. This was due to the fact that the gap in the web is very small, about 2.5 mm (0.1 in.), and the tight fit joint may provide enough friction to reduce the movement. No web cracking was observed.

A few of the end floor beams are connected to the bearing stiffeners. The bearing stiffeners had a tight fit end at the top and mill-to-bear end at the bottom. Four strain gauges were installed, two at the top and two at the bottom at location B-27 NW. See Fig. 10 and Fig. 11. It was found while installing the strain gauges that the tight fit end of the bearing stiffeners had a larger gap between stiffeners and the top flange than was anticipated. The top gauge readings, shown in Fig. 12, clearly indicated that the web was pushed out-of-plane by the rotation of the end floor beam. The stress in the web as computed from strain gauge readings is shown in Fig. 13. The web is subject to this high stress every time there is a live load on the floor beam. After many occurrences, web cracking due to fatigue is inevitable and a crack was observed. The measurement at the bottom indicated that the stress in the web was smaller. See Figs. 14 and 15.

Interior Floor Beam - Positive Moment Regions

The interior floor beams in positive moment regions were connected to the girders in the same manner as discussed above except the top of the floor beam is set near the mid-depth of the girder. In addition, a stiffener was welded to the outside web and the stiffener was undercut by 16 mm (5/8") at the tension flange.

Strain gauges were installed at location B-27FBI-W, the first interior floor beam west of pier 27, ramp B. See Fig. 16. Some of the gauge readings are shown in Fig. 17, others are shown in Fig. 12. There was very little movement in the web at this location. This is due to the inability of the flange to resist lateral movement because of lack of torsional stiffness, thereby relieving substantially the strain which might be introduced in the web gap. No crack was observed. None will likely develop in the future.

Interior Floor Beams - Negative Moment Regions

The connecting plates in the negative moment region were welded to the bottom flange and had a tight fit at the top. Web cracks at the top were observed at several locations. The strain gauges installed at location B-26FBI-W (see Fig. 18), showed some movement in the web. The stress in the web induced by the movement is shown in Fig. 19. The stress is less than the fatigue limit of category C. However, since web cracking at the upper end of the connecting plate was observed on the inside face of the web, it was apparent that the large web bending stress, which was even larger than measured by strain gauge, had been present at some time.

It is interesting to note that two types of deformations at the web gap region are possible. One is translation which creates double curvature bending; the other, single curvature bending as shown in Figure 20. This variance is not clearly understood from the limited test data. A tentative explanation may be:

1. When the floor beam is set close to the web gap region, the connection plate becomes very stiff and could not be bent due to the shorter distance between the floor beam connection and the web gap. Hence, the translation type deformation results.
2. When the floor beam is set at some distance away from the web gap region, the bending of the connection plate is possible.

However, it can be concluded that the out-of-plane movement of the web was the only cause producing the web crack.

LABORATORY TESTS

Laboratory test were carried out by the Research Team of the Illinois State Department of Transportation in order to determine the cause of the bearing seizure. A pilot test was made on a one-third size model. Loads were applied in increments up to a maximum load which produced a unit bearing pressure of 228 Mpa (33 Ksi) on the contact surface of the bearing pin. Examination of the pin after testing had revealed evidence of galling on both the pin and the saddle as shown in Figs. 21 and 22. The galling had produced a build-up of hard, solid material which could lock the pin to the saddle.

A series of four tests were performed under the same loading pressure, 70 Mpa (10 Ksi), and the same 2000 cycles of movement. The bearing pins were made of the same material with different surface treatments.

A mild steel pin without surface treatment was tested first. Galling appeared on the surface of the pin as shown in Fig. 23, specimen T-1. A second specimen was of the same mild steel pin but was case hardened. The amount of wear experienced was not significant as can been seen in Fig. 23, specimen T-2. A third specimen was of a mild steel pin with no surface treatment but lubricated with a heavy duty grease. Galling to some extent was evident as shown in Fig. 23, specimen T-3. The last specimen was a case hardened pin with a dry film lubricant. The result of this test showed little benefit in the use of dry lubricant. See Fig. 23, specimen T-4.

It was interesting to learn that the coefficient of friction for specimen T-1, T-2 and T-4 increased with increases in the number of cycles of movement and gradually tapered off after 200 to 300 cycles. However, the coefficient of friction for specimen T-3 which had the heavy grease lubricant was constant throughout the test and about one-half of the value obtained for pins without grease lubricant. See Figs. 24 and 25.

A conclusion can be drawn from these tests that use of the pin with a case hardened surface and lubricated with a heavy duty grease would be highly beneficial as a means of improving the behavior and life expectancy of a pin supported bearing.

