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RETROFITTING FATIGUE DAMAGED
COVER-PLATED BRIDGE MEMBERS

by

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ABSTRACT

This paper summarizes the results of laboratory and field studies on post weld treatment of the termination of welded cover plates. Both as-welded and fatigue damaged members were tested in the laboratory to determine ways to improve fatigue strength and to retrofit fatigue damaged bridge members.

Three treatments were examined in the laboratory: grinding, peening, and gas tungsten arc remelting. These methods were applied to details prior to fatigue testing and to members which had experienced fatigue crack growth. Grinding the weld toe with a burr provided the least reliable method. Some improvement was noted at the lower stress range levels, but erratic results were apparent. Gas tungsten arc remelting at the weld toe termination was observed to provide the most reliable and consistent method of improving fatigue strength and retrofitting fatigue damaged members. Peening the weld toe was observed to be most effective when dead load remained on the beam during peening or else the minimum stress was low. Also, only very shallow fatigue cracks could be effectively retrofitted.

Based on the results of the laboratory investigation, two bridge structures with known fatigue cracks at the ends of cover plates were retrofitted using the gas tungsten arc remelt procedure or peening. The results of a detailed inspection in 1976 revealed that 22 of 40 cover plate ends had fatigue cracks in the beam flange at the toe of the end welds. These cracks varied in size up to 1/2 in. (12 mm) deep. Only those beams

with cracks less than 1/8 in. (3 mm) deep were retrofitted by peening. The gas tungsten arc remelt procedure was applied to all other cracked beams. The remelt penetration was about 0.25 in. (6 mm) which was verified by ultrasonic inspection and a sample plate which was sectioned, polished and etched.

The residual life of the large embedded cracks which remained after retrofitting were estimated from the frequency of occurrence and measured stress histories of these details.

1. LABORATORY STUDIES ON COVER-PLATED BEAMS

Fatigue studies on beams with welded cover plates and long attachments have demonstrated that large reductions in fatigue strength occur when fatigue crack growth occurs at the micro-sized discontinuities that exist at the weld periphery.

In addition, fatigue cracking has been observed in the field at cover-plated beam bridges that carried an unusually high volume of heavy truck traffic causing large numbers of stress cycles[1].

The formation of these cracks showed the desirability of examining methods for improving (upgrading) the fatigue strength of welded joints without changing the design details. In addition, methods are needed for arresting the progress of fatigue damage that occurs at the weld toes of severe notch-producing details where the probability of failure is greatest.

An experimental program was carried out on sixty steel cover-plated beams in either the as-welded or precracked condition, to determine the fatigue strength of these details when treated by techniques intended to extend their fatigue life.* Three of the most successful methods reported in the literature for as-welded details were utilized[2,3,4,5]. They

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* This study was conducted under National Cooperative Highway Research Program Projects 12-15(1) and 12-15(2). The opinions and findings expressed or implied in this paper are those of the authors. They are not necessarily those of the Transportation Research Board, the National Academy of Sciences, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, nor of the individual states participating in the National Cooperative Highway Research Program.

included: (1) grinding the weld toe to remove the slag intrusions and reduce the stress concentration, (2) air hammer peening the weld toe to introduce compression residual stresses, and (3) remelting the weld toe using the Gas Tungsten Arc process.

Grinding the weld toe with a burr to provide a smooth transition and minimize the size of the initial discontinuities was the least reliable method. Some improvement was noted at the lower stress range levels as illusrated in Fig. 1, but none at all at the highest level of stress range. Similar results were obtained in earlier studies on as-welded details which indicated that erratic results could be expected.

The results of earlier tests on ground cover-plated beams are also summarized in Fig. 1 and compared with the results of this study and the as-welded beams. It is apparent from the comparison that grinding accompanied by fine finishes decreased the stress concentration condition and resulted in substantial improvements in the fatigue strength. The results also indicate that substantial scatter can be expected from the ground details.

Peening the weld toe was observed to be most effective when the minimum stress was low. This was true for as-welded and precracked details. This appeared to be directly related to the effectiveness of the compressive residual stresses introduced by the peening process. When peening was carried out on unloaded beams, the application of a high minimum stress and/or high stress range decreased the effectiveness of the residual compressive stresses that were introduced. Several tests were carried out on beams which were peened under a simulated dead load condition. Under these conditions about the same improvement was noted at both high (10 ksi) and low (2 ksi) minimum stress levels and at higher stress range levels as well.

The results of all beams with peened details that were tested under a low minimum stress level (2 ksi) or that were peened under their minimum load, are summarized in Fig. 2. Those details that were peened in the absence of dead load are not plotted in Fig. 2. When the 10 ksi minimum stress was applied to these beams it eliminated most of the beneficial effects of the peening treatment.

The test points designated as PA were as-welded beams treated prior to testing. The test points designated as PL were beams that were first precycled to 75% of the life corresponding to design Category E. After being precycled the beams were then treated. They had initial cracks of varying sizes.

Three series of precracked beams and one series of as-welded beams were tested to determine the effectiveness of peening. Cracks as large as 19 mm (0.75 in.) in length and between 1.3 and 3.8 mm (0.05 and 0.15 in.) deep were observed prior to peening. After peening the precycled cracks were no longer visible. Inspection of the fracture surfaces indicate that movement occurred between the crack surfaces to a depth of 3.8 mm (0.15 in.). The precracked details usually failed from continued crack growth from the original crack, but at a slower rate. In a few cases failure was observed from the weld root.

It is readily apparent that substantial increases in life were achieved for as-welded and precracked beams after peening, when peening was applied in the presence of dead load. The fatigue strength was increased by at least one design category[6].

Also shown in Fig. 2 are test results on small plate specimens with 152 mm (6 in.) longitudinal gussets welded to their surface. These tests were reported by Gurney and were made on as-welded specimens[5]. The studies on welded attachments reported in NCHRP Report 147 have demonstrated that the attachment length has a significant effect upon fatigue strength. Hence, these 152 mm (6 in.) longitudinal gusset plates were expected to exhibit slightly more life than those provided by cover-plated beams. This was confirmed by the test data. All of the peened plate specimens fell near the upper limit provided by peened cover-plated beams. This suggests that other details can be expected to exhibit a similar increase in fatigue strength when subjected to peening at the weld toe.

Transverse sections through several peened weld toes, revealed numerous lap-type defects which were the result of extensive surface deformation. An example of this deformation is shown in Fig. 3. The depth of these laps was in order of 0.05 mm (0.002 in.) to 0.25 mm (0.010 in.) which was approximately the same depth as the original slag intrusions. These defects are believed to be typical of the whole weld toe since they were found on all transverse sections.

Gas tungsten arc remelting at the weld toe termination was observed to provide the most reliable and consistent method of improving the fatigue strength in the as-welded or previously precracked condition. In a few instances the initial crack was not removed. Application of the gas tungsten arc remelt process did not succeed in completely fusing the fatigue crack in these specimens and no improvement was observed. These cases were encountered before suitable procedures were developed to obtain a desired depth of penetration.

The results of all three test series are summarized in Fig. 4. The test points indicated as as-welded were treated prior to applying any cyclic load. The test points identified as precracked 75% LCL were precycled to 75% of the life provided by Design Category E. At that time the detail was treated. It may or may not have had a detectable fatigue crack. Those points indicated as visible precracked had clearly detectable cracks. Except for those failures in precracked beams that occurred because of failure to incorporate the complete crack into the gas tungsten arc remelt (see Fig. 4), approximately the same increases in life were achieved by all specimens. None of the test series exhibited an influence of minimum stress. Stress range was observed to account for nearly all of the variation in fatigue strength.

All the as-welded details failed from the crack root. No further improvement can be made in fatigue strength than that which results in failure from the weld root. In the initial precracked tests three details failed from the toe and thirteen details failed from the root. The toe failures were a result of inadequate penetration. These three cracks quickly grew through the remelt region toward the weld toe. After penetrating the free surface the crack continued to grow through the flange thickness. In the second series of precracked tests, half the beams failed from the weld toe. These toe failures were not the result of inadequate penetration. Higher heat inputs were used to achieve penetration for beams with fatigue cracks. The higher heat inputs caused weld ripples which acted as crack initiation sites. One toe failure occurred due to undercutting at the weld toe of a beam which had not been sandblasted to remove mill scale. All beams retrofitted by the gas tungsten arc remelt resulted in substantial increases in life.

Data available from other sources is primarily on small plate specimens with transverse gussets that provide a non-load carrying joint[3,4]. The studies on NCHRP Project 12-7 have indicated that this type of specimen provides fatigue behavior that is similar to stiffener type details[6]. No data was available on cover-plated beam details that had been subjected to gas tungsten arc remelting at fillet weld toes.

An etched cross-section of the transverse end weld is shown in Fig. 5. The remelt penetration is visually evident at the weld toe. It was possible to provide up to 5 mm (0.2 in.) penetration in the gas tungsten arc remelt. Figure 5 also demonstrates the reason that an upper bound to fatigue strength was observed for welded cover-plated beams. Improvements in the condition at the weld toe could not affect the growth of cracks from the weld root. Most of the details treated by gas tungsten arc remelt passes their life governed by failure from the weld root. Treatment at the weld toe forced the failure to the less severe weld root and resulted in greater life.

2. FATIGUE DAMAGE IN A COVER-PLATED BEAM BRIDGE

In October-November 1970, during cleaning and repainting of the Yellow Mill Pond Bridge, one of the cover-plated steel beams on the eastbound bridge on span 11 was found to have a large crack[1]. The crack had developed at the west end of the primary cover plate on Beam 4. It had grown from the toe of the cover plate transverse fillet weld into the tension flange and up 406 mm (16 in.) into the web.

A visual inspection (10X magnification) showed that Beams 3 and 5 in span 11 of the eastbound roadway which were adjacent to the casualty girder had cracks along the cover plate end. These cracks were subsequently verified by ultrasonic testing and a depth of penetration equal to 16 mm (0.625 in.) was measured. They were about half the flange thickness in depth and were found to have a semielliptical shape. An indication of possible fatigue cracking was also observed at five other details on span 10 and two on span 11. No ultrasonic confirmation could be obtained at the other possible crack locations.

In December 1970, after the detailed inspection, a section of the fractured girder was removed and all three damaged girders were subsequently repaired with bolted web and flange splices. The section of fractured girder was taken to Lehigh University for the prupose of investigating the fracture surface and determining the material characterization.

In November 1973, the east end of Beams 2 and 3 in the eastbound roadway of span 10 were inspected again by J. W. Fisher for fatigue damage. This was the first inspection at Beam 2. An indication of possible cracking was observed at Beam 3 in 1970. Cracks were detected visually in both girders at the toe of the primary cover plate transverse weld. A magnetic crack definer[7] indicated that the crack in Beam 2 was approximately 9.5 mm (0.375 in.) deep at one point. The magnetic crack definer could not verify the presence of a crack in Beam 3.

In June 1976, forty cover plate details in the east and westbound span 10 bridges were inspected for fatigue cracking using visual, magnetic particle, dye penetrant, and ultrasonic procedures prior to retrofitting these girders during Phase I of NCHRP Project 12-15(2). Twenty-two of these details were found to be cracked by visual inspection. The smallest visual crack indication was 6.4 mm (0.25 in.) long. Fifteeen of these cracks had propagated deep enough to be detected by ultrasonic inspection.

To inspect for cracks it was first necessary to blast clean and remove paint, dirt and oxide which had accumulated in the weld toe region. The visual (10X magnification), magnetic particle and dye penetrant inspection provided data regarding the length of the surface cracks. The magnetic particle inspection was discontinued after examining several cover plates due to difficulty in working with the probe in the overhand position.

The ultrasonic inspection provided data regarding both the length and depth of cracks. Cracks at the weld toe smaller than approximately 2.5 mm (0.1 in.) deep could not be reliably detected by the ultrasonic probe. The deepest crack depth indications of 13 mm (0.5 in.)

were found at the west end of the eastbound span 10 bridge in Beams 3 and 7. Comparisons of estimated crack depths from ultrasonic inspection and actual measured crack depths after a fracture surface was exposed indicate that deviations of 1.6 mm (±0.06 in.) are possible.

Figure 6 shows the approximate location of the details which were inspected in span 10 and summarizes the findings. Nine details in span 11 were also visually inspected. Indications of cracking were found at seven details. Very large cracks were observed at the east end of Beam 5 of the eastbound bridge and Beam 4 of the westbound bridge - span 11.

In November 1976, a brief inspection was made by J. W. Fisher at span 13. Four large cracks were detected without removing the paint. These cracks were first observed with field glasses from the ground. It is believed that these cracks must be approximately 152 to 254 mm (6 to 10 in.) long and about 13 mm (0.5 in.) deep for the crack to break the paint film at the weld toe. This condition is probably also related to the ambient temperature. Decreasing temperatures cause a more brittle paint coat and increase the likelihood of the paint to crack.

3. RETROFITTING FATIGUE DAMAGED BRIDGE MEMBERS IN SPAN 10 - YELLOW MILL POND

Peening and gas tungsten arc remelting procedures were used to retrofit the cover-plated beams in span 10 of the Yellow Mill Pond Bridge which were found to have fatigue damage.

Grinding of the weld toe to reduce the size of the initial discontinuities and severity of the stress concentration had shown little or no improvement of fatigue strength of fatigue damaged members. Hence no attempt was made to employ this procedure at Yellow Mill Pond.

Peening of the weld toe introduces compressive residual stresses. The weld toe was mechanically air-hammer peened until it was plastically deformed. Peening was performed with a small pneumatic air hammer operated at 0.17 N/mm^2 (25 psi) air pressure. The end of the peening tool had an 18 mm (3/4 in.) radius about one axis and a 3 mm (1/8 in.) radius about a second axis. All sharp edges were ground smooth. Several minutes were required to peen the weld toe. Peening was continued until the weld toe became smooth. A peened weld toe at Yellow Mill Pond is shown in Fig. 7. The depth of indentation due to peening was approximately 0.8 mm (0.03 in.).

The gas tungsten arc process (GTA) removes the nonmetallic intrusions at the weld toe and reduces the magnitude of the stress concentration by smoothing the weld termination. The tungsten electrode was manually moved along the toe of the fillet weld. This melted a small amount of the fillet weld and base metal. Provided that the cracks are not too deep, the metal around the cracks can be sufficiently melted that after solidification the cracks will have been removed.

The welding equipment used was a 200 amp DC power souce with drooping V-I characteristics. A high frequency source was used to start the arc. The electrode was 4.0 mm (0.156 in.) in diameter with a 4.8 mm (0.188 in.) stick out. The composition of the electrode was 2 percent thoriated tungsten. A Linde HW-18 water cooled torch was used. The entire welding unit was mounted on a Bernard portable carriage which also contained the water supply and a recirculating pump to cool the torch. A sketch of the equipment is shown in Fig. 8. The portable carriage was mounted on the rear of a truck with the portable gasoline power supply. A 15 m (50 ft.) line from the welding unit to the torch permitted the welder access to the girder.

A series of preliminary tests were conducted in Ref. 6 to find the effect of welding variables on GTA remelt penetration. The results of this study indicate that maximum penetration is obtained by the use of helium shielding gas and a cathode vertex angle between 30 and 60 degrees.

All retrofit welds on span 10 were performed in the overhead position. The areas to be welded were sandblasted to remove the mill scale that promotes undercutting. A helium and argon mixture shielding gas and a cathode vertex angle between 30 and 60 degrees were used as the mixture provided about the same penetration as helium alone. Travel speed was approximately 1.3 mm/sec. (3 in./min.). The retrofit weld was started on the longitudinal weld toe and continued along the transverse weld toe. The weld finally terminated at the opposite longitudinal weld toe. Intermediate terminations were made at approximately 100 mm (4 in.) intervals because of the duty cycle of the portable welding unit. Each of these terminations were carried up to the weld face to prevent cratering at the weld toe. Figure 9 shows a transverse fillet weld after the gas tungsten arc retrofit.

Twenty-five of the cover plate details in span 10 were repaired after being inspected. Fourteen were peened and eleven were gas tungsten arc remelted. Figure 10 summarizes the type of repair which was made at each cover plate weld toe.

Seven of the remelted details which had cracks detectable by ultrasonic examination were reinspected after the repairs were completed. The east primary details on Beams 2 and 4 (eastbound bridge) both produced a spot indication at a depth of 3.2 mm (0.125 in.). The ultrasonic examination of the west primary details on Beams 3 and 7 which had cracks about 13 mm (0.5 in.) deep, (eastbound bridge) indicated a large embedded crack. The remelt at these details did not change the crack depth. These cracks were purposely treated without gouging and rewelding by conventional means in order to evaluate the effectiveness of the treated detail. The length of time required for the crack to penetrate back through the weldment could be compared with theoretical estimates of life extension. The depth of remelt penetration was approximately 6.4 mm (0.25 in.) (see Fig. 11). No crack indications were found at the west primary detail of Beam 2 (eastbound bridge) or at the east primary and secondary details of Beam 3 (westbound bridge).

Residual Fatigue Life After Retrofitting

Since the field repair of the Yellow Mill Pond Bridge members was only recently completed, the effectiveness of this repair must be judged on the basis of available laboratory studies on similar members. Fortunately both experimental data and analytical techniques exist to make this assessment.

Peening was most effective in the laboratory when the initial cracks were very small. For this reason, peening was selected for retrofitting all beams where ultrasonic inspection was unable to confirm a visual indication of cracking or where neither inspection technique detected cracking. All cracks greater than 3.2 mm (0.125 in.) deep were gas tungsten arc remelted.

No cracks were indicated by ultrasonic inspection at ten of the cover plate ends which were peened in span 10. Four cover plates which were peened had a maximum depth indication of approximately 3.2 mm (0.125 in.). Therefore, the effectiveness of peening at Yellow Mill Pond should be comparable to the results plotted in Fig. 2.

The laboratory studies on fatigue damaged details that were retrofitted by peening indicated a greater tendency for improvement at the lowest level of stress range tested {82.7 MPa (12ksi)}. The details yielded fatigue lives up to 10^7 cycles. Since the stress range experienced at Yellow Mill Pond seldom exceeds 41.4 MPa (6 ksi), this procedure should be even more successful in prolonging life. The lower level of applied stress range will make the peened detail more effective because the induced compressive residual stresses at the crack tip are not likely to be overcome. As a result the details should be subjected to cyclic stresses that are well below the effective crack growth threshold. Since no test data are currently available at low levels of stress range this presumed behavior is a reasonable hypothesis.

The increased fatigue strength developed by the retrofitted (gas tungsten arc remelted) precracked beams also suggested that substantial increases in fatigue strength could be expected at the lower stress ranges to which the Yellow Mill Pond Bridge beams were subjected. The crack growth threshold of Category D appears to be about 58.4 MPa (7 ksi), which is substantially above the stress ranges experienced at Yellow Mill Pond (see Fig. 4). Hence, retrofitting by the gas tungsten arc remelt procedure should eliminate the possibility of subsequent cracking.

The probability of a root failure occurring is dependent on the relative size of the weld with respect to the thickness of the cover plate. As the ratio between weld throat width and cover plate thickness increases, the probability of root failure decreases. For the W14X30 cover-plated beams the ratio of throat width to cover plate thickness is 0.31. This ratio at the primary and secondary cover plate details of the interior beams (W36X230) at Yellow Mill Pond is 0.25 and 0.32, respectively. Therefore, comparable results should result at Yellow Mill Pond. The scatter in the fatigue lives of remelted details is due primarily to the effectiveness of melting the material surrounding the fatigue cracks. The maximum crack depth closed in the remelting test beams was approximately 3.8 mm (0.15 in.). Ultrasonic inspection of the large fatigue cracks at the west end of Beams 3 and 7 (eastbound roadway) after remelting indicate that the depth of penetration was approximately 6.4 mm (0.25 in.). A sample plate was cleaned and gas tungsten arc remelted at the Yellow Mill Pond. The specimen was then sectioned, polished and etched. The depth of penetration was measured between 3.5 mm (0.14 in.) and 5.8 mm (0.23 mm).

After the remelt retrofit was completed, the details that had provided indications of cracking were ultrasonically inspected. No indications of residual cracks were found at the primary or secondary details of Beam 3 (east end, westbound roadway) and at the primary detail of Beam 2 (west end, eastbound roadway). This indicated that the gas tungsten arc remelt procedure had effectively eliminated the small fatigue cracks that were detected at those details.

The increased fatigue life as a result of peening or remelting should increase the crack growth threshold stress range, $\Delta\sigma_{TH}$. If the peening operation is capable of embedding the crack initiaion sites in a compressive residual stress field a significant increase in the threshold stress range will be observed. The gas tungsten arc remelt procedure reduces the stress concentration by smoothing the transition at the weld toe and also minimizes the embedded discontinuities and fatigue cracks. Therefore, $\Delta\sigma_{TH}$ will also be increased.

The shape of the large embedded cracks at the west primary detail of Beam 3 (eastbound bridge) and at the west detail of Beam 7 (eastbound bridge) are shown in Fig. 11. The stress intensity model for these embedded cracks is shown in Fig. 12. This approximate model combines the solution for an eccentric crack[8] with the stress gradient correction factor, F_G, defined in Ref. 9. Utilizing this model and the crack growth rate $da/dN = 3.8 \times 10^{-9} \Delta K^3$ (ΔK in units of $MPa\sqrt{mm}$, da/dN in units of mm/cycle), the number of cycles necessary for the crack to propagate through the retrofit weld toward the weld toe was estimated. It was a assumed that when the embedded crack penetrated the exterior flange face it would quickly become an elliptical surface crack with the major semi-diameter axis being defined by the crack shape ratio prior to retrofitting.

For this study the retrofit weld penetration was assumed to be 4.8 mm (3/16 in.). The estimated number of cycles necessary to propagate the embedded cracks through the retrofit weld at a stress range of 13.1 MPa (1.9 ksi) for Beams 3 and 7 were 7.0 and 6.7 million cycles, respectively. The elliptical surface cracks for both beams were approximately 13.5 mm (0.53 in.) deep at the beginning of the final stage of crack growth. An additional 1.0 and 2.7 million cycles would be necessary for the cracks to grow through the flange thickness for Beams 3 and 7, respectively.

The stress intensity model for the growth of embedded cracks probably overestimates the fatigue life since it does not account for crack growth which is occurring simultaneously from the weld toe. Nevertheless, substantial improvement in fatigue strength can be expected even if the entire crack has not been completely remelted, if the crack initiation sites along the weld toe have been effectively reduced.

Ultrasonic inspection of the primary detail of Beam 2 (east end, eastbound roadway) and the secondary detail of Beam 3 (east end, eastbound roadway) produced a spot indication at a depth of 3.2 mm (0.12 in.). These embedded discontinuities may be below the crack growth threshold. Since their size and shape is nearly impossible to estimate, an exact evaluation is not possible.

4. SUMMARY AND CONCLUSIONS

Extensive laboratory experimental work on welded details has demonstrated that fatigue damaged details can be retrofitted and their fatigue life extended. Two of the most effective methods were used to retrofit two fatigue damaged bridges.

Three repair or improvement methods were studied experimentally and observed to be effective to varying degrees in extending the fatigue life of welded details. Grinding was not as effective as peening under dead load and the gas tungsten arc remelt pass.

Peening was observed to produce good results with both uncracked as-welded details and fatigue damaged details with surface cracks less than 3 mm (1/8 in.) deep. The application of a high minimum stress after peening caused a reduction in the effectiveness of peening as it caused a decrease in the compression residual stress. Peening was used to retrofit fatigue damaged bridge details that showed no significant crack growth.

The gas tungsten arc remelt pass was the most effective method examined in the laboratory and was also effective in repairing fatigue damaged details with surface cracks less than 5 mm (3/16 in.) deep. The procedure was used to retrofit bridge beams with cracks up to 12 mm (1/2 in.) deep. This did not permit the fusion of all of the crack surface. However it was predicted that the embedded crack would provide several years additional life. Bridge beams with cracks at cover-plated weld toes that were 5 mm (3/16 in.) or less deep could be retrofitted and the fatigue crack removed by the remelt procedure.

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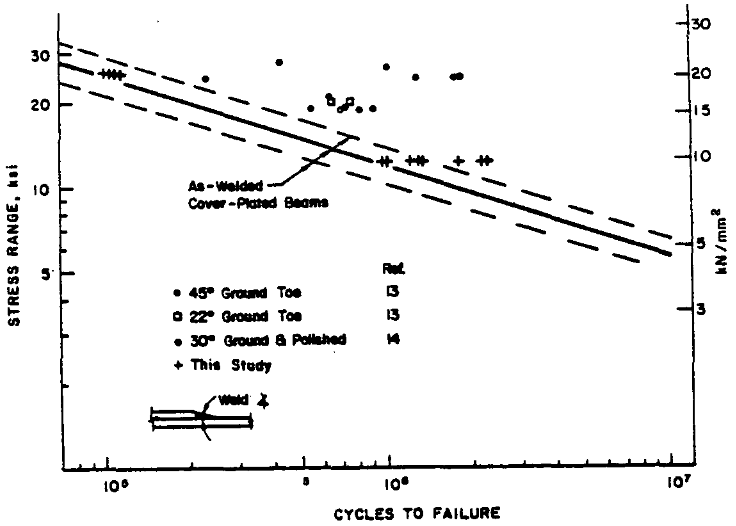


Fig. 1 Effect of Grinding Weld Toe on Fatigue Strength

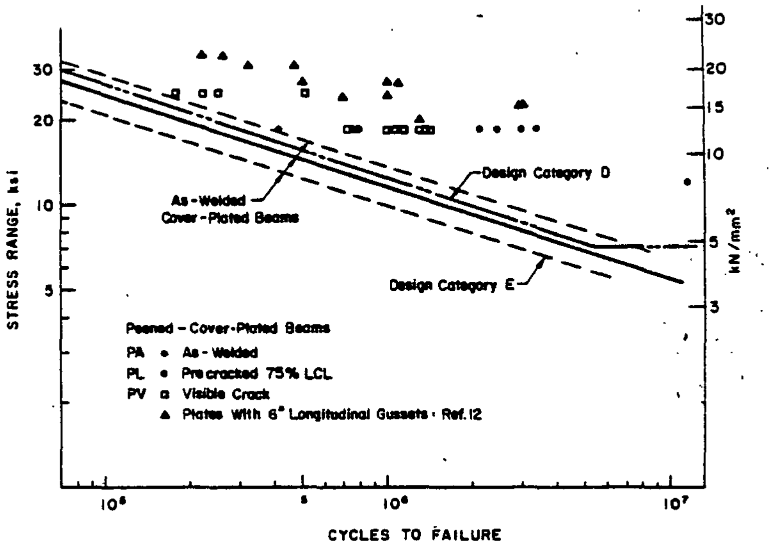


Fig. 2 Effect of Peening on Fatigue Strength

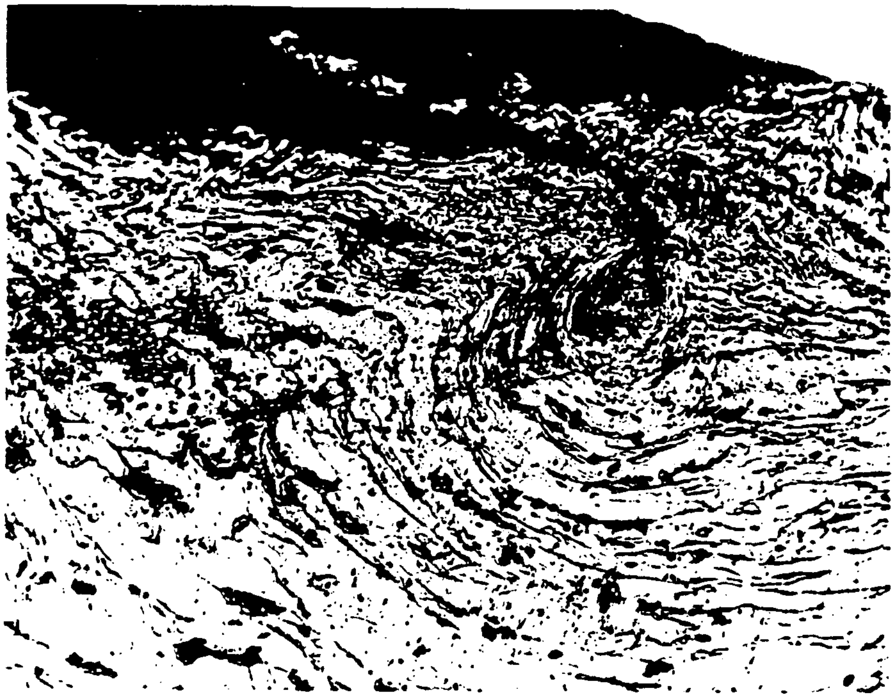


Fig. 3 Lap-type Defect in a Peened Weld Toe

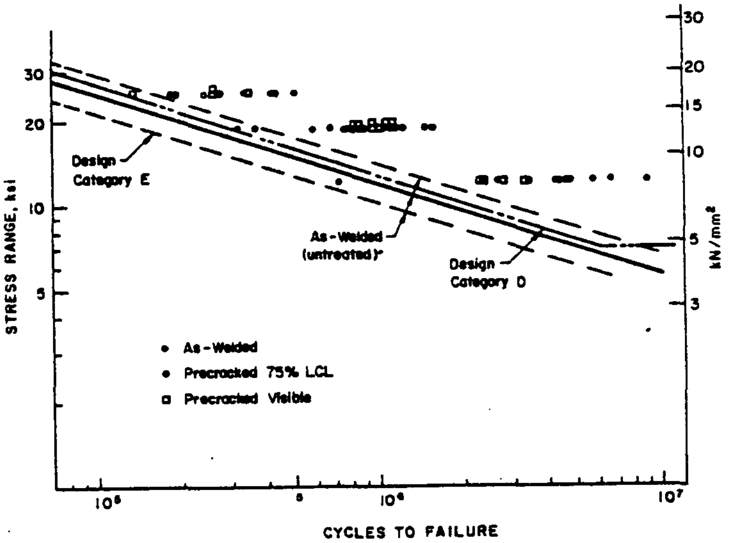


Fig. 4 Effect of Gas Tungsten Arc Remelt on Fatigue Strength

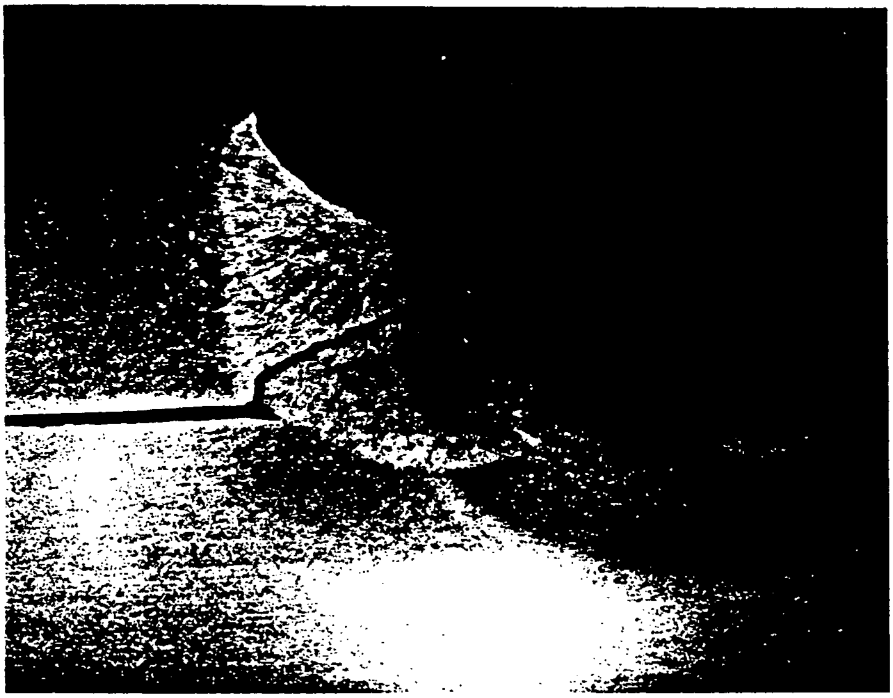


Fig. 5 Cross-Section of Cover Plate End Weld

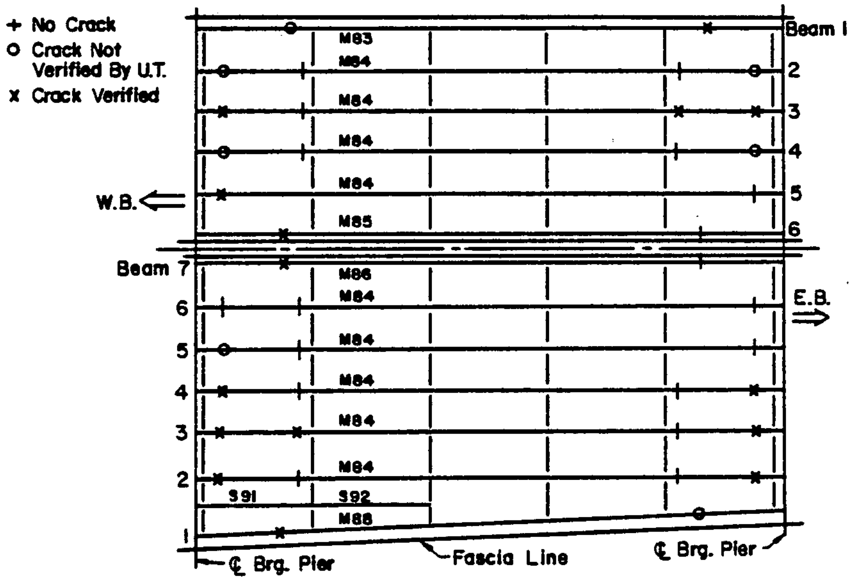


Fig. 6 Plan of Inspected Details in Span 10,
Yellow Mill Pond Bridge

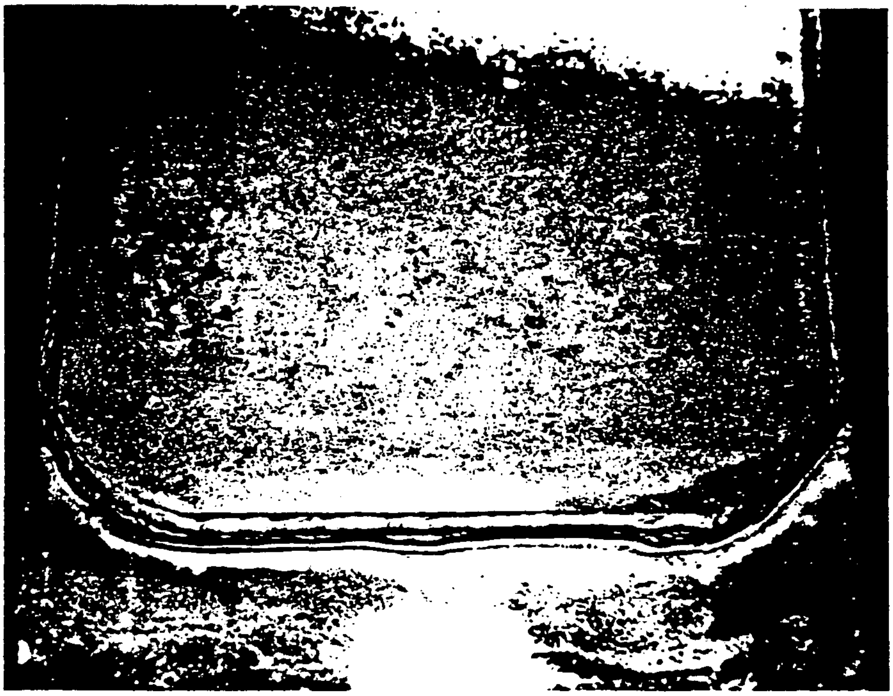


Fig. 7 Peened Weld Toe on Yellow Mill Pond Bridge

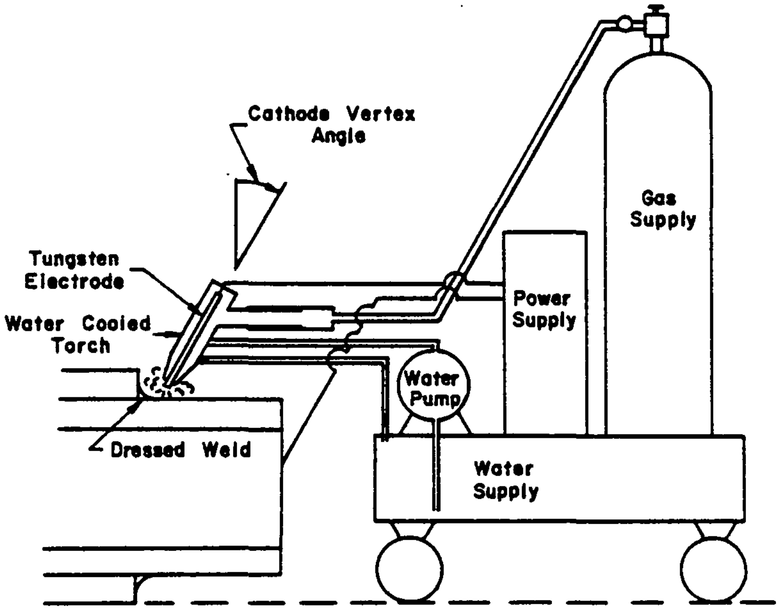


Fig. 8 Schematic of Gas Tungsten Arc Remelt Equipment

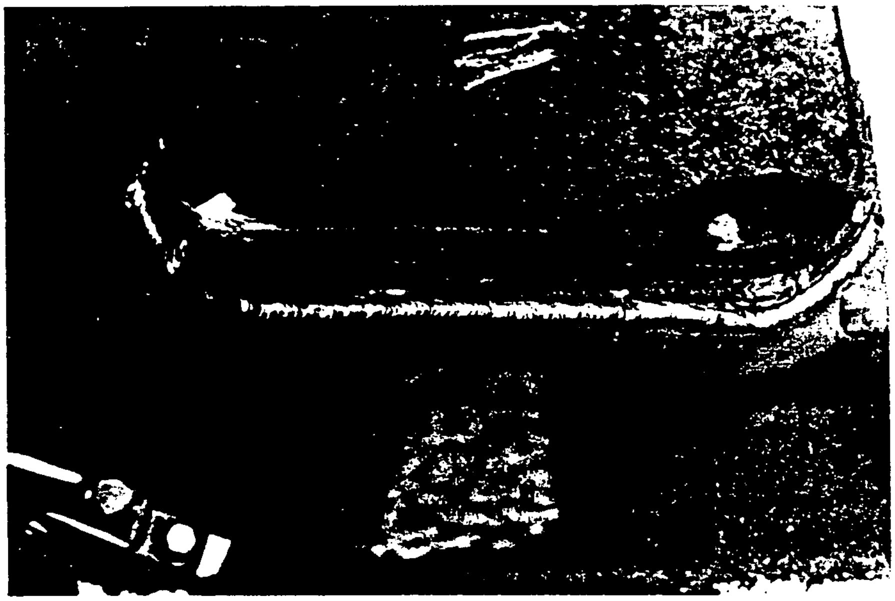


Fig. 9 Transverse Fillet Weld after Gas Tungsten Arc Remelt

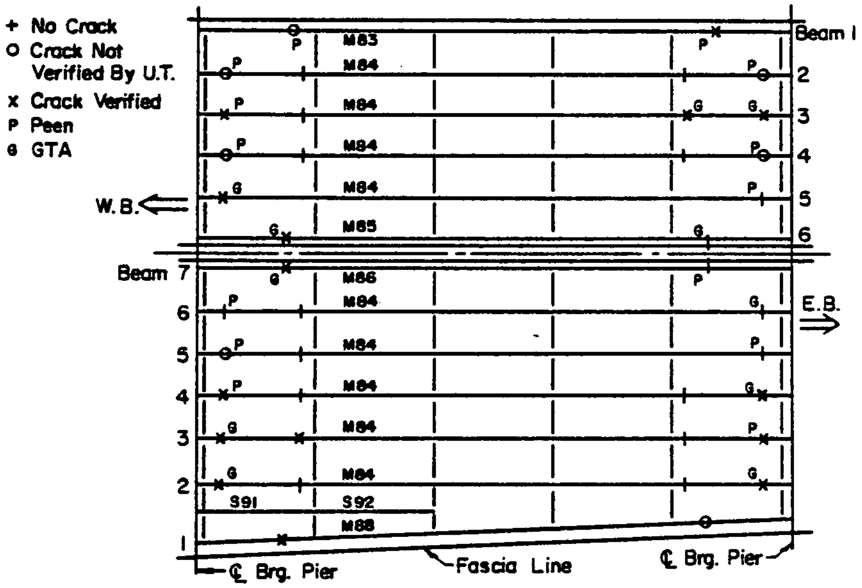


Fig. 10 Repair Methods on Span 10, Yellow Mill Pond Bridge

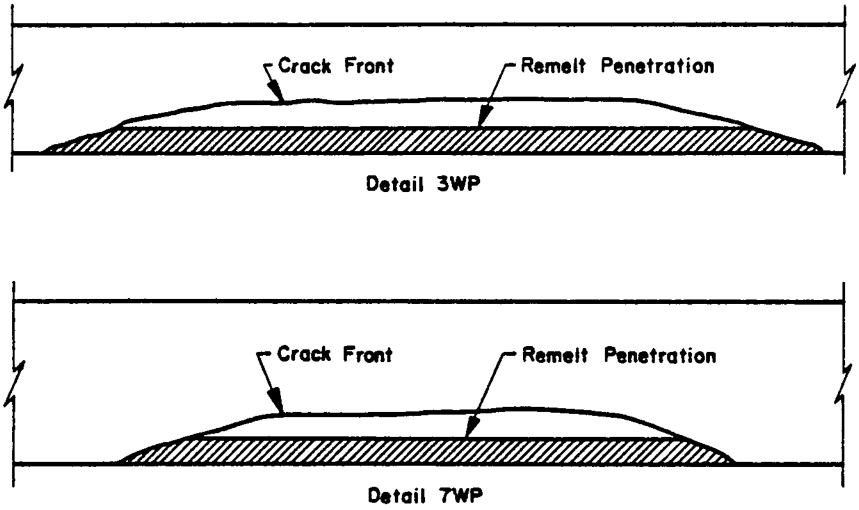
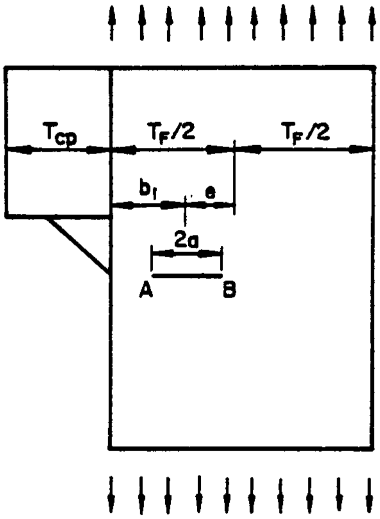


Fig. 11 Crack Shape for Beams 3 and 7 (1976)



$$K_{I,A} = \sigma\sqrt{\pi a}\ F_A\left[\frac{a}{T_F/2 - e},\ \frac{e}{T_F/2}\right] F_G\left[\frac{b_1 - a}{T_F},\ SCF\right]$$

$$K_{I,B} = \sigma\sqrt{\pi a}\ F_B\left[\frac{a}{T_F/2 - e},\ \frac{e}{T_F/2}\right] F_G\left[\frac{b_1 + a}{T_F},\ SCF\right]$$

F_A, F_B from Ref. 8

$$F_G = \frac{SCF}{1 + \frac{1}{0.1473}\left(\frac{a}{T_f}\right)^{0.4343}}$$

Fig. 12 Stress Intensity Model for Embedded Cracks