IMPROVING FATIGUE STRENGTH

AND REPAIRING FATIGUE DAMAGE

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SUMMARY OF FINDINGS

The research described in this study is intended for use in improving the fatigue strength of details susceptible to fatigue damage when crack growth occurs at weld toes. Sixty rolled steel beams with welded cover plates were fabricated and tested to define the influence of post-weld treatment at the weld toe termination. Three treatments were examined: grinding, peening, and gas tungsten arc remelting. These processes were applied to as-welded details prior to testing and to details which had experienced crack growth prior to the treatment.

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 and application of the gas tungsten arc remelt process did not succeed in completely fusing the fatigue crack and no improvement was observed. These cases were encountered before suitable procedures were developed to obtain a suitable depth of penetration.

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, 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.
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 and low minimum stress levels and at higher stress range levels as well.

During the test program efforts were made to detect the small micro-cracks that form and grow at the weld toe termination. Generally these cracks could be detected at about the same stage of growth by ultrasonic inspection using a shallow surface wave and by visual inspection using a 10X magnifying glass. These cracks were usually about 1/4 in. (6 mm) long when detected and were estimated to be about 1/16 in. (1.5 mm) deep. Smaller cracks at the weld toe were only detectable by destructive examination.

An upper bound to fatigue strength was observed for welded cover plated beams. Improvements in the condition at the weld toe could not effect the growth of cracks from the weld root. Most of the details treated by gas tungsten arc remelt passes had 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.
A special study was also made of a cracked bridge detail to determine the cause and progress of cracking. This study showed that crack growth originated at a partial penetration weld that existed in a longitudinal stiffener and propagated in a subcritical crack growth mode through the web thickness. A brittle fracture then occurred in the web which arrested near the bottom surface of the tension flange. This crack subsequently propagated in subcritical crack growth through the flange before a repair was made.
1. **INTRODUCTION AND RESEARCH APPROACH**

Fatigue studies on steel beams with welded cover plates and other types of welded attachments have demonstrated that relatively large reductions in fatigue strength occur for most of these details when the fatigue cracks initiate and grow from the small micro-sized discontinuities that exist at the weld periphery. This behavior has been reported in detail in NCHRP Reports 102 and 147.

The results of this work on the behavior of welded built-up details has been used to define the fatigue strength over a wide range of design life\(^1,2\). This information has been used to develop specification provisions for welded details in the as-welded conditions\(^3\).

Some fatigue crack growth has occurred in a few bridge structures. The possibility of fatigue cracking under relatively high stress range conditions was demonstrated by the cover plated steel beam bridges of the AASHO Road Test\(^4\). Recently fatigue cracking has been observed in the field where complete fracture of the tension flange of a beam in a multiple beam bridge occurred from fatigue crack growth at the end of a welded cover plate\(^5\). In this instance the bridge was only thirteen years old and carried an unusually high volume of heavy truck traffic which caused large numbers of high stress cycles. Subsequent inspection of other cover plated beams revealed that the two beams adjacent to the cracked member were also cracked through about one-half the flange thickness. Several small cracks have been detected at other cover plate details since that time.

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The formation of these cracks showed the desirability of examining methods for improving (upgrading) the fatigue strength of welded joints without changing the design detail. Experimental studies have demonstrated that fatigue crack growth commenced at some initial flaw or discontinuity. In welded details small sharp discontinuities exist at the weld periphery or in the weld metal of fillet and groove welds and crack growth has invariably started at these discontinuities when they are perpendicular to the applied stress range.

1.1 Objectives and Scope

The principal objectives of this project were:

1. To compile a state of the art review of existing methods of non-destructive inspection and to evaluate the reliability and adaptability of these methods to the detection of fatigue cracks in welded highway bridges. This review was reported in NCHRP Research Results Digest No. 66 and is also provided in Appendix A of this report.

2. To compile a state of the art review of typical existing and currently designed welded bridge details and evaluate those most susceptible to fatigue crack growth. This review was to identify potentially low fatigue strength details that may experience fatigue crack growth. This review was published as NCHRP Research Results Digest No. 59. This state of the art review is given in Appendix B.
3. Review and evaluate methods for improving the fatigue life and arresting the progress of fatigue damage that occurs at the weld toes of severe notch producing details where the probability of failures is greatest. The methods were to be confirmed by tests of as-welded and fatigue damaged cover plated beam specimens. The experimental variables were to include crack size at the time of the repair or improvement, the methods of improvement, stress range and minimum stress.

4. Recommend methods for improving the fatigue life of and arresting the progress of fatigue damage in welded highway bridges.

During the experimental research program, sixty steel cover plated beams were tested 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 were utilized for this purpose\textsuperscript{6,7,8,9,10,11}. They 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, (GTA), also commonly referred to as the TIG or Tungsten Inert Gas process.

The beams were tested under constant amplitude cyclic loading, similar to that used in NCHRP Project 12-7.\textsuperscript{1,2} The steel cover plated beams were identical in size and configuration to those fabricated and used on NCHRP Project 12-7.
1.2 Design Variables and Test Specimens

The principal design variables in this study were those associated with the three improvement methods that were selected. These were: (1) grinding the weld toe, (2) peening the weld toe, and (3) remelting the weld toe using the Gas Tungsten Arc process. Because the studies reported in NCHRP Reports 102 and 147 had shown that type of steel was not a significant variable, it was assumed that this condition also existed for the welded details of this study. All specimens were fabricated from A36 steel.

These improvement methods have been successfully applied by others to a variety of details in the as-welded condition and improvements of 100-200% have been observed when they were cyclically loaded after the improvement was applied.

Fatigue cracks in the laboratory and field are difficult to repair. Welded repairs have often cracked again after only a few years of service. Often the cracked detail has been repaired by bolting splice plates across the cracked member to reduce the stress intensity at the crack tip and transfer the stresses around the cracked plate. This is a reliable but costly method of repair.

Since the three improvement techniques cited above have extended the life of as-welded details, these methods were applied to fatigue damaged cover plated beam specimens in this study in order to evaluate their effectiveness. The beams with cover plates were W14 x 30, 10 ft. - 6 in. (3.2 m) long and tested on a 10 ft. (3 m) span under three
point loading as shown in Fig. 1. For each test series, minimum stress and stress range were selected as the controlled stress variables. The nominal flexural stresses in the base metal of the tension flange adjacent to the end of the cover plate termination were used as the design stress variable. Most of the tests were made at a 10 ksi (68.9 N/mm²) level of minimum stress. A few tests were also run at a 2 ksi (13.7 N/mm²) minimum stress level to provide some indication of the influence of the minimum stress condition.

Since the fatigue strength of the cover plated beams in the as-welded condition has been documented in NCHRP Report 102 and subsequent studies, it was convenient to use an identical specimen for the improvement and repair methods used in this study so that direct comparisons could be made. This provided a means of assessing the effectiveness of the repair or improvement procedure.

Three basic series were conducted. Series I was for cover plated beams in the as-welded condition and Series II and III involved beams that had been pre-cycled to predetermined numbers of cycles or crack sizes. In each of these series the three improvement procedures were applied. For Series I beams in the as-welded condition, the ground, peened, and gas tungsten arc remelt were designated as GA, PA and TA specimens. For Series II precracked beams, cyclic loading was applied until 75% of the lower confidence limit of the as-welded details was reached. At this stage of loading, visible cracks were detected on a number of beams. These are indicated in Table G2 and mainly occurred at the highest level of stress range. Beams in this series were designated
as GL, PL, and TL specimens. For Series III, designations of GV, PV, and TV were used for beams precycled to a visible crack. This crack was usually less than 3/4 in. (19 mm) long on the surface of the flange at the transverse weld toe. Its depth was estimated to be between 1/16 in. (1.5 mm) and 1/8 in. (3 mm). Examination of the fracture surfaces of the GV and PV beams indicated that the larger surface cracks were a combination of shorter cracks that had linked up. Only two beams were observed to have visible cracks before 75% of the lower confidence limit was reached (see Appendix G).

Each beam series was arranged into a partial factorial experiment that was defined by the stress variables. The factorials used for all three test series is given in Fig. 2 in terms of minimum stress and stress range. The specimens that were treated by grinding at the weld toe were only tested at the 12 ksi (82.7 N/mm²) and 24.8 ksi (171.0 N/mm²) stress range levels.

All beams were fabricated by a local fabrication shop. The fabricator was instructed to use normal fabrication and inspection procedures. Each rolled beam section was produced from the same heat. The sections were cut to length and cover plates welded to each flange. The cover plates were 9/16 in. (14 mm) thick and 4 ft. (122 mm) long. Quarter inch (6.3 mm) fillet welds were placed along each side of the cover plates and were made simultaneously by the automatic submerged arch process. The quarter inch transverse fillet welds at the cover plate ends were made manually by the gas metal arch process and were continued around the cover plate end for a distance of about 3/4 inches (19 mm) to avoid leaving a crater at the cover plate end.
1.3 Experimental Procedures

The 14 in. (355 mm) deep cover plated beams were mounted on the dynamic test bed and cyclically loaded. The loads were applied by a jack at the midpoint as shown in Fig. 3. The cyclic load was applied with an Amsler variable stroke hydraulic pulsator operated at a constant frequency of 260 or 520 cycles per minute depending upon the stress range. The slower speed was used at the 24.8 ksi (171 N/mm$^2$) stress range level because of the longer stroke necessary to apply the load. Other stress ranges were applied at the higher rate of loading. The loading cycle was sinusoidal; the minimum applied stress was always tensile.

Series I test beams were treated at the cover plate ends by one of the three improvement-repair methods before cyclic load was applied. The grinding, peening or TIG remelt was applied at the toe of the transverse fillet welds. The beams were then placed in the dynamic test bed and were cycled until failure. Failure in all tests was defined as the life required to propagate the crack through the flange thickness. About 75% of the flange area was destroyed at that time. All testing was in the temperature range of 60° to 80° F.

Testing was continued after failure at a detail, by splicing the cracked region. The splicing was accomplished by placing lap plates on both sides of the tension flange and fastening them in place with C-clamps$^2$. Testing was then resumed until failure occurred at the other cover plated detail. The order of testing the specimens for each series was randomized so that uncontrolled variables would be randomly distributed.
For Series II the beams were cyclically loaded to a predetermined number of cycles and then treated. The number of cycles varied with the level of stress range and corresponded to 75% of the lower confidence limit that had been previously established for the as-welded cover plated beam details in NCHRP Report 102. The studies on Project 12-7 had indicated that very small elliptical surface cracks would exist at the ends of the cover plate termination after that degree of cyclical loading. These cracks were too small in most instances to be detected without destructive examination. When detected, they were about 0.1 in. (2.5 mm) long. This series was designated GL, PL, and TL depending on the repair method and was intended to determine the effectiveness of repairing or removing shallow fatigue cracks that may exist after a structure has been subjected to cyclic load. The depth of the cracks depended upon the severity of the stress concentration at the fillet weld toe and the initial discontinuity condition. After the fracture surfaces were exposed it was determined that the depth was variable and quite shallow.

Series III involved beams that were precycled until a crack was visible along the transverse fillet weld toe of the tension flange. The crack size in these cases was about 1/8 in. to 1/4 in. (3 mm to 6 mm) long. These specimens were designated as GV, PV, or TV beams. After repair, the beams were cycled to failure. The GV beams were all peened after grinding because the CGL studies had shown no improvement in fatigue life. Since larger initial cracks were expected, nothing would be gained by grinding alone. Although considerable care was exercised in monitoring these cracks, there was still variation in their depth and length when detected.
They were in general deeper than the cracks that were detected after beams were precycled to 75% of the lower confidence limit.