Two steel bearings were removed from the east abutment of ramp B as mentioned before. These bearings were cut open to inspect the contact surface of the pin and the saddles. See Figs. 26, 27 and 28. A layer of highly compacted rust was found on the contact surfaces of the pin and the saddles. After approximately 95 percent of the rust material was removed by a rust solvent, the contact surface of the pin was inspected again and the visual inspection did not reveal any severe sign of galling as observed on the laboratory specimens. The absence of galling indicates that the formation of compacted rust was probably the primary factor contributing to the seizure of the bearings.

REPAIR

The repair plans were prepared in late 1974, and the contract was let in early 1975. The corrective measures were developed based on our initial study. The method of repair was to stiffen the ends of the girders so as to carry the secondary stresses induced from the out-of-plane movement of the web or from the eccentric reaction.

Web Cracking

The web cracks were due to the out-of-plane movement of the web. The method of repair was to stop the movement or to minimize the damage. The repair procedure was as follows:

At Grider End.

a. Drill a 13 mm. (1/2") hole in the web at the end of the crack.
b. Clean and prepare the edge of the crack for a full penetration butt weld.
c. Weld the connecting plate to the bottom flange by continuous fillet weld.
d. Weld a new plate 203x13 mm. (8"x1/2") on the outside face of the girder opposite to the inside connecting plate as shown in Fig. 29.

At Negative Moment Regions.

The web cracks at the top of the web in the negative moment regions were repaired by a different technique. Due to the stress range in the tension flanges, to weld the connecting plate to the flange would create a fatigue problem in the flanges. The repair was done as follows:

a. If there was no crack in the web, a 13 mm. (1/2") hole was drilled just below the web-to-flange weld at 102 mm. (4") on each side of the connection plate and a 13 mm. (1/2") hole was also drilled on each side of the top end of the connecting plate.
b. If there were cracks in the web, 13 mm. (1/2") holes were drilled at each end of the cracks. See Fig. 30

Web Buckling

It was concluded that the buckling of the web at the girder end was due to the eccentric reaction created by the seized bearing pin. The repair procedure was:

a. Split the girder web a few inches above the buckled web.
b. Place clamping plates on both sides of the web.
c. Apply force on the clamping plates to straighten the web.
d. The cut portion, then, shall be welded together.
e. After the web is straightened, weld a stiffening plate on each side of the web as shown in Fig. 31.

Frozen Bearing Pin

Most of the expansion bearings at the girder end were seized. This resulted in the separation between the bottom flange and the top bearing plate, therefore causing the web to buckle. In order to provide uniform bearing area and to allow freedom of thermal movement, bearings at the girder ends were replaced with elastomeric bearings as shown in Fig. 7. Steel bolsters were provided to make up the difference in height between the elastomeric bearing and the original bearing.

RECOMMENDATION FOR FUTURE DESIGN

To prevent similar problems from developing in future designs, the following are recommended:

1. The connection plates for the floor beams or the cross frames shall be welded to both flanges. In this case, the stress range in the tension flange shall be limited to the category C fatigue allowable range. An alternate is to provide a sufficient gap between the end of the connection plate and the inner face of the tension flanges. A large gap can provide the web a "breathing" room and then a higher stress will not be introduced in the web. Stiffeners should not run the full depth of the web on the opposite side of the connection plate if this plate is cut short. See Fig. 32.
2. When pin supported type bearings are used, double bearing stiffeners shall be detailed to prevent the end of the web from buckling if the bearing is misaligned or seized. The surface of the bearing pin shall be treated for case hardening. Grease inserts shall be also provided and the pin shall be lubricated upon installation and at regular intervals thereafter in order to reduce the friction and extend the life expectancy of the pin.

SUMMARY AND CONCLUSION

The most important conclusion of the study reported here is that the web cracks at the gap between the end of the floor beam connection plates and the girder flanges are all fatigue related. The cracking has resulted from cyclic web bending stresses in the gap region. Field tests confirmed that the rotation of the floor beam which was rigidly connected to the main girder pushed the web out-of-plane. Since the connection plate with the strong axis perpendicular to the web acts like a rigid bar, the out-of-plane movement is forced into the web gap between the end of the connection plate and the girder flanges due to the lack of resistance to this movement in this gap region. The severity of this movement is greater at the places where the flanges are restrained from movement. In the middle of the span, the inability of the flange to resist the lateral movement relieves substantially the strain which might otherwise be introduced in the web gap.

In addition to the above, the study also yielded the following conclusions:

1. The seizure of the pin supported bearing was related to the presence of packed rust between the contact surfaces of the pin and the supporting saddles.
2. The seized bearing pin forced the girder to bend in order to accommodate the thermal movement and rotation. The bending of the girder lifted the bottom flange up from the bearing shoe, and shifted the reaction from the bearing shoe to behind the bearing stiffeners, therefore causing the web to buckle.

REFERENCES

1. Investigation Report on Poplar Street Complex Bridge. East St. Louis, St. Clair County, Illinois -- By Illinois Department of Transportation, Bureau of Design, Bridge and Traffic Structures Section, June, 1974.
2. Investigation of Bridge Approach Spans to Poplar Street Bridge. East St. Louis, Illinois -- By Illinois Department of Transportation, Bureau of Materials and Physical Research, May, 1975.
3. Report on Investigation of the Girder Web Cracking at Floor Beam Connection Plates of the Poplar Street Complex -- By John W. Fisher, October, 1975.

Figure 1. Vicinity map.

Figure 2. Web cracking.

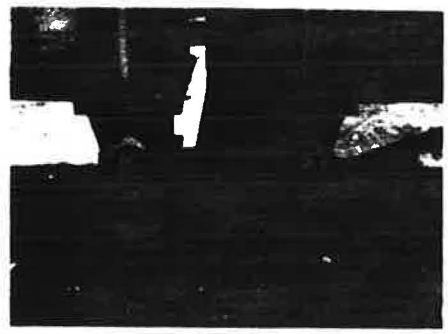


Figure 3. Web buckling.

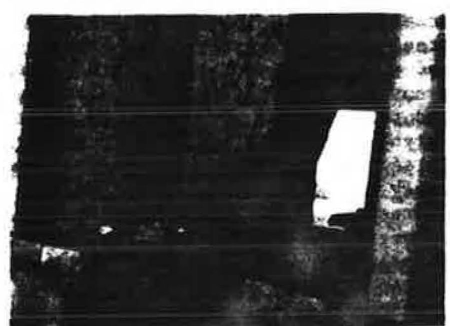


Figure 4. Separation between bottom flange and bearing shoe.

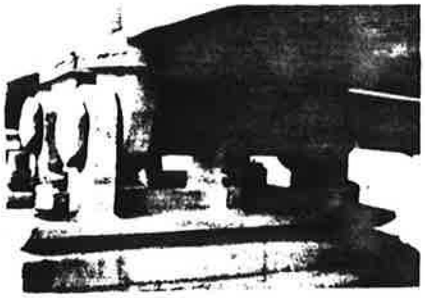


Figure 5. End floor beam connection.

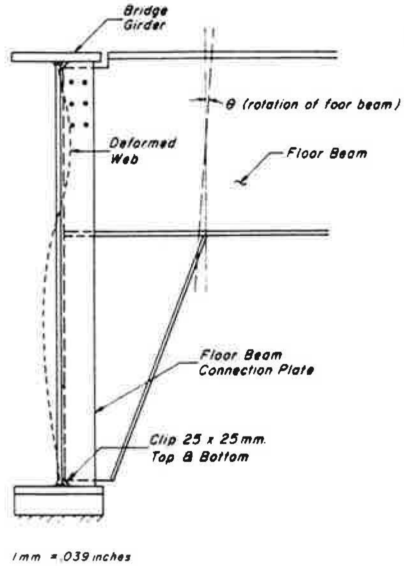


Figure 6. Instrumentation at seized bearing.

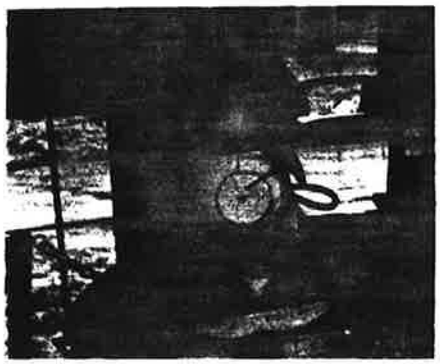


Figure 8. Thermal movement at elastomeric bearing.

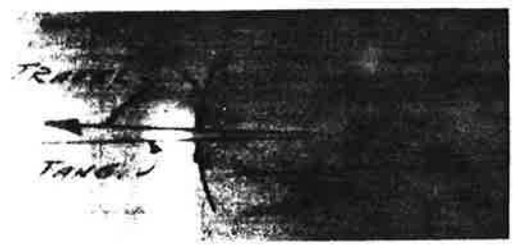


Figure 7. Elastomeric bearing.

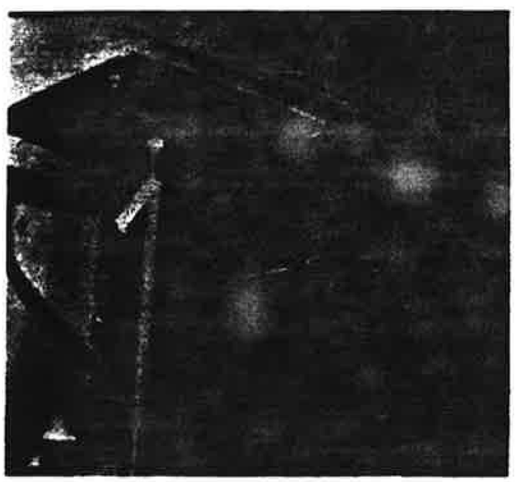


Figure 10. Strain gages at gap near top flange at Pier B-27 NW inside face.

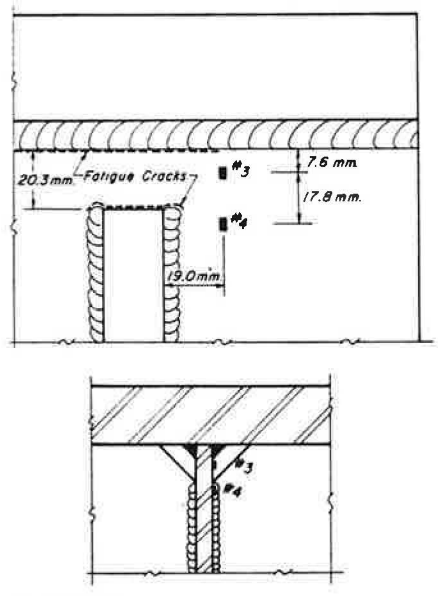


Figure 9. Strain gages at Pier C-26NW.

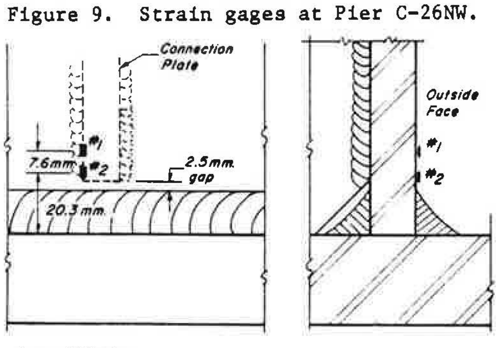


Figure 11. Strain gages near bottom flange gap at Pier B-27 NW.

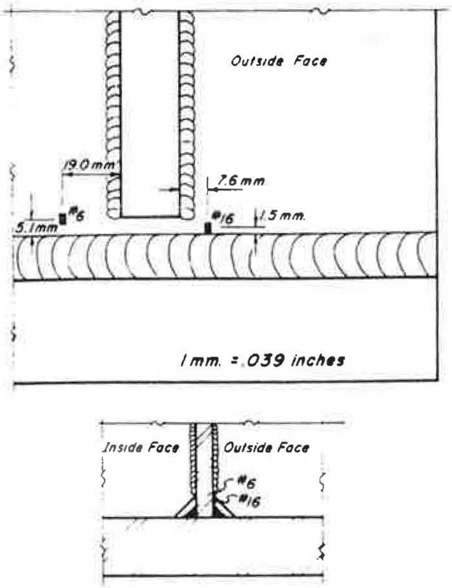


Figure 12. Typical strain response at B-27 NW, B-27 FBI-W.

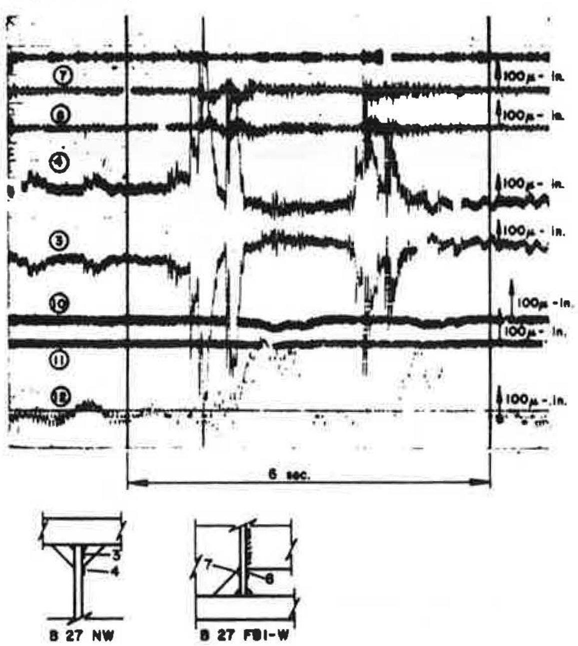


Figure 13. Stress gradient at top gap B-27 NW.

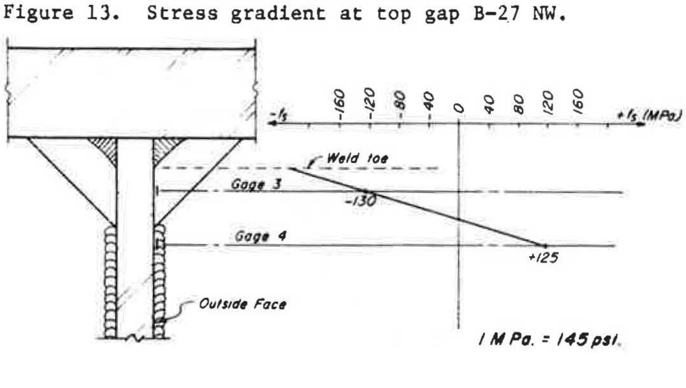


Figure 14. Typical strain response at B-27 NW, C-26 NW.

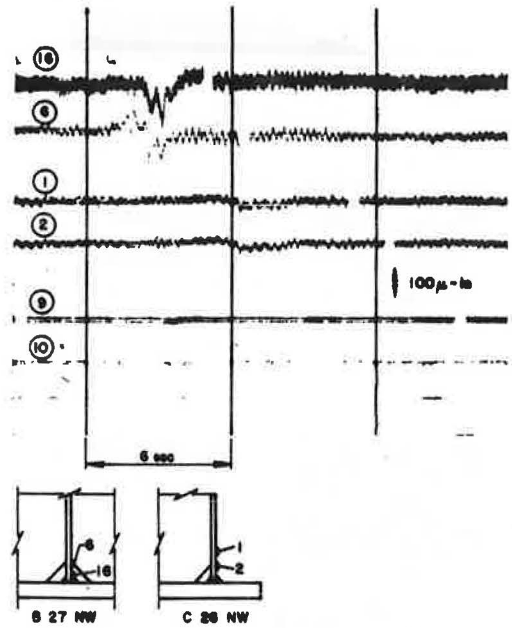


Figure 15. Stress gradient at bottom gap B-27 NW.

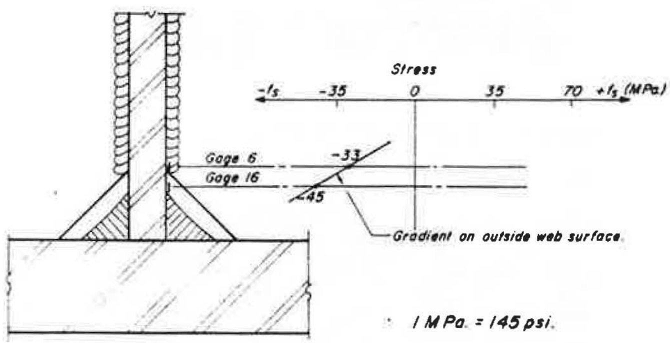


Figure 16. Strain gages near bottom flange gap at floor beam B-27 FBI-W.

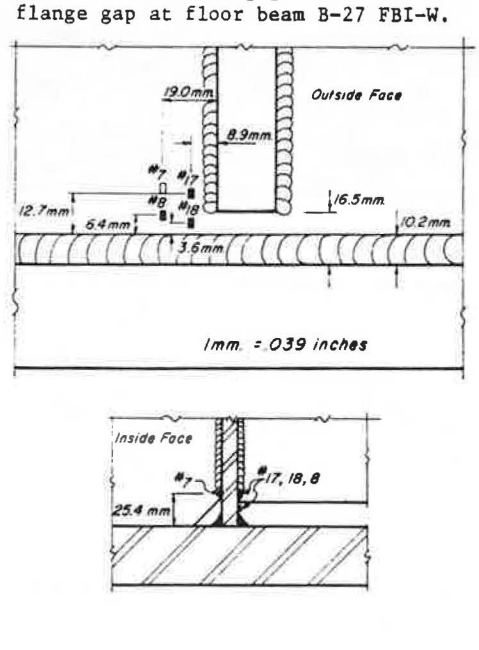


Figure 17. Typical strain response at B-27 NW, B-27 FBI-W.

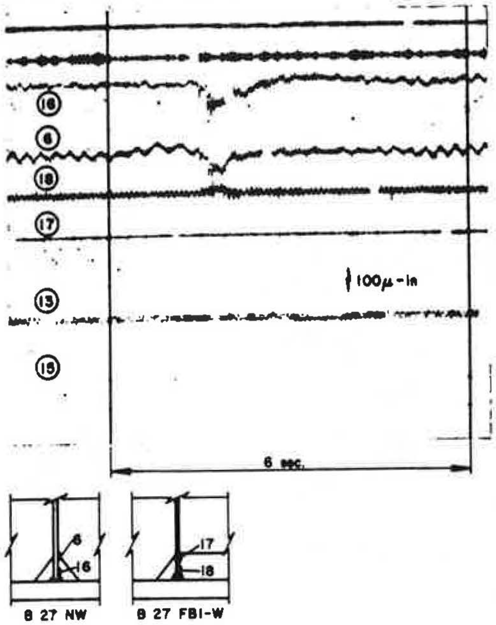


Figure 18. Strain gages near web gap at interior floorbeam B-26 FBI-W.

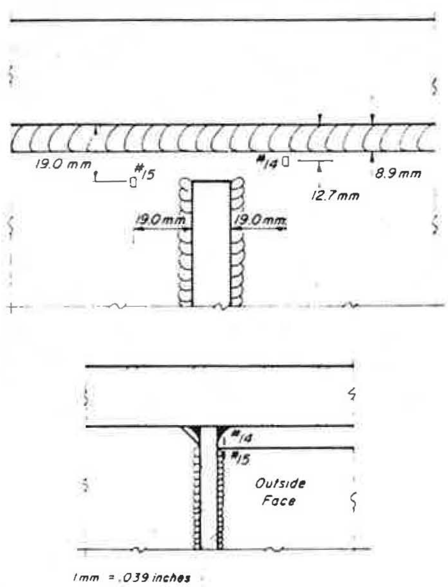


Figure 19. Stress gradient at interior floorbeam B-26 FBI-W.

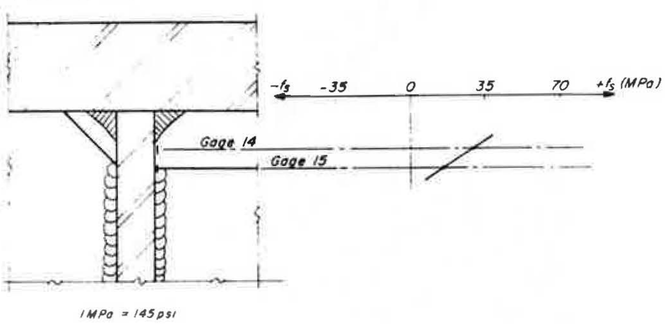


Figure 20. Possible movement at gap region.

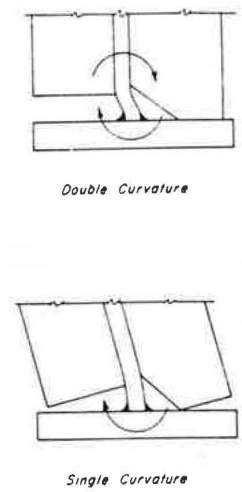


Figure 21. Galling on the surface of the bearing pin (1/3 size model).

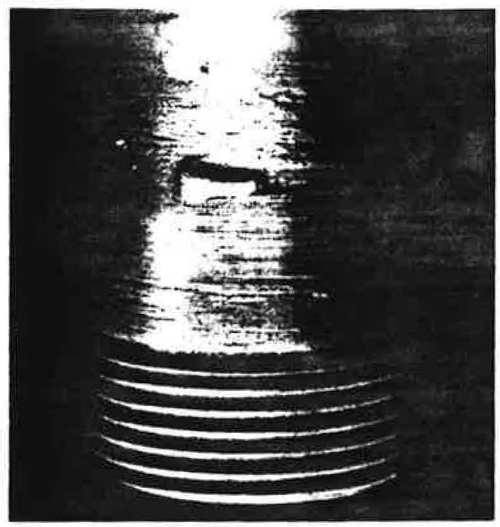
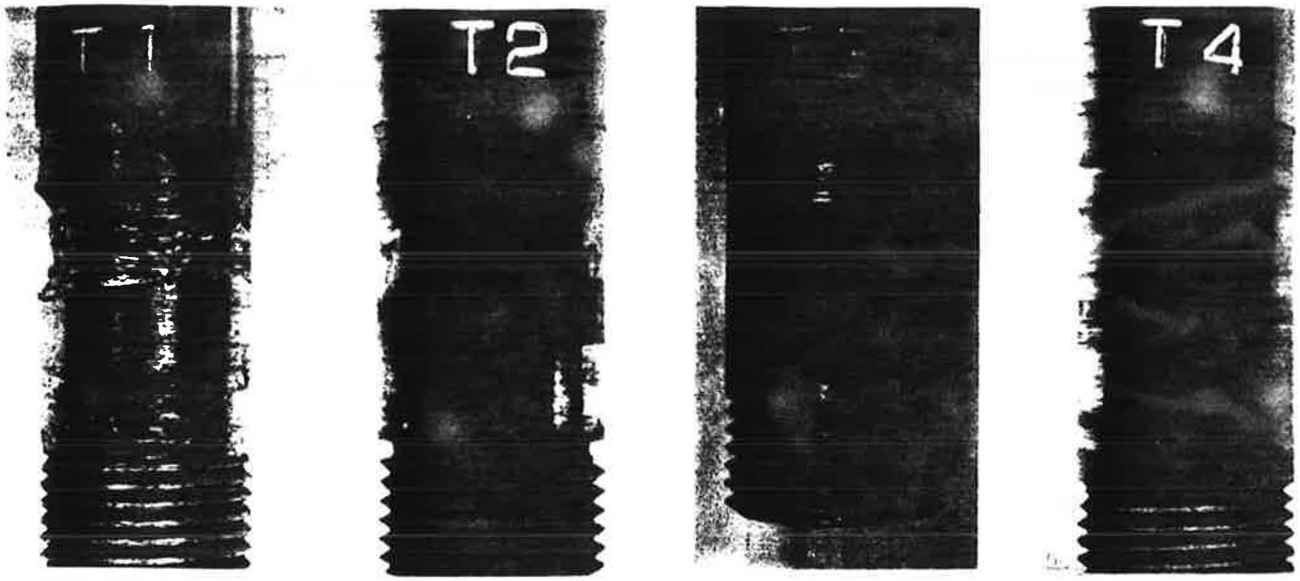


Figure 22. Galling on the supporting saddle (1/3 size model).

Figure 23. Specimens after cyclic test.



Mild steel only | Mild steel case harden (dry) | Mild steel (greased) | Case harden (dry lube)

Figure 24. Coefficient of friction of dry, mild and case hardened pins.

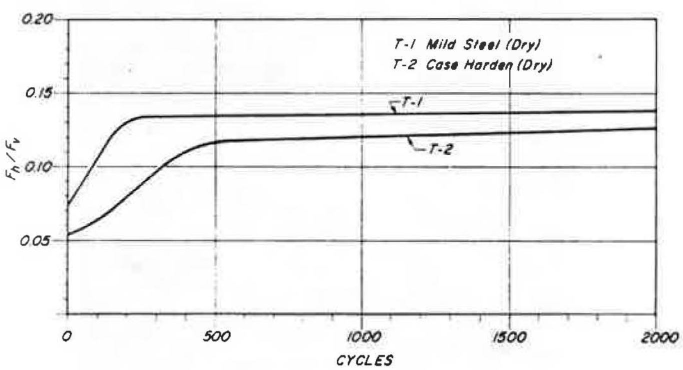


Figure 25. Coefficient of friction of lubricated, mild and case hardened pins.

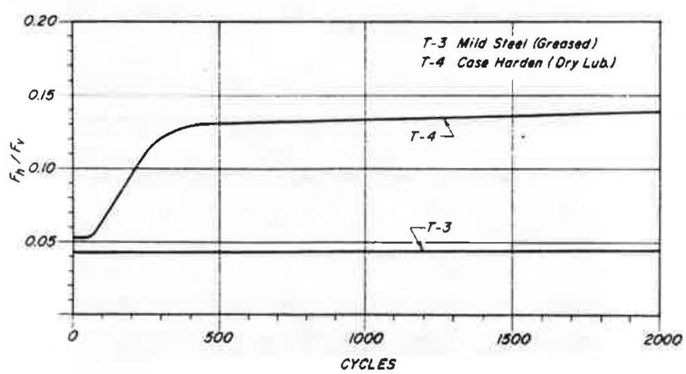


Figure 26. Pin from removed bearing assembly of E. Abut., Ramp B.

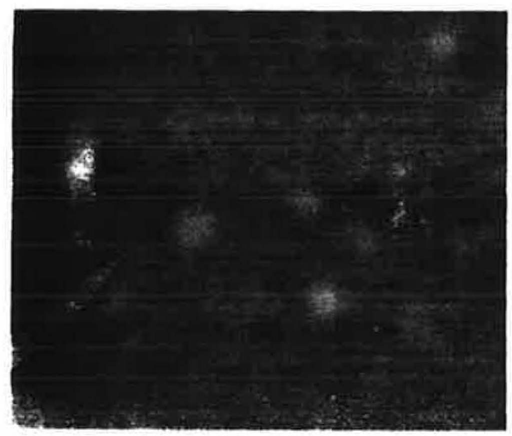


Figure 27. Saddle from removed bearing assembly of E. Abut., Ramp B.

Figure 28. Saddle from removed bearing assembly of E. Abut., Ramp B.

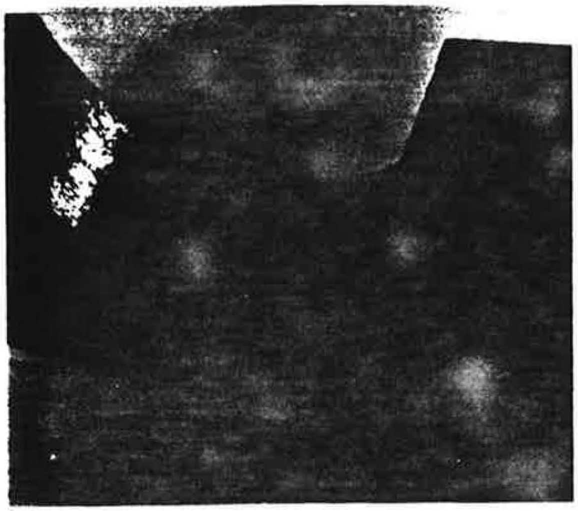


Figure 31. Repair of buckled webs.

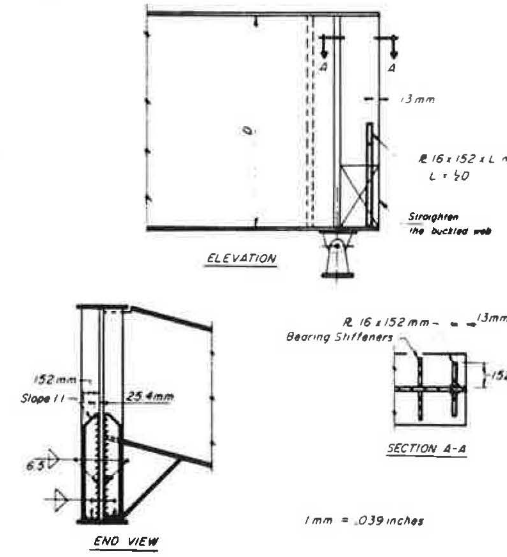


Figure 29. Repair of cracked webs.

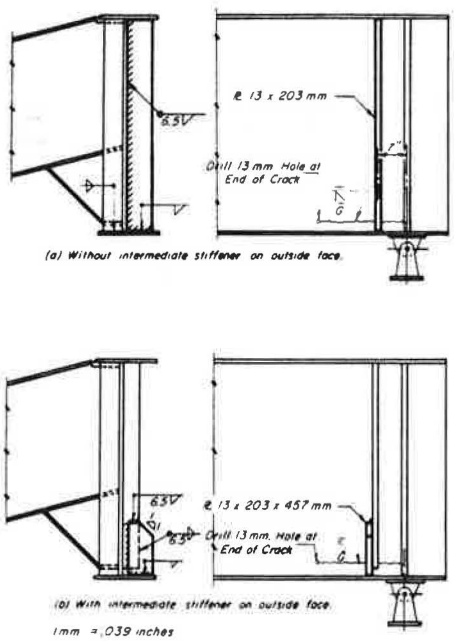


Figure 32. Suggestions for future designs.

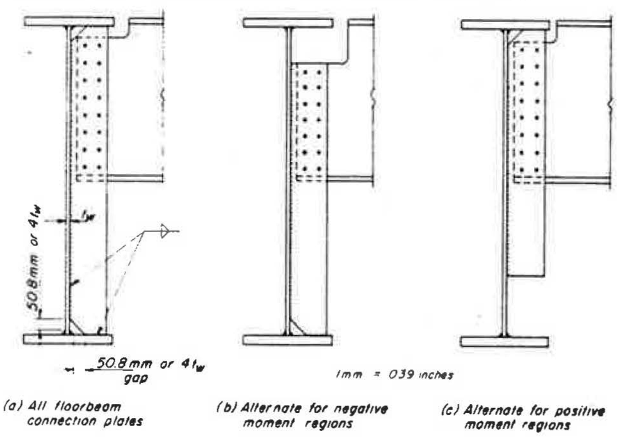


Figure 30. Location of drilled holes to arrest crack.