Failure was considered to have occurred when the crack had penetrated through the tension flange. Since failure was accompanied by a considerable loss in stiffness, midspan deflection of the beam provided a convenient means of determining failure. In most cases the midspan deflection increased about 0.020 in. (0.5 mm) when 75% of the flange was cracked. The cyclic deflection range was between 0.1 and 0.2 in.

1.4 Repair Methods

Grinding: Grinding is an accepted method of reducing the stress concentration condition and has been used successfully in the past to increase the fatigue life of welded details\(^7,12,13\). Since fatigue crack growth originated from the junction of the weld bead and the plate, grinding was confined to the toe of the fillet weld. No attempt was made to grind the entire weld surface nor to taper and feather the weld end. The depth of grinding at the weld toe was between 1/32 (0.8 mm) and 1/16th (1.5 mm) of an inch. Grinding was continued until the weld toe was smooth and free of visible defects. A rotary file was used and is shown in Fig. 4. Fig. 5 shows a typical as-welded fillet weld after grinding and before cyclic loading was applied.

When grinding was applied to precracked details in this study, it was continued until the crack was no longer visible. As the weld toe region was ground, the crack appeared as a fine line. When this line was no longer visible (without magnification), the grinding operation was
discontinued. Care was taken not to leave grind marks perpendicular to the direction of the applied load in order to avoid introducing new crack initiation sites. Previous studies have indicated that grinding provides an increase in fatigue life by increasing the length of time required for crack initiation\textsuperscript{10,11}. This is accomplished by reducing the stress concentration at the weld toe and by removing the tiny nonmetallic intrusions or undercut which exist at the weld periphery.

**Peening:** Peening is an established method to obtain improved performance. It has frequently been used in machine design and has been shown to be applicable for improvements on both small specimens and beams\textsuperscript{6,7,8,10,11}. In this study the weld toe was mechanically air-hammer peened until it was plastically deformed. This introduced compressive residual stresses and prevented the full stress range from being effective in the vicinity of the weld toe. This affected both crack initiation and crack growth.

Peening was performed with an Ingersoll-Rand Model 1940 pneumatic air hammer operated at 25 psi (0.17 N/mm\textsuperscript{2}) air pressure. The peening tool is shown in Fig. 6. Peening was continued until the weld toe became smooth. When a visible crack was present, peening was continued until the crack was no longer visible. These variable criteria were necessary because of the variation in weld bead shape and crack depth. Examples of the peening treatment at the weld toe are shown in Figs. 7 and 8, which show an as-welded peened weld toe and a detail that was peened after precycling. Many specimens in the PL series had cracks that became visible after a light peening. The peening was continued until
the crack had disappeared. The Series III beams in the GV series were both ground and peened at the weld toe.

**Gas Tungsten Arc Remelt:** In the gas tungsten arc process (GTA) metal at the weld toe was remelted. The tungsten electrode was manually moved along the weld toe at a constant rate and melted a small volume of the fillet weld and base metal. A sketch of this process is given in Fig. D2. This process removes the nonmetallic intrusions present along the weld toe and reduces the stress concentration conditions. When a crack was present a sufficient volume of metal surrounding the crack was melted to incorporate the crack so that upon solidification the crack ceased to exist.

This method of improvement has been successfully applied to improving the fatigue life of as-welded fillet welded specimens. In this program its effectiveness was also evaluated for the presence of pre-existing cracks as provided by the TL and TV test series.

The welding apparatus used in this study was a 300 amp DC power source with drooping V-I characteristics. High frequency was used to start the arc. A Linde HW-18 water cooled torch with a 5/32 in. (4 mm) diameter, 2% thoriated tungsten electrode was used.

The depth of the remelted zone was critical to the success of this procedure because insufficient penetration would leave a crack buried below the surface and would result in premature failure. Argon was used successfully for shielding throughout the TA series tests. The welding
current was 200 amps and the travel speed was about 3 in. (76 mm) per minute and resulted in penetration on the order of 1/10 in. (2.5 mm).

It was soon apparent that the depth of penetration would be insufficient for Series II and III which involved precracked beams. Since penetration had been shown to increase with the proper selection of shielding gas\textsuperscript{13} and electrode cone angle\textsuperscript{14}, an experimental program was undertaken to determine the most effective combination of these two variables. Details of this study are presented in Appendix H. From the results, it was determined to use helium shielding gas and an electrode cone angle of 60°. With this combination, 42% more penetration could be achieved than was obtained with argon shielding for the same current of 200 amps.

The area near the transverse fillet welds of all of the GTA series was sand blasted to remove all mill scale since it was discovered that undercutting resulted when the scale was not removed. The welds were started at the longitudinal weld about 3/4 in. (19 mm) from the transverse fillet weld, and continued along the toe of the transverse fillet weld and around again to the longitudinal weld. This procedure was necessary to avoid weld craters in the critical toe region. When it was necessary to terminate a weld along the transverse weld, care was taken to stop the weld along the face of the fillet weld and not along the toe. The procedures recommended by Millington\textsuperscript{9} regarding weld terminations were followed. These are illustrated in Fig. 9. A GTA remelted weld toe is shown in Fig. 10. An etched cross-section is shown in Fig. 11.
and demonstrates the condition that existed for the as-welded beams when approximately 1/10 in. (2.5 mm) penetration was achieved.

The welds in the TA series were made in the flat position under what could be described as comfortable conditions. This resulted in uniform travel speed and a smooth weld bead shape. The TL and TV series were welded in the overhead position in an attempt to simulate field conditions. This resulted in somewhat nonuniform results. Deep penetration was harder to maintain because the puddle tended to droop as the heat input was increased. The heat input for the TL and TV series varied according to the estimated depth of the crack. A constant current of 200 amps was used and the travel speed was changed to vary the heat input.
2. FINDINGS

The findings of the project are summarized in this chapter. They include those provided from the literature and from the analysis of the results obtained in this study. A detailed evaluation of the data is given in Chapter 3. Documentation of the test results are contained in the appendices.

2.1 Literature Survey

1. Fatigue tests on small specimens and beams showed that the principal methods of improving the fatigue strength of welded details that are simple and effective achieve their objective by one or more of the following means.

   a. Modification of the shape of the weldment and any associated micro-discontinuities so as to reduce the stress concentration.

   b. Modification of the residue stress distribution so as to reduce the magnitude of the effective stress range.

2. Among the methods that have been used are: grinding, machining, hammer peening, spot heating, local pressing and prior overloading. When materials are sensitive to atmosphere or corrosive environment, surface protection has also been used. Fatigue strengths have also been improved by remelting metal at the weld toe-base metal interface.
3. Earlier studies indicated that peening, grinding and gas tungsten arc remelting of the weld toe region were reliable and reasonable to apply to as-welded details.

4. No test data were available on beams or specimens that had been precycled or precracked prior to application of the improvement techniques.

2.2 The Effect of Grinding Weld Toes

1. Grinding the weld toe with a rotary file did not appreciably influence the fatigue strength of any of the ground details. Some improvement, although slight, was observed at the lowest level of stress range.

2. All beams that had been precracked and then ground at the weld toe, failed by crack growth at the toe. A few beams in the as-welded ground conditions did develop fatigue cracks from the weld root at the low stress range levels.

3. Observations of the crack initiation point indicated that many cracks developed from a slag particle which had not been removed by the grinding operation.

4. The improvement provided by the GV series can be attributed to the fact that the weld toe was peened after grinding. This series incorporated both grinding and peening when it was observed that grinding alone had little influence.
2.3 The Effect of Peening

1. Minimum stress was found to be a significant design factor for any detail that was peened and then subsequently subjected to a high minimum stress condition. The application of 10 ksi (68.9 N/mm²) minimum stress after peening, relieved part of the compression residual stresses that had been introduced at the weld toe.

2. Significant increases in fatigue strength were achieved when low minimum stresses were applied or when the specimens were peened under a simulated dead load condition at the higher minimum stress.

3. Nearly all as-welded and precracked details were observed to fail from crack growth at the toe of the transverse fillet weld.

4. Peening is an effective method of improving the fatigue characteristics of as-welded details subjected to low levels of minimum stress or to details that can be peened under dead load.

2.4 Effect of Gas Tungsten Arc Remelt

1. Stress range was the dominant stress variable for all details treated by the gas tungsten arc remelt procedure.

2. Minimum stress was not a significant design factor when improving or strengthening a detail by gas tungsten arc remelting.
3. Nearly all specimens treated by the gas tungsten arc process failed by fatigue crack growth from the weld root.

4. An upper bound to the fatigue strength of cover plated beam details appears to be provided by the gas tungsten arc remelt conditions. No treatment of the weld toe can be expected to provide fatigue strengths that exceed those provided by the weld root.

5. Application of the gas tungsten arc remelt is sensitive to the presence of micro-discontinuities or cracks that may exist from a member subjected to cyclic load. Extreme care is necessary in order to assure removal of embedded cracks by the remelt process (see Appendix D).

6. The gas tungsten arc remelt dressing of the weld toe can reliably improve the fatigue strength one design category (i.e. for cover plated beams from Category E to Category D)^3.

7. No brittle or sudden fracture was observed during the testing of any specimens. All tests were at room temperature (60° - 80° F).

8. The cracks which formed originated at the weld root. After propagation upward through the transverse fillet weld they eventually moved laterally and propagated down into the beam flange through the longitudinal weld.
9. A practical range of gas tungsten arc dressing conditions exist provided that a minimum standard of cleanliness can be achieved by removal of any slag or mill scale by blasting the surface and exercising care when establishing the welding conditions.

2.5 Crack Detection by Nondestructive Inspection

1. Examination of the transverse weld toes during precycling and prior to application of the improvement procedure indicated that small semielliptical surface cracks could be detected at about the same stages of crack growth by ultrasonic inspection and by visual examination with 10X magnification.

2. Crack depths could not be reliably defined non-destructively for the small surface cracks that were observed. Comparisons of the estimated crack depth and the measured crack depth after the fracture surface was exposed indicated that deviations of ± 1/16 in. were possible.

3. The minimum crack sizes that were detectable by either the ultrasonic or visual inspection procedures can be repaired by either peening or gas tungsten arc remelting the weld toe. Considerable difficulty can be expected in the field in locating weld toe cracks as small as those detected in the laboratory.
2.6 Application

1. The improvement provided by peening or gas tungsten arc remelting the toe welds can be relied upon for both as-welded initial construction and for details that have experienced sub-critical crack growth.

2. For purpose of design the gas tungsten arc remelt procedure can improve the fatigue strength by one category for all stress range levels.

3. Peening is affected by the level of minimum stress. For as-welded details, the application of high dead loads can eliminate the beneficial effects of peening, hence it appears desirable that peening be limited to improving details subjected to low levels of minimum stress or to field conditions where the dead load stress is not removed after peening.

4. The gas tungsten arc remelt provides an effective means to retrofit details suspected of being fatigue damaged and to upgrade the design category for as-welded details.

5. Details subjected to cyclic load that experience visible signs of crack growth at weld toes can be repaired by the gas tungsten arc remelt process providing the crack depth penetration does not exceed the capability to melt out the crack and incorporate it into the solidified metal.
3. RESULTS AND EVALUATION OF IMPROVEMENT TECHNIQUES

The results of the experimental and theoretical work undertaken on this project are summarized in this chapter. Three series of tests on beams with welded cover plates which had their transverse weld toe treated by either grinding, peening or subjecting it to a gas tungsten arc remelt pass were evaluated. Each detail was examined in terms of the crack initiation and growth that occurred. The results are compared with the data acquired on NCHRP Project 12-7 on as-welded cover plated beams and with earlier studies on as-welded details. Complete documentation of the test data and details of the evaluation are given in the appendices.

3.1 Fatigue Strength of Ground Weld Toes

Eight rolled W14 x 30 beams with welded cover plates were tested with the weld toe termination treated by grinding. Each of the beams had two details. Four of the beams were tested after treating the as-welded detail. The remaining four beams were tested after the beams had been subjected to cyclic load and precracked to varying degrees.

3.1.1 Crack Initiation and Growth

The earlier studies\(^1\),\(^13\) had demonstrated that the fatigue crack initiated at the toe of the transverse fillet weld joining the cover plate to the beam flange. This was the point of greatest stress intensity due to the applied stress, the geometry of the fillet weld to flange connection, and the microscopic discontinuities at the fillet weld toe due to welding.
Crack growth in these beams could be characterized by a stage of growth during which the crack grew through the thickness of the flange in an elliptical shape. After reaching the lower flange surface most of the fatigue life was exhausted. Very little life remained as the crack grew toward the flange tips and into the web. In beams that had the weld toe treated by grinding, the location of crack initiation was more variable than observed in the earlier studies. Crack growth was mainly confined to the toe region for nearly all of the ground weld toes. Figure 12 shows a photograph of a cracked detail that had the toe ground prior to subjecting the member to cyclic load. Crack formation and growth was in the ground region. In only a few instances was the improvement at the weld toe sufficient to force the crack to originate from the weld root as indicated in Figure 13. As the fracture surfaces illustrate in Fig. 13b, crack growth was experienced from the root of the weld and propagated across the face of the weld, transverse to the stress field until it intersected the longitudinal weld at which time it penetrated into the surface of the beam flange.

3.1.2 As-Welded Ground Fillet Weld Toes - GA Series

The results of the fatigue tests on as-welded beams with ground weld toes are summarized in Fig. 14. Two levels of stress range were examined at a single level of minimum stress. Testing at the higher levels of stress range was discontinued after one detail failed because the second detail had very large cracks and only a small amount of life was expected. The test data at the high level of stress range fell within
the scatter bands for as-welded details without treatment. At the lower level of stress range, the data points were at or above the upper confidence limit. The average increase in life was less than 10% over the as-welded details.

Damage to the weld toe surface caused by the grinding burr may have contributed to the lack of improvement in fatigue life. Examination of the crack initiation points in several specimens revealed defects caused by poor grinding techniques. Figures 15 and 16 show two initiation sites. One crack developed from a slag particle which had not been removed but had been covered by a layer of smeared metal (see Fig. 15). The other failure (see Fig. 16) started at a series of transverse nicks caused by the grinding burr. Also apparent from close examination of the ground surface was a large amount of cold work caused by the grinding burr. Apparently as the burr became dull the metal was smeared instead of cut.

3.1.3 Effect of Grinding Weld Toes After Pre-cracking

Four beams, each with two details were examined in this test series. All details failed at the weld toe. The results are compared with the as-welded mean and scatter bands in Fig. 17. All data fell within the confidence limits of the as-welded cover plated beams and indicated that attempts to remove the small cracks at the weld toe were not effective. It became apparent, after failure of the detail, that the crack tip was not removed by the grinding operation. No visible crack was apparent at the weld toe after grinding. This behavior appears reasonable because the depth of grinding was limited to approximately 1/10 in. (2.5 mm) below the surface. As a result, insufficient material was removed.
Any reduction in the stress concentration at the weld toe due to grinding had a negligible effect on the propagation of the remaining crack.

In the GL series, cracks grew from the initial slag intrusions that existed at the weld toe before any repair was attempted. Grinding the weld toe as was done in the GA series did not appreciably alter these discontinuities. The shallow surface cracks were observed to be between 1/8 in. and 3/16 in. deep after failure, which was in most cases deeper than the grinding depth of 1/10 to 1/8 in. Since improvement would only be a reduction in the stress concentration, this had little effect on the rate of crack growth.

Because of the poor results achieved by this method of repair, the planned third series of tests on beams precracked to visible crack size was altered. This series was modified to combine peening and grinding in order to increase the depth of the compression stress field. The results of this study are discussed in the section on peening.

3.1.4 Comparison with Previous Results

The results of earlier tests on ground cover plated beams are summarized in Fig. 18 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.
The improvement in fatigue strength at the end of cover plated beams appears to be very sensitive to the grinding at the weld toe. The operation is not nearly as effective as indicated by tests on small specimens with non-load carrying fillet weld. The stress concentration provided by the cover plated beam was not decreased as much as observed with non-load carrying fillet welded tension specimens\textsuperscript{12}. Only when extreme care was exercised in the grinding and polishing operation were substantial improvements observed. The degree of improvement may also be limited by crack growth from a weld root.

3.2 Fatigue Strength of As-Welded Beams With Peened Weld Toes

3.2.1 Crack Initiation and Growth

The fatigue tests on beams with peened weld toes, nearly all experienced failure from crack growth at the weld toe in the peened region. Figure 19 shows a crack that developed in the peened region at the weld toe. Also visible is a root crack that had penetrated through the weld but did not result in failure.

Peening severely deforms the metal in the vicinity of the weld toe. This blunts the crack-like slag intrusions and introduces compression residual stresses which slow crack initiation and growth within the deformed zone. Figure 20 shows a section through a typical peened weld toe. The severity of the deformation indicated by the elongation of the grains decreased with the depth below the surface as can be seen in Fig. 21. At the surface the individual grains cannot
be distinguished. 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. 22. The depth of these laps was on the order of 0.002 in. (0.05 mm) to 0.010 in. (0.25 mm) 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.

It would appear that these laps behave similarly to the slag intrusions by providing locations for crack initiation and growth. A thin layer of metal was seen extending from the top of many fracture surfaces indicating that cracks either started or at least ran through the base of these laps. This similarity was also indicated in the work by Harrison\(^7\) who showed that when welds were peened and then stress relieved, they provided the same fatigue strength as the untreated weld toe.

Figure 23 shows a fracture surface for an as-welded beam that was peened prior to testing. The fracture surfaces indicate that crack growth was experienced in two primary regions with the crack growing as a semi-elliptical surface crack until penetration of the flange. Peening was more effective near the center of the flange and prevented these surface cracks from joining until after they had penetrated the flange thickness.

3.2.2 Analysis of the Test Data

The effects of the primary variables of stress range and minimum stress were analyzed using statistical techniques and visual comparisons
of the crack growth behavior and test data. Since only small partial fact-
torials were examined, direct comparisons could only be made at the inter-
mediate stress range level where specimens were tested at two levels of
minimum stress.

Figure 24 summarizes the test results of as-welded peened weld
toes. It is apparent from the figure and was confirmed by the analysis
that peening provided an effective means of increasing the fatigue strength
at the 2 ksi (13.7 N/mm²) minimum stress level. Some increase was also
observed at the lowest level of stress range at the higher level of mini-
imum stress. At the intermediate level of stress range, the lower minimum
stress provided an increase of approximately 170% over those beams that
were tested at the 10 ksi (68.9 N/mm²) minimum stress level.

The test data plotted in Fig. 24 show clearly that the level of
dead load (minimum stress) applied after peening has a significant influ-
ence upon the life extension for a peened detail. The application of a
high minimum stress decreases the effectiveness of the compression resid-
ual stresses that are introduced at the weld toe by the peening operation.
This observation is compatible with earlier data reported by Harrison who
showed that stress relieving a peened detail would remove the beneficial
effect of the peening operation⁷.

3.3 Fatigue Strength of Peened Precracked Details

3.3.1 Crack Initiation and Growth

Nearly all precracked details that were subsequently peened, or
ground and peened, failed by crack growth from the weld toe. In a few
cases at the lowest minimum stress level, failure was observed to result from cracks originating from the weld root. These eventually propagated across the transverse end weld and into the beam flange. Prior to peening, toe cracks as large as 0.75 in. (19 mm) in length were observed on the beam surface. The best approximation of their penetration into the flange was between 0.05 and 0.15 in. (1.2 and 4 mm). Figure 25 shows a series of cracks that existed at a weld toe prior to peening. After peening, plastic deformation of the metal in the region of the weld toe was such that the crack was no longer visible and could not be detected by eye. Figure 8 shows the peened surface at a precracked weld toe. The toe crack that existed prior to peening cannot be seen.

Fracture surfaces from these series of tests were examined to determine the effect of peening of an existing crack. Figures 26 and 27 are photographs of fatigue crack and fracture surface. The fracture surface in Fig. 27 shows the existence of cracks across the end of the cover plate. Figures 28 and 29 show magnified portions of two such peened beam repairs for a shallow and a deep crack. In both cases the initial crack appeared burnished indicating relative movement had occurred between the two crack faces. The burnishing became less apparent with increasing crack depth and disappeared at a depth of about 0.15 in. (4 mm). Upon recycling after repair, the crack continued to grow from the original crack, although at a slower rate due to the induced compressive stress field.
3.3.2 Analysis of Test Data

The test results for the PL series are summarized in Fig. 30. The influence of minimum stress is apparent at the intermediate and low stress range levels. Three beams were tested at a minimum stress of 2 ksi (13.7 N/mm²), two at a stress range of 18 ksi (123 N/mm²) and one at 12 ksi (82.7 N/mm²). A very large increase in life was experienced at the intermediate and low stress range level. Even though these beams were precycled to within 75% of the lower confidence limit, peening the weld toe had a beneficial effect. Failure by crack growth from the weld root was observed for beam PLA231 tested at a minimum stress of 2 ksi. No further crack growth was observed at the weld toe. One detail tested at a stress range of 18.6 ksi also failed from the root (PLA241). It is also readily apparent that beams tested at the higher minimum stress level showed very little improvement over the as-welded cover plated beams, particularly, at the highest level of stress range.

The GV and PV beam series were all precracked to visible cracks prior to peening. In the GV series, the visible crack was first ground prior to peening the ground region. The results of these two series are plotted in Fig. 31. Because of observations in the PA and PL series, a number of details in the PV series were also peened under minimum stress. This was done in an attempt to simulate the influence of dead load stresses in actual structures. The data points shown as open circles and squares correspond to specimens that were not peened under dead load (minimum stress).
It is readily apparent from Fig. 31 that peening the specimens under dead load provided substantial improvements and very large increases in fatigue strength. Even at the highest stress range level, four details which were peened under the minimum stress of 10 ksi (68.9 N/mm²) averaged nearly a 300% increase in life. At the intermediate stress range level two details which had developed large cracks very early in the test were peened under no load and subsequently failed prematurely with no increase in life. Three other beams tested at the same stress range level were peened under minimum load and all showed large increases in life.

The difference in life due to the influence of minimum stress was particularly apparent in the PA and PL series. This difference can be directly attributed to the fact that application of the minimum load after peening removed a substantial amount of the beneficial compressive residual stresses that were introduced during the peening operation.

It should be also noted in Fig. 31 that three beams for the GV series were first ground and then peened, two at a stress range of 24.8 ksi (167 N/mm²) and one at 12 ksi (82.7 N/mm²). The test data do not show any appreciable difference in the fatigue strength for these three beams. Hence, grinding the weld toe prior to peening did not appear to be necessary.

Since actual structures which may exhibit sub-critical crack growth prior to peening in the field will be subjected to their minimum stress level, those structural components can be expected to exhibit the same behavior as the precracked beams that were peened under minimum loads. Very substantial improvements in life can be developed under these conditions.
The results of all beams with peened details that were tested under a low minimum stress level or that were peened under their minimum load, are summarized in Fig. 32. Those details that were peened in the absence of dead load are not plotted in Fig. 32. When the 10 ksi minimum stress was applied to these beams it eliminated most of the beneficial effects of the peening treatment. 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.

Also shown in Fig. 32 are test results on small plate specimens with 6 in. (152 mm) longitudinal gussets welded to their surface. These tests were reported by Gurney and were made on as-welded specimens. 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 6 in. (152 mm) 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.

The substantial scatter observed with the peened cover plated beams can be directly attributed to the variability in crack depth and the depth of peening. When the crack is shallow, compressive residual stresses can be induced around the crack tip and result in substantial increases in fatigue strength as the effective stress range is decreased. When very
large cracks exist, the crack tip cannot be reached by the peening process and hence little beneficial effect is provided. Furthermore, application of a high minimum stress level reduces or eliminates the effectiveness of the compression residual stress introduced by peening. These factors should be considered in the application of this criteria to retrofit structural details.

3.4 Fatigue Strength of As-Welded Details

After Gas Tungsten Arc Remelting the Weld Toe

3.4.1 Crack Initiation and Growth

The as-welded details treated by the gas tungsten arc remelt all failed from crack growth at the weld root. No failures were observed from the toe. Figure 33 shows a photograph of a cracked detail. It is apparent that crack growth originated from the weld root, penetrated through the transverse fillet weld, and eventually grew into the flange via the longitudinal fillet welds. This can be seen in Fig. 34 which shows the fracture surface of a beam flange. The growth of the crack from the root is visually apparent as is its progress through the transverse fillet weld as an elliptical crack. After penetrating the transverse fillet weld surface it is apparent that the crack moved across the transverse width and eventually penetrated into the beam flange via the longitudinal fillet welds.

Because all failures of the as-welded series were from the weld root, it was concluded that the slag intrusions and other surfaces discontinuities were removed or corrected. The resulting gas tungsten arc remelt solidification structure did not promote further crack initiation
or growth. Close observation of the weld toe region of all specimens did not reveal any potential crack growth sites (see Fig. 11).

3.4.2 Analysis of Test Results

The results of the TA series are summarized in Fig. 35. In this series of tests the fillet weld toes were remelted by the gas tungsten arc before the beams were cycled. As demonstrated in Fig. 35 a very high degree of success was achieved at all levels of stress range. Increases in life ranged from 270 to 360 percent depending on the level of stress range. Minimum stress was not very significant. The results were comparable to the original as-welded beam studies which had indicated little influence of minimum stress.

The gas tungsten arc remelting was especially effective when applied before the detail was cycled because the failure causing discontinuities present at the as-welded toe of the transverse weld were only a few thousandths of an inch below the surface and could easily be reached with shallow weld penetration. Earlier studies have demonstrated that these defects take the form of nonmetallic intrusions which penetrate into the surface along the weld toe. The presence of these intrusions is one of the reasons when coupled with high stress concentration conditions that fatigue cracks always initiate and propagate at this location. Their shape and size cause them to act as preexisting cracks. These crack-like defects were effectively removed by the gas tungsten arc remelting before they were allowed to grow.
The TA series were retrofitted under conditions that would be classified as in-shop conditions. The beams were arranged so as to allow the gas tungsten arc remelt pass to be made in the down hand flat position which resulted in a uniform penetration and smooth weld contour. The remelt welds were continued for a short distance around the corner of the transverse fillet weld to avoid leaving a crater in an area susceptible to fatigue crack growth.

The test results also demonstrate that an upper bound to fatigue strength is provided by crack growth from the weld root. No further improvements at the toe can have any benefit when cracks grow from the weld root. The test data plotted in Fig. 35 provide an upper bound estimate to the improvement that is possible at the transverse welds of cover plated beams. An analysis of the test data indicated that stress range was the only significant variable accounting for the variation in fatigue strength.

3.5 Fatigue Strength of Pre-cracked Details After Treatment by Gas Tungsten Arc Remelting the Cracked Region

3.5.1 Crack Initiation and Growth

Crack growth in the TL and TV test series was dependent on whether or not the repair of the preexisting cracks was successful. When the repair was successfully made, crack growth was usually experienced from the weld root. In the TL series there were three toe failures and thirteen root failures. The toe failures were caused by an inadequate
remelt penetration. Figures 36 and 37 show typical failures of this type. The clam shell marks in the center of the beam mark the extent of the initial crack. The remelted region was characterized by a course interdendritic fracture surface which varied in depth across the flange from a maximum of 0.28 in. (7.1 mm) to a minimum of 0.06 in. (1.5 mm). After repairing the cracked zone by remelting and solidification, cyclic loading was resumed. When the crack was not melted out, the remaining portion of the original crack quickly grew up through the remelted region and continued down through the flange. These tests served to illustrate the need for completely removing the crack, as partial penetration repairs are not effective.

During the TV series, higher heat input was used since the cracks were expected to be deeper. This eliminated the problem of inadequate penetration. Although there were no failures due to inadequate penetration, there were eight toe failures and eight root failures observed. Four of the toe failures were examined in detail. This examination revealed that the failures were the result of mechanical discontinuities. There was no evidence of failure due to adverse metallurgical properties resulting from the remelt. Figure 38 shows a fracture surface for the gas tungsten arc toe failure. The principal crack initiated at a ripple near the weld toe of the gas tungsten arc weld and is shown by an arrow. A secondary crack also started at a weld ripple. The crack propagated through the course grain heat affected zone and weld metal following the undercut at the weld toe. It sometimes propagated along a weld ripple and indicated a lack of preference for a particular microstructure.
The microstructure of the area near the initiation site, along with the microstructure near the top of the flange is shown in Fig. 39. The fine grain size at the top of the flange indicates that the whole thickness of the flange had been transformed from above $A_3$.

Figure 40 shows a failure that started at a depression and weld ripple .12 in. (3 mm) away from the toe of the gas tungsten arc weld. A slag-like material was firmly attached to both initiation sites. The crack propagated mainly along the gas tungsten arc remelt zone, although it did travel for a short distance through the heat affected zone. This failure occurred on a beam which was not sandblasted prior to making the gas tungsten-arc remelt. The mill scale that was still present appears to be deposited in the weld metal. Furthermore, it is probable that some undercutting resulted from welding on a surface that had not been blast cleaned since the weld metal does not wet as readily on mill scale as on the clean surface. This clearly indicates the desirability of blast cleaning the weld area prior to application of the gas tungsten arc remelt pass.

Although a number of toe failures did occur in both the TL and TV series, for the most part these were still accompanied by a substantial increase in life. The frequency of toe failures was greater with the TV series where all beams were precycled to a visible crack. The higher incidence of toe failures is believed to be caused by geometrical factors such as weld bead shape and undercutting which were the result of the higher heat input needed to close the preexisting cracks. The weld bead shape for the TV series tests was usually much rougher than observed for the TL and TA series. There was no evidence of any metallurgical changes
as a result of the high heat input which could be associated with the toe failure modes.

3.5.2 Analysis of Test Data

The test results for the TL and TV series are summarized in Figs. 41 and 42. It is apparent from both Figs. 41 and 42 that the gas tungsten arc repair procedure can successfully strengthen and improve the fatigue characteristics of cover plated beam details.

Those test points which fall within the scatter band of the as-welded beams failed from crack growth at the weld toe. As was noted in the earlier section, this was caused when the crack was not eliminated by the remelt process. As better welding procedures were developed, it was possible to eliminate this mode of failure. This is demonstrated in Fig. 42 which shows the stress-life plot for beams with visible cracks. None of these beams experienced the premature failure that was observed in the TL series (see Fig. 35 and the three test points falling inside the scatter band). Although a number of toe failures did occur in the TV series, these failures were not due to lack of penetration. As was noted, all started at the surface in or near the gas tungsten arc remelt zone.

It is clear from this test series that even relatively deep cracks (.18 in. - 5 mm) can be gas tungsten arc repaired successfully. Although a number of toe failures occurred, they still resulted in an increase in life which was in excess of 200%. This resulted because the toe crack must again initiate in the gas tungsten arc weld from new sources of discontinuities that exist after the repair is made.
The results of all three test series are summarized in Fig. 43. Except for those failures in precracked beams that occurred because of failure to incorporate the complete crack into the gas tungsten arc remelt, approximately the same increases in life was 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.

Data available from other sources is primarily on small plate specimens with transverse gussets that provide a non-load carrying joint\textsuperscript{9,10}. The studies on NCHRP project 12-7 have indicated that this type of specimen provides fatigue behavior that is similar to stiffener type details\textsuperscript{2}. No data was available on cover plated beam details that had been subjected to gas tungsten arc remelting at fillet weld toes.

3.6 Detection of Cracks at Weld Toes

During the course of this experimental study, considerable effort was made during the precracking operations to detect the small semielliptical surface cracks that formed at the termination of the transverse fillet welds. The primary crack detection methods employed were ultrasonic inspection at the weld toe termination utilizing a shallow surface wave, visual inspection with 10X magnification, magnetic particle, and dye penetrant.

These detection procedures revealed the presence of the small semielliptical surface cracks (1/4 in. or larger) at about the same time.
None of the methods provided a reliable means of ascertaining the shallow crack depth. Approximations were made using the ultrasonic test method. However, comparisons of the response with known calibration blocks still revealed substantial variation and scatter. A reasonable estimate of the crack depth could be made in most cases by employing the relationship between crack width and depth at the time of observation. (The width is between 2 and 2.2 times the depth).

Because these tests were undertaken under controlled laboratory conditions, it is probable that comparable detection capability would not be possible under field conditions unless very skilled personnel were available and trained to look at the sites of crack initiation.
4. RECOMMENDATIONS AND APPLICATION

1. This study has shown that two methods can be reliably used to either improve or upgrade (retrofit) the fatigue strength of welded details that experience crack growth from weld toes when applied to as-welded details or to details that have experienced cyclic loading and have cracks less than 1/8 in. deep. This can be accomplished by peening the weld toe region or applying a gas tungsten arc remelt pass to the weld toe region. The fatigue strength can be expected to increase at least one design category (i.e. from Category E to Category D for the cover plated beam).

2. Peening the weld toe region is mainly effective under low dead load or when the peening operation is carried out on structural components while they are subjected to dead load. This latter procedure prevents the beneficial compressive residual stresses from being reduced by the application of dead loads. Hence peening should not be used unless it is applied under dead load conditions.

3. The gas tungsten arc remelt procedure was not dependent upon the level of minimum stress. For design purposes, stress range fully accounted for the variation in fatigue life.

4. The improvement or repair provided by peening or gas tungsten arc remelt of the weld toe can be satisfactorily applied to details suspected of having sustained fatigue damage. They provide a
retrofit procedure that can be utilized on bridge structures that are suspected of having micro-size discontinuities or cracks along the weld toe region. Application of peening or the gas tungsten arc remelt can effectively strengthen the detail and provide substantial increases in life.

5. Crack growth at the toe of terminating fillet welds can be observed at about the same time by ultrasonic inspection and visual inspection with magnification. Under good conditions, surface cracks between 1/8 in. (3 mm) and 1/4 in. (6 mm) long, can be detected by these methods; that is, the crack penetration into the beam flange must exceed 0.05 in. (1.5 mm) in order to be detected.

6. Grinding the toe of fillet welds is a well known improvement technique that was found to result in substantial scatter and variability in this study. Unless considerable care is exercised during the grinding operation, questionable improvements result. Both peening the weld toe or applying the gas tungsten arc remelt pass appeared to be more favorable procedures. Radiused transitions such as those used in groove welded flange splices or at the ends of longitudinal attachments to the web or flange which have been ground to smooth the transition radius are effective in increasing the fatigue strength of a detail\(^1,2\). The stress concentration and the initial discontinuity conditions are reduced to a much greater degree than experienced with grinding the weld toe. The radiused transition which is subsequently ground
provides a condition similar to the tests carried out by Graf on cover plated beams with tapered ends ground smooth.

7. An important factor to be considered when deciding which of the available improvement techniques is to be used is the cost, ease, and reliability of the application. Peening and the gas tungsten arc remelt pass appear to be more economical than grinding.

8. Although this study was conducted on A36 steel cover plated beams, the results can be applied to other structural steels. Earlier tests on small specimens indicate that the comparable improvements can be expected for other structural details and for other grades of steel.

9. No improvement at the weld toe region can provide a detail that will exceed the fatigue strength which results from crack growth from the weld root. Cover plated beams treated by either peening or gas tungsten arc remelt methods can be upgraded one design category. Higher improvements are not possible because crack growth from the weld root cannot be prevented.
5. CONCLUSIONS

Conclusions in this chapter are based on the analyses and evaluation of the test data and earlier published work. Fatigue tests were conducted on cover plated beams with and without preexisting cracks that were treated by several improvement techniques. The results permit the following conclusions to be made about the effectiveness of the three repair-improvement procedures studied.

1. The three repair or improvement methods are effective to varying degrees in extending the fatigue life of cover plated beams. Grinding was not very effective. It resulted in the removal of discontinuities that were near the surface. With increasing crack depth, the method was less effective. Furthermore, it was not effective at the higher stress range levels. The early failure of several specimens could be directly attributed to mechanical notches that were caused by the grinding burr.

2. Peening was more effective than grinding as a repair method and can be applied with good results to both uncracked as-welded details and details with surface cracks having depths up to about 1/8 in. (3 mm). This method was found to be minimum stress dependent. It was less effective at higher stress range levels and under high minimum stress. The application of high minimum stress caused a reduction in the effectiveness of peening because
it caused a decrease in the compression residual stress. Approximately the same fatigue strength resulted for low levels of minimum stress and for specimens peened under minimum stress. Under these latter conditions, the fatigue strength was improved one design category (from E to D)\textsuperscript{3}.

3. The gas tungsten arc remelt pass was the most effective method examined and showed the least amount of minimum stress dependency. This method can be successfully applied to repair details with surface cracks up to about 1/8 in. (3 mm) deep.

4. Crack initiation at the toes of the fillet weld is caused by non-metallic intrusions which result from the welding process\textsuperscript{10,16}. The presence of these intrusions was confirmed in this study.

5. Crack initiation in repaired beams generally resulted from defects introduced by the repair method. While an increase in life was usually experienced, additional increases in life could be obtained when the repairs were made with greater care. The application of the gas tungsten arc remelt pass to as-welded beams will provide an increase in fatigue strength comparable to one design stress category.

6. Details subject to cyclic loads can be repaired or improved providing the cracks do not exceed about 1/8 in. (3 mm) penetration into the flange (approximate width at toe of 1/4 in. to 3/8 in.). Retrofitting such details by either peening or application of
the gas tungsten arc remelt procedure will provide a detail that equals or exceeds its original condition.

7. Cracks with depths that exceed the penetration capability of the gas tungsten arc remelt pass and the effectiveness of peening cannot be repaired by these procedures. The most reliable method of repair for large cracks is the application of bolted splice plates which transfer the stress around the crack.

8. Small cracks at weld toes can be detected by either ultrasonic inspection using a shallow surface wave or visual inspection with magnification. A trained inspector can detect surface cracks approximately 0.25 in. (6 mm) long under good conditions. Smaller cracks cannot be readily detected by available methods of nondestructive inspection. The crack depth will usually be slightly less than one-half the surface crack length.
6. RECOMMENDATIONS FOR FURTHER WORK

The experimental work reported in NCHRP Reports 102 and 147 has indicated that the primary factors influencing fatigue strength are the range of stress and the type of detail. These studies show that the cover plated beam represents one of the most severe conditions that can be expected and yields a lower bound condition. A number of other details were shown to exhibit comparable behavior.

In the studies reported herein, two methods of strengthening severe notch producing details, such as the cover plated beams, were found to be successful. Peening the weld toe region was observed to strengthen details subjected to low levels of minimum stress or when peening was done in the presence of the minimum stress (dead load). Both as-welded and precycled-precracked beams were examined. Limitations in the effectiveness of this procedure depending on the depth of penetration of the crack into the flanges were noted. The application of a gas tungsten arc remelt pass at the weld toe was also observed to provide a satisfactory method of retrofitting or improving the fatigue strength of as-welded and precracked details. The gas tungsten arc remelt was able to incorporate the shallow surface crack into the solidified metal when the depth of crack penetration did not exceed 0.15 in. (4 mm). It is believed that crack depths up to 1/8 in. can be reliably repaired.

These studies have pointed out the need for additional studies of these improvement procedures.
Suggested Studies

It is recommended that consideration be given to the following studies so that appropriate design criteria and retrofit procedures and techniques can be developed. A number of these studies are listed in NCHRP Reports 102 and 147 and are repeated here for completeness.

1. The improvement provided by peening or applying the gas tungsten arc remelt pass should be applied to several fatigue critical details such as flange and web attachments which are comparable to the cover plated beams. Further improvements can be expected when crack growth is not possible from the weld root. Consideration should also be given to studies on thicker flanges where the depth of penetration of the crack into the flange can be varied to a greater degree.

2. Preliminary studies indicate the gas tungsten arc remelt procedure does not metallurgically damage the repaired toe area, however the remelt procedure should be applied to other structural steels to determine if this is also true for the higher strength heat treated materials. Some high strength steels, such as those in the A514 group, are much more sensitive to the heat of welding. The extensive heating of the flange area necessary to eliminate existing deep cracks may have an adverse effect on the properties of the repaired area. Research extending the tungsten arc remelt procedure to one or more of these steels would establish the suitability of this repair method to newer materials.
3. Studies are needed on groove welded attachments and cross beams, as these are commonly used details. The groove welded plate attached to a tension flange tip or beam web is commonly used in bridge construction to attach lateral bracing and diaphragms. Often nothing is done with the weld toe termination on the flange tip or web and crack growth can be expected at these weld toes under high cyclic stress. Substantial reductions in fatigue strength can also be expected from groove welded plates. Further experimental studies are needed on this detail and it would provide an opportunity to examine the improvement provided by peening or the gas tungsten arc remelt dressing of the weld toe as well as changes in transition geometry.

4. Further studies are needed to define the behavior of a variety of attachments to beams and girders. These details should be placed on deeper girders and thicker flanges. Among factors needing consideration are the relationship of stiffner or other attachment thickness to the flange or web thickness, the geometrical configuration of the weld, and sizes of copes. These variables can be examined and the effectiveness of the suggested repair and improvement procedures evaluated on the same specimens.

5. It is common practice to use longitudinal groove welds with a backup bar in box girder sections. Studies are needed on this weld configuration to determine whether or not the flaw condition and fatigue strength under these welding conditions are more
severe than the plain welded beam conditions. Replacement of the backing bar with glass tape could be part of such a study. An examination of the influence of intermittent welds is also needed as the current study has shown that little information is available in the literature. Such details may be penalized using existing design criteria.

6. Studies are also needed to evaluate the significance of a variety of manufacturing and fabrication discontinuities. For example, the influence of seams, laminations and inclusions that are parallel to the stress field and welding discontinuities that are parallel to the stress field need to be systematically examined. Although an inclusion, seam, or other comparable discontinuity may be critical, when oriented so that the applied forces are perpendicular to the discontinuity, available information indicates such discontinuities have a minor or negligible effect when located parallel to the line of stress. Seams have been observed in cover plated beams with the longitudinal welds attaching the cover plate to the beam flange adjacent or over the longitudinal seams. In some cases shrinkage has opened the seams. Other conditions that have developed are in rolled plates where seams have opened along the edge when welds have been placed along the plate surface near the edge. Although analytical indications and available information indicate they are not significant, tests are desirable to confirm such observations.
7. Further studies are needed on the effectiveness of arc air gouging and subsequently rewelding of fatigue cracked details. Gouging and rewelding should be similar to GTA remelting, moreover it could be applied to much deeper cracks. Since this procedure involves the deposition of weld metal, it may also lead to high residual stresses and weld defects. Existing laboratory experience does favor this as a repair method, however, no systematic study of this repair procedure has been undertaken.

8. A systematic study of the fatigue strength of welds in shear is needed. The current design provisions adopted by AASHTO are based on studies in the 40's. It results in the only stress range cycle life relationship that is not compatible with other details as it deviates substantially from the slope of all other details.
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Both Flanges

\[ \frac{1}{4} \]

\[ P \]

\[ 9\frac{1}{16}'' \times 4\frac{1}{2}'' \quad (11\text{mm} \times 114.5\text{ mm}) \]

\[ W14 \times 30 \]

\[ 3' - 0'' \]
\[ 914.4 \text{ mm} \]

\[ 4' - 0'' \]
\[ 1219.2 \text{ mm} \]

\[ 3' - 0'' \]
\[ 914.4 \text{ mm} \]

\[ 3'' \]
\[ 76.5 \text{ mm} \]

Fig. 1 Schematic of Test Setup and Member Details
<table>
<thead>
<tr>
<th>Minimum Stress</th>
<th>12 (82.7)</th>
<th>12 (82.7)</th>
<th>12 (82.7)</th>
<th>12 (82.7)</th>
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<tbody>
<tr>
<td>Stress Range, $S_r$, ksi (N/mm$^2$)</td>
<td>24.8 (171.0)</td>
<td>18.6 (128.1)</td>
<td>24.8 (171.0)</td>
<td>18.6 (128.1)</td>
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</tbody>
</table>

### Series I

- **PAA Series**
  - PAA241
  - PAA242
  - PAA331
  - PAA341
  - PAA351
  - TLA331
  - TLA341
  - TLA351

- **TLA Series**
  - TAA241
  - TAA242

### Series II

- **PAA Series**
  - PLA231
  - PLA241
  - PLA242
  - PLA331
  - PLA341
  - PLA351
  - TLA331
  - TLA341
  - TLA351

- **TLA Series**
  - TLA241
  - TLA242

### Series III

- **PAA Series**
  - PVA241
  - PVA242
  - PVA331
  - PVA341
  - PVA351
  - TVA331
  - TVA341
  - TVA351

- **TLA Series**
  - TVA241
  - TVA242

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*Fig. 2 Experiment Design*
Fig. 3 Test Setup on Dynamic Test Bed
Fig. 4 Tree-shape Burring Bit Used for Grinding

Fig. 5 Typical As-welded Ground Weld Toe
Fig. 6 Peening Tool

Fig. 7 Typical As-welded Peened Weld Toe
Fig. 8 Typical Precracked Peened Weld Toe
- Spec. PLA 352b
(a) Simple Procedure to Restart

(b) Preferred Alternative Procedure

Fig. 9 Procedure Used for GTA Weld Termination
After Millington (9)
Fig. 10 GTA Remelted Weld Toe Showing Root Failure

Fig. 11 Etched Cross-section Showing GTA Remelt Zone at Toe and Root Crack
Fig. 12 Failure at Toe of Ground Detail
   - Spec. GAA331a

Fig. 13a Failure of Root at Ground Detail
   - Spec. GAA331b
Mean and 95% Confidence Limits for 95% Survival

Fig. 14 Comparison of Test Results for As-Welded Ground Details and As-Welded Details

 Minimum Stress = 10 ksi
Fig. 13b Fracture Surface Showing Root Crack and Entry Into Beam Flange

Fig. 15 Embedded Slag Particle at Toe of Ground Detail - 16X
Fig. 16a  Weld Toe

Fig. 16b  Fracture Surface

Transverse Nicks From Grinding Burr 16X
Minimum Stress = 10 ksi

Fig. 17 Summary of Test Results for GL Test Series
Fig. 18 Comparison of As-Welded Coverplated Beams with Ground Coverplated Beams

- 45° Ground Toe
- 22° Ground Toe
- 30° Ground & Polished
- This Study

As-Welded Cover-Plated Beams

Stress Range, ksi

Cycles to Failure
Fig. 19 Failure at As-welded Peened Detail

Fig. 20 Section at a Peened Weld Toe
Fig. 21 Macro-Etched Section at Peened Weld Toe

Fig. 22 Lap-Type Discontinuity at Peened Weld Toe
Fig. 23 Fracture Surface at Peened Weld Toe With Root Crack in Transverse Weld - PAA352a

Fig. 25 Shallow Surface Crack at Weld Toe
Fig. 26: Cracks at End of Coverplate at Peened Weld Toe And in Transverse Weld - PAA341b

Fig. 27: Fracture Surface at Precracked Peened Weld Toe - PVA331b
Fig. 24 Summary of Test Results for PA Test Series
Minimum Stress = 2 ksi
Minimum Stress = 10 ksi

Fig. 30 Summary of Test Results for PL Series
Fig. 28  Shallow Precrack (0.025 in.) at Peened Weld Toe 12X

Fig. 29  Deep Precrack (0.160 in.) at Peened Weld Toe
Fig. 33 Crack Growth from Weld Root Across Full Width of Transverse Weld

Fig. 34 Crack Growth Into Beam Flange Via Longitudinal Weld
Minimum Stress = 2 ksi Peened Under $S_{\text{min}}$

Minimum Stress = 10 ksi, Peened Under $S_{\text{min}}$

Minimum Stress = 10 ksi Ground Before Peening

Fig. 31 Summary of Test Results for GV and PV Series
Fig. 32 Comparison of Test Results With Tests on 6 in. Gussets
Fig. 35 Summary of Test Results for TA Series

- Minimum Stress = 2 ksi
- Minimum Stress = 10 ksi
Fig. 41 Summary of Test Results for TL Series

- Minimum Stress = 2 ksi
- Minimum Stress = 10 ksi
Fig. 36 Crack Growth From Weld Toe of GTA Remelt Which Did Not Remove Precrack

Fig. 37 Close-up of Toe Failure From Inadequate Remelt
Fig. 38a GTA Weld

Fig. 38b Fracture Surface

Crack Growth From Weld Ripple At Weld Toe
Fig. 39a Near Crack Initiation Site

Fig. 39b Near Top of Flange Surface

Photomicrographs of Flange of GTA Remelt Specimen 532X
Fig. 40a  Depression Near Weld Ripple

Fig. 40b  Fracture Surface

Crack Growth From Weld Ripple of GTA Remelt - TVA33lb
Fig. 42 Summary of Test Results for TV Series

- Minimum Stress = 2 ksi
- Minimum Stress = 10 ksi
Fig. 43 Comparison of all GTA Remelt Tests

- As-Welded
- Pre-cracked 75% LCL
- Pre-cracked Visible

Design Category D

Design Category E

STRESS RANGE, ksi

CYCLES TO FAILURE

10^5  5  10^6  10^7  2
APPENDIX A

CLASSIFICATION OF

WELDED BRIDGE DETAILS FOR FATIGUE LOADING

Research Results Digest

Digest 59 - March 1974
APPENDIX B

NONDESTRUCTIVE METHODS OF FATIGUE CRACK DETECTION

IN STEEL BRIDGE MEMBERS

Research Results Digest

Digest 66 - January 1975
APPENDIX C: MATERIAL PROPERTIES AND BEAM CHARACTERISTICS

Details of the test beams are given in Fig. 1 with nominal dimensions and weld details. The fourteen inch rolled wide flange beams were identical in geometry to the cover plated beams reported in Ref. 1. The thickness of flanges and webs were measured with a micrometer. Widths of flanges and depth of beams were measured using a dial gauge mounted on a fixed caliper. Average measurements were used to determine cross section properties.

Table C1 summarizes measured dimensions and cross-section properties of typical cover plated beams. These measured properties are compared with tabulated handbook values in Table Cl.

Tension specimens were fabricated from sections of the beam flanges and web. These test sections were randomly selected from typical beams. All test specimens conformed to ASTM-A370. The width of the specimens was 1.5 in. (38 mm). All tests were conducted in a 120 kip (536 N) capacity screw-type mechanical testing machine. Specimen dimensions, yield load, static yield load, ultimate load, fracture load and location of break were recorded. Testing speed was 0.025 in. (.63 mm) per minute until the yield point was established. The speed was increased to 0.100 in. (2.54 mm) per minute and maintained at that rate up to rupture after strain hardening was observed. The initial gage length of 8 in. (203.2 mm) was used to determine elongation characteristics. The results of these tests are summarized in Table C2.
The results of the mill tests are also given in Table C2. The mechanical properties include dynamic yield point usually provided at 0.100 in. (2.54 mm) per minute, tensile strength, and elongation. Also given are the chemical composition specifications required by ASTM.
### TABLE C1

**MEASURED BEAM CHARACTERISTICS**

<table>
<thead>
<tr>
<th>Beam Type</th>
<th>Flange Width (in.)</th>
<th>Flange Thick. (in.)</th>
<th>Web Thick. (in.)</th>
<th>Depth (in.)</th>
<th>Coverplate Width (in.)</th>
<th>Coverplate Thick. (in.)</th>
<th>Moment of Inertia Plain Coverplate (in.⁴)</th>
<th>Section Modulus Plain Coverplate (in.³)</th>
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<tr>
<td>Plain Rolled</td>
<td>6.71</td>
<td>0.386</td>
<td>.275</td>
<td>13.92</td>
<td>4.50</td>
<td>.55</td>
<td>289.0</td>
<td>549.0</td>
</tr>
<tr>
<td>W14 x 30</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Handbook Properties</td>
<td>6.733</td>
<td>0.383</td>
<td>0.270</td>
<td>13.86</td>
<td>--</td>
<td>--</td>
<td>290.0</td>
<td>41.9</td>
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TABLE C2

PHYSICAL AND CHEMICAL PROPERTIES OF ROLLED BEAMS

(a) Coupon Tests

<table>
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<tr>
<th>Component</th>
<th>Thickness (in.)</th>
<th>No. of Spec.</th>
<th>Yield Tension (ksi)</th>
<th>Stress St. Dev. Mean</th>
<th>Tensile Strength (ksi) St. Dev. Mean</th>
<th>Mean Elong (%) In Area (%)</th>
<th>Mean Reduc. In Area (%)</th>
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</thead>
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<tr>
<td>Flange</td>
<td>0.386</td>
<td>7</td>
<td>36.5</td>
<td>2.7</td>
<td>62.7</td>
<td>2.2</td>
<td>25.4</td>
</tr>
<tr>
<td>Web</td>
<td>0.275</td>
<td>5</td>
<td>40.0</td>
<td>1.2</td>
<td>63.5</td>
<td>1.9</td>
<td>30.3</td>
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</table>

(b) Mill Report

Heat 172K116 W14 x 30 42.27 67.0 23.2
Carbon 0.23; Mn 0.59; Phosphorus 0.018; Sulfur 0.028
APPENDIX D: PROCEDURES USED FOR WELD TOE TREATMENT

1. **Grinding**

The equipment used to grind the weld toe region consisted of a 3/8 in. (9.5 mm) electrical drill which operated at 1100 rpm and a burring bit Nicholson type S7EW tree-shaped with radius end.

Only the transverse toe of the weld was ground. Grinding was continued until a smooth uniform surface was obtained. In cases where there was a crack, the grinding was continued until the crack was not visible if at all possible. The depth of grinding was approximately 0.03 in. (0.76 mm). Beams in the GV series were ground in the same manner. However, after grinding, the weld toe region was peened.

2. **Peening**

Peening was carried out with an Ingersol-Rand Model 1940 air hammer. The air hammer was operated at an air pressure of 25 psi (0.17 N/mm²). Mechanical peening was applied using the peening tool profile suggested by the British Naval Construction Research Establishment. The geometry of the peening tool is given in Fig. D1. All corners were removed at the end of the tool so that smooth surfaces were present and no sharp indentations would result during the peening operation.
Peening was continued until a smooth uniform surface was obtained. After a few passes the depth of the indentation did not significantly change. The average depth of indentation at the weld toe due to peening was approximately 0.03 in. (0.76 mm). When cracks existed at the weld toe, peening was continued until the crack was not visible with 10X magnification.

3. Gas Tungsten Arc Remelting

The gas tungsten arc remelt procedure was carried out using a Linde HW-18 water cooled torch and a Linde Model SVI-300 (D.C.S.P. mode) 40 V open circuit (100% duty cycle) power source. A sketch of the general arrangement of equipment for this process is shown in Fig. D2. A high frequency starting package was used to make arc initiation easier and prevent electrode contamination on the start cycle. A 2% thoriated tungsten electrode 5/32 in. (3.8 mm) in diameter was used with a 3/16 in. (5 mm) stickout. The entire welding unit was mounted on a Bernard portable carriage which also contained a water supply for the torch and a recirculation pump to cool the torch. After a series of preliminary tests were made (see Appendix H), the shielding gas employed was helium. The torch was moved manually along the weld toe and depth of penetration controlled by travel speed (and shielding gas). Travel speed was about 3 inches/minute (1.27 mm/sec.).

The initial penetrations achieved by this procedure were about 0.1 in. (2.5 mm). This penetration was considered insufficient
for precracked beams, and was difficult to reproducably achieve in the overhead position. The series of studies reported in Appendix H, however, showed that the use of helium shielding gas and careful control of the cathode (torch) vertex angle would give improved penetration and more uniform penetration. Using the results of this study, cathode vertex angles between 30 and 60 degrees were employed along with the helium shielding gas. The resulting penetration was about 0.25 in. (7.7 mm).

Surface preparation of the areas to be welded was by sandblasting, since the presence of mill scale promoted undercutting. The welding procedure was to initiate the weld on the longitudinal weld toe, continue around the transverse weld toe and terminate in the opposite longitudinal toe. Necessary terminations on the transverse weld were carried up to the weld face to avoid crater cracks in the toe area.

Although initial welds in the TA series were in the flat position, subsequent welds were in the overhead positions. In the overhead welds, some variations in penetraters occurred as high heat inputs were harder to maintain. The arc current was set at 200 volts and travel speed varied to give greater penetration as needed. The limiting condition on travel speed (and thus penetraters) occurred when the weld puddle was no longer possible to control in the overhead position.
Fig. D1 Schematic of Peening Tool
(From British Naval Construction Research Establishment)
Fig. D2 Schematic of Gas Tungsten Arc Remelt Equipment
APPENDIX E: CRACK INITIATION AND GROWTH

There is evidence from many investigations that the fatigue strength of fillet welded details depends only on the rate of crack growth. Crack initiation is considered to be nearly complete after the weld is made, due to the frequent occurrence of sharp discontinuities in the vicinity of the weld toe caused by the intrusion of nonmetallic material. These intrusions have been examined by a number of investigators\textsuperscript{10,16}. It has been determined that the intrusions result from welding slag present in the locally melted regions of the base metal or in the weld metal. The size of these discontinuities has been estimated to be in the range of 0.015 in. (0.38 mm) long and several thousandths of an inch (hundreds of a millimeter) deep with an extremely sharp root radius of 0.0001 in. (0.0025 mm) or less. Many of these investigations were made on shielded metal arc welds where slag was present from the electrode covering. Since the welds in this investigation were made by the gas metal arc process, they were examined in detail to determine if the same type of defects were present.

The scanning electron microscope was used to examine both the fatigue fracture surfaces and polished surfaces of the weld toe region. The fracture surfaces examined were from the compression flanges of several beams. As the studies reported in Refs. 1 and 2 have demonstrated, cracks can be expected to grow in regions of residual tensile stress. No cracks would be expected in the compression flange without residual stress. Cracks present in the compression flange were detected by destructive
examination and found to be about 0.010 in. (0.25 mm) deep and 0.060 in. (1.5 mm) long. Scanning electron microscope photographs of typical cracks are shown in Figs. E1 to E3. It is significant that each crack appears directly below a slag particle and not in the presence of any obvious defect. Figure E4 shows a crack which initiated at the termination of a weld ripple. The same crack is shown at a higher magnification in Fig. E5. A slag network is seen clinging to the weld metal and a small depression is visible in the base metal which is also filled with slag. Figure E6 shows a much higher magnification and demonstrates the intimate contact between the welding slag and the base metal. Although the degree to which the slag and base metal are joined is not obvious, it does appear that the slag penetrates a short distance into the base metal and suggests that some part of the base metal at the weld toe had been melted and thrown around the slag particles.

Figure E7 shows a section taken parallel to the base metal surface at the weld toe. Several distinct slag particles can be seen embedded in the base metal. The numerous pin holes are evidence that the base metal had been melted in the vicinity of the embedded slag particles. A crack is seen to traverse the melted area and run adjacent to the slag particles. Further evidence that the metal had been melted is shown by the swirl pattern on the polished surface adjacent to the rough area. A close examination of the rough area reveals many laps with sharp crack-like features, any of which appear to be a likely location for cracks to form.

This evidence continues to confirm the presence of weld discontinuities which intrude locally into the base metal along the weld.
Comparable discontinuities were observed by Harrison and others for a number of welding processes. In addition to the gas metal arc welds from the fatigue specimens, several shielded metal arc welds were made using electrodes conforming to AWS No. E7016 classification. These welds were ground down to the weld toe, polished, and then examined on the scanning electron microscope. The results are shown in Figs. E8 through E10. These figures clearly demonstrate the presence of slag particles embedded in the locally melted base metal. Figure E10 shows a crack-like defect only 0.001 in. (0.025 mm) wide and partially filled with slag. It is likely that the crack tip radius is considerably smaller than the crack width. Earlier investigators have estimated that the radius at the tip of the slag intrusion is less than 0.0001 in. (0.0025 mm), which is compatible with this observation.

In summary, the investigation made using the scanning electron microscope has confirmed the presence of weld slag embedded in the base metal at the toe of fillet welds. This embedded weld slag or slag intrusions appear to exist in all welding processes. These intrusions were observed in both gas metal arc and shielded metal arc welds, although the frequency of occurrence appear to be much higher in the shielded metal arc welds.

The embedded slag was seen to take a variety of shapes including very sharp crack-like discontinuities. It is these discontinuities which appear to act like precracks. Because they are located in regions of high stress concentration at the termination of the welded cover plate, they result in low fatigue life.
Fig. E1  Slag Particle at Fatigue Crack - 130X

Fig. E2  Slag Particle at Fatigue Crack - 110X
Fig. E3  Fatigue Crack Starting at Slag Particle - 150X

Fig. E4  Fatigue Crack Starting at Weld Ripple
Fig. E5  Fatigue Crack Starting at Weld Ripple - 500X

Fig. E6  Fatigue Crack Showing Contact Between Welding Slag and Base Metal - 1120X
Fig. E7  Slag Particles Embedded in Base Metal Surface on Section at Weld Toe - 600X

Fig. E8  Embedded Slag at Submerged Arc Weld Toe - 720X
Fig. E9  Large Slag Particle Embedded in Base Metal at Weld Toe - 700X

Fig. E10  Crack-like Discontinuity Filled With Slag - 600X
In November 1973 a large crack was discovered in a fascia girder of the suspended span of the Quinnipiac River Bridge near New Haven, Connecticut. Figure F1 is a photograph showing the bridge profile. The crack was discovered approximately 34 ft. from the left or west end of the suspended span. The suspended span is 165 ft. (58 m) long. The structure is noncomposite and the girders are 9 ft. - 2.75 in. (2.8 m) deep at the crack location.

Figure F2 shows the crack that developed in the girder web. The crack propagated to the mid-depth of the girder and as shown in Fig. F3 had penetrated the bottom flange surface when discovered.

The structure was opened to traffic in 1964. Thus it had experienced approximately nine years of service at the time the crack was discovered.

Two studies were undertaken on this cracked structure. One involved the use of the FHWA Magnetic Crack Definer to ascertain the locations of the crack tips. A detailed study was also made of the causes of crack growth after removing the crack surfaces so that a determination could be made as to how and why the crack had formed. To accomplish this latter task, half of the fracture surface was removed for visual examination. Figure F4 shows a schematic of the materials that were removed at the cracked cross-section. They included a flange piece with a small portion of the web, two web pieces, and the left and right pieces of the longitudinal stiffener adjacent to the crack.
The Quinnipiac River Bridge had an existing crack which was visually apparent as shown in Fig. F2 and F3. The FHWA Magnetic Crack Definer (MCD) as well as dye-penetrent was used to define the ends of the crack in the flanges so that crack arrest holes could be drilled at the crack tips. On the basis of this examination holes were drilled at the apparent crack tips with the center of the hole placed at the estimated crack tip. Subsequent field inspection with visual examination revealed that the crack had extended beyond the hole radius by at least one-half inch. Neither the dye-penetrent nor Magnetic Crack Definer had adequately defined the location of the crack tip. Care must be exercised at the time of discovery of such cracks to insure that the end of the crack is defined if it is desired to drill such arrest holes.

Examination Fracture Surface and Material

The fracture surfaces and material characteristics were evaluated in order to ascertain the reason for crack formation and growth. Figure F5 shows the flange-web fracture surface (flange piece from Fig. F4). Figure F6 is a photograph which shows the web-longitudinal stiffener intersection at which the crack originated. The ends of the longitudinal stiffener at the fracture location are shown in Fig. F7. Examination of the fracture surfaces indicated that the fracture had initiated at the web stiffener intersection. The fracture surfaces indicated that a butt weld in the longitudinal stiffener had been made at this location but had never been completely fused, as is apparent from Fig. F8. Close examination revealed that only a surface pass had been made and the
reinforcement removed by grinding. The surfaces of this portion of the fracture were severely corroded from their exposure to the environmental conditions.

Replicas were made at the web-longitudinal stiffener intersection (see Fig. F9) so that the fracture surface could be examined by transmission electron microscopy. Visual examination at low magnification indicated that fatigue crack growth was very probable in the web. The fracture surface in the web on each side of the longitudinal stiffener indicated that a cleavage or "brittle fracture" had occurred after the crack penetrated the web thickness. As can be seen in Fig. F5 the cleavage fracture extended throughout the depth of the fractured web and penetrated some distance into the flange before it had arrested.

Examination at the web-stiffener intersection confirmed that fatigue crack growth had occurred. Fatigue crack growth striations were observed adjacent to the longitudinal web stiffener break. Figures F10 and F11 show photographs at high magnification (49125X) of replicas of the fracture surface. The fatigue crack striations are apparent. Estimates of the rate of crack propagation were made on the basis of the striation spacing. These indicated that crack growth rates between $7 \times 10^{-7}$ and $2 \times 10^{-6}$ in./cycle ($1.8$ and $5.1 \times 10^{-5}$ mm/cycle) were occurring in the region examined (see Fig. F9).

A detailed examination was also made of the fracture surface near the flange web intersection. Replicas were made and examined under the electron microscope. These revealed that the cleavage fracture extended about 1 in. into the flange (see Fig. F12). The crack appeared to
assume a semielliptical shape as shown schematically in Fig. F13. Subsequent crack growth appeared to be due to cyclic loading. However, no fatigue crack growth striations were detected on the fracture surface of the flange available for study. Other portions of the fracture surface in which fatigue is likely were destroyed by the drilled holes.

Standard ASTM Type A Charpy V-notch (CVN) specimens were fabricated from both the web and flange material. A standard tensile specimen was taken from the web material. The tensile coupon provided a yield strength of 36.8 ksi (252 N/mm²), an ultimate strength of 60.9 ksi (417 N/mm²) with a 43% reduction in area and 32% elongation in an 8 in. (203 mm) gage length.

Fourteen CVN specimens were taken from the flange adjacent to the fracture surface and twenty were taken from the web. The results of these tests are summarized in Fig. F14. Both flange and web satisfied the toughness requirements for Group 2 of the 1974 interim AASHTO Specifications. The average CVN impact value for the web was 20 ft.-lbs. (27 J) at 40° F (4° C). The flange provided an average value of 35 ft.-lbs. (47 J) at 40° F (4° C). In Fig. F14, the LS specimens are cut longitudinal to the rolling axis of the flange but are notched in the plate surface. The LT specimens are also cut longitudinal to the rolling axis of the flange but are notched transverse to the plate surface.

It is apparent from Fig. F14 that the web impact absorption decreased significantly at temperatures near 0° F (-18° C). Using the $K_{IC}$ - CVN correlations suggested in Refs. 17 and 18, $K_{IC}$ values in the range of 25-30 ksi $\sqrt{\text{in.}}$ (850-1000 N/$\sqrt{\text{mm}}$ ) result, for the minimum service temperature.

-F4-
ANALYSIS OF CRACK GROWTH

From examination of the fracture surfaces, it was apparent that crack growth had occurred in the Quinnipiac River Bridge in a number of stages and modes. These are illustrated schematically in Fig. F13.

Stage I corresponded to the initial fabrication condition. Apparently during fabrication a very crude partial penetration weld was placed across the width of the longitudinal stiffener. It is probable that this cracked during transport or erection and constituted the initial crack condition. This would result in a large initial crack, \( a_i \) equal to 4.5 in. (114 mm) long.

Under normal truck traffic, Stage II of crack growth could occur. The electron microscope studies of the fracture surface have shown that fatigue crack growth striations exist. The crack growth rate was evaluated from the striation spacing. Yielding crack growth rates between \( 7 \times 10^{-7} \) and \( 2 \times 10^{-6} \) in./cycle (1.8 and 5.1 \( \times 10^{-5} \) mm/cycle) near the mid-depth of the web in the Stage II zone. The corresponding \( \Delta K \) values would be between 10-20 ksi \( \sqrt{\text{in.}} \) (700-1000 N/mm \( ^2 \)), as defined by Eq. F2.

An estimate of the time required to propagate the crack through the web thickness was made assuming the crack penetrated the web as an edge crack. The stress intensity factor was assumed to be defined by

\[
K = 1.12 \sigma \sqrt{a} \sqrt{\sec \frac{\pi a}{2t}} \tag{F1}
\]

where \( a \) was the initial 4.5 in. (114 mm) long edge crack. The root-mean-square stress range was approximated from the gross vehicle weight
distribution given in Ref. 20 assuming a value $\alpha = 0.7$ for the stress range reduction factor. This results in $S_{\text{Rms}} = 1.95$ ksi (13.4 N/mm$^2$) in the flange versus the design stress range $S_{\text{D}} = 4.35$ ksi (29.9 N/mm$^2$). The stress at the longitudinal stiffener is about 60% of the maximum flange stress. Hence, at the crack $S_{\text{Rms}} = 1.17$ ksi (7.3 N/mm$^2$). The cyclic life was estimated from the crack growth relationship given in Refs. 2 and 19 which showed that

$$\frac{da}{dN} = 2 \times 10^{-10} \Delta K^3$$ \hspace{1cm} (F2)

The life was estimated by integrating the crack growth relationship as the crack penetrated the web

$$N = \frac{10^{10}}{2} \int_{a_1}^{a_f} \frac{da}{\Delta K^3}$$ \hspace{1cm} (F3)

This yielded about 15,000,000 cycles of random cyclic stress. The average daily truck traffic crossing the bridge was estimated to result in about 1,600,000 random stress cycles per year, corresponding to the $S_{\text{Rms}} = 1.17$ ksi (7.3 N/mm$^2$). This corresponds to an ADTT of about 4,300 trucks per day. This rate of loading would result in crack propagation through the web thickness in about ten years. The estimated life is in reasonable agreement with the performance of the bridge. The structure was subjected to cyclic stress from 1964 until discovery in 1973 a nine year interval.

After the fatigue crack penetrated the web a through the thickness crack results and the stress intensity is defined as

$$K = \sigma \sqrt{\pi a}$$ \hspace{1cm} (F4)
Since two continuous fillet welds connected the longitudinal stiffener to the web the stress at the crack would equal the yield point due to residual tensile stresses. This would result in a \( K \) value of about 40 ksi \( \sqrt{\text{in.}} \) (1400 N\( \sqrt{\text{mm}} \)). The fracture toughness \( K_{IC} \) can be estimated from the CVN values given in Fig. F14. At 0° F (-18° C) a value of about 25-30 \( \sqrt{\text{in.}} \) (850-1000 N\( \sqrt{\text{mm}} \)) results. Considering the possible beneficial effect of a slower strain rate still results in a \( K \) value that exceeds the fracture toughness of the girder web. It is visually apparent in Figs. F5 and F6 that a cleavage fracture occurred. Observations of the fracture surface (see Fig. F5), indicated that the crack arrested near the bottom of the flange.

The crack ran out of a high residual tensile stress region in the flange before arresting. Fig. F12 shows an electron micrograph of the lower left-hand corner of the flange (see Fig. F5) and shows a cleavage fracture mode still existing at that level. It is probable that the "brittle fracture" that occurred during Stage III (see Fig. F13) occurred during the period of December 1972 - March 1973, when the material toughness would be decreased by low temperature. After Stage III of crack growth, subsequent cyclic loading during the balance of 1973 would result in fatigue crack propagation and enlargement of the flange crack until its discovery in November 1973.

It should be noted that substantial increases in fracture toughness would not have materially affected the behavior of this girder. The random truck loading would have continued to grow the web crack in a stable manner until a critical crack length was reached.
Fig. F1 Profile of Quinnipiac River Bridge
Fig. F2 Crack in Web of Fascia Girder

Fig. F3 Crack on Bottom of Beam Flange
Fig. F4 Schematic of Girder Showing Sections Removed for Examination at Crack
Fig. F5 Fracture Surface at Flange-Web Junction

Fig. F6 Fracture Surface of Web Near Longitudinal Stiffener
Fig. F7 Ends of Longitudinal Stiffener at Crack

Fig. F8 Fracture Surface of Longitudinal Stiffener Showing Lack of Penetration of Transverse Weld
Fig. F9 Schematic Showing Location Examined by Electron Microscope
Stage I: Fatigue Crack Growth thru Web

Stage II: Brittle Fracture in Web Arrested in Flange

Stage III: Fatigue Crack Growth in Flange

Fig. F13 Schematic of Crack Growth Stages
Fig. F10  Crack Growth Striations Nearest
Longitudinal Stiffener - 49125X

Fig. F11  Crack Growth Striations Nearer
Web Surface - 49125X
Fig. F12 Cleavage in Flange Near Bottom Surface - 4300X
Fig. F14  CVN Results for Web and Flange Adjacent to Crack
APPENDIX G: TEST RESULTS OF WELDED COVER PLATED BEAMS WITH TREATED DETAILS

The results of the tests for each cover plate end detail are summarized in Tables G1 through G3. The test results are from the tension flanges and were subjected to stresses in the basic design factorial. The nominal stress range and minimum stress at the cover plate terminus are listed together with the cycles to first observed crack, the cycles to failure, and the location of failure. A "T" symbol indicates that crack growth originated from the weld toe, "R" indicates crack growth originated at the weld root.

For the as-welded treated details, the number of cycles to the first observed crack is given when available. It was not always possible to observe a crack prior to failure since the beams were cycled 24 hours a day and not continuously observed. The same condition also existed for several beams that were precracked to 75% of the lower confidence limit for as-welded details. In a number of instances, small surface cracks were visible at the weld toe after precycling. After application of the improvement procedure, the beam was subsequently subjected to cyclic loading. In a few cases, it was possible to observe a crack prior to failure of the specimen if failure occurred at a time convenient for observation.

Analysis of Results

The statistical analysis of the effect of the controlled variables was done using analysis of variance procedures. Regression analyses were also used where possible to supply additional information on the quantitative effects of the variables.
The regression analysis model used to relate the number of cycles to failure to the stress range at the crack initiation point had the exponential form utilized in NCHRP Project 12-7. The results indicated that the ground details were not significantly different than the as-welded details at the highest levels of stress range, ground details were observed to provide a significant increase in fatigue life over the as-welded detail. This is visually apparent in the plotted test data shown in Fig. 17.

The studies on beams with peened weld toes indicated that minimum stress was a significant factor when the peening was applied prior to application of minimum stress. Regression curves were developed for the peened and gas tungsten arc remelt test series as there were sufficient data at three levels of stress range for such an analysis. The analyses was undertaken on the PA and PL series for the minimum stress of 10 ksi (69 N/mm²). It was apparent that the exponential model would not account for the effect of minimum stress. The results of the analyses of peened beams are summarized in Figs. G1 and G2. The 95% confidence limits are plotted as hyperbolic limits because of the finite sample size. For large samples the variance at the point of estimation is generally small and a satisfactory approximation of the confidence limits is given by twice the standard error of estimate. The analysis points out the desirability of further experimental studies to provide better estimates of the tolerance limits. This is particularly desirable when deriving design procedures and criteria.
Similar analysis were also carried out on the three gas tungsten arc remelt test series. These results were summarized in Figs. 3 through 5. The analyses demonstrate that the gas tungsten arc remelt provided at least one category of fatigue strength improvement. The lower confidence limits for as-welded cover plated beams approximates the category D design condition. It is readily apparent that the confidence limits provided in this study are at or above the design line.
Fig. G1 Mean and Confidence Limits for PA Series

$log N = 10.889 - 4.176 \log S_r$

$S = 0.121$

95% Confidence Limits

- Minimum Stress = 2 ksi
- Minimum Stress = 10 ksi
log N = 10.322 - 3.422 log $S_r$

$S = 0.100$

- Minimum Stress = 2 ksi
- Minimum Stress = 10 ksi

Fig. G2 Mean and Confidence Limits for TA Series


\[
\log N = 10.602 - 3.77 \log S_r
\]

\[S_r = 0.280\]

- Minimum Stress = 2 ksi
- Minimum Stress = 10 ksi

Fig. G3 Mean and Confidence Limits for TL Series
\[ \log N = 9.946 - 3.25 \log Sr \]
\[ S = 0.137 \]

- Minimum Stress = 2 ksi
- Minimum Stress = 10 ksi

Fig. G4 Mean and Confidence Limits for TV Series
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* Peened under minimum stress
APPENDIX H: EFFECT OF WELDING VARIABLES ON GTA REMELT PENETRATION

In order to determine the effect of shielding gas composition and cathode vertex angle on weld penetration, two series of tests were performed. The first was simply a bead on plate test to determine the effect of cathode vertex angle (CVA) and shielding gas on depth penetration. The second series showed the effect of GTA torch orientation on the location of the maximum penetration relative to the fillet weld toe. All welds were made on A36 plate, sandblasted, vigorously wire brushed and degreased with acetone. GTA welds were made with a Linde HW-18 water cooled torch and Linde 300 amp. DCSP power supply. A high frequency starting unit was used to prevent electrode contamination on starting. A 5/32 in. (3.8 mm), 2% thoriated tungsten electrode, extending 3/16 in. (5 mm) beyond the ceramic insulator was used throughout the tests. The torch was mounted on an electronically controlled traveling head which maintained a constant travel speed of 3 ipm. (1.27 mm/sec.). A schematic diagram of this equipment showing CVA is seen in Fig. D2.

1. Experiment Design

In the bead on plate series, five cathode vertex angles of 30°, 60°, 90°, 120°, 150° were tried while the welding current and cathode to work distance were held constant at 200 amps and 0.060 in. (1.53 mm) respectively. The specimen size was 6 x 7 x .5 in. (153 x 178 x 12.7 mm). Five welds were made on each plate. The end welds were 1.5 inches away from the edge.
of the plate to prevent overheating, and the plate was allowed to cool to room temperature before the next weld was made. The tests were performed using argon as the shielding gas and then repeated using helium as the shielding gas. The specimens were then sectioned, polished and etched with metal. Depth of penetration was measured with a 3X stereo microscope and calipers. An average depth was computed from six depth measurements taken along the length of the plate.

Using the results of the bead on plate test, the vertex angle which gave the greatest penetration for each shielding gas was used in the next series to determine the effect of torch orientation on the location of maximum penetration with respect to the fillet weld toe. This was done by melting a fillet weld toe with the GTA torch held at three different angles from the vertical.

Fillet welds were dressed at 0°, 10°, and 20° to the vertical. The vertical dressing was unsuccessful because the ceramic insulator interfered with the face of the weld before proper arc length was established. These specimens were then sectioned, polished and etched. The orientation which produced the deeper penetration directly below the original fillet weld toe was then evident. The original fillet weld toe was determined as shown in Fig. H1. A line was scribed along the test plate 1 inch (25.4 mm) away from the fillet weld toe before melting. After TIG melting, the plate was sectioned, polished and etched. The
1 inch (25.4 mm) distance was measured back from the scribed line, and the intersection of this line with the top of the plate marked the location of the original weld toe.

2. Results

The results of the bead on plate tests are shown in Fig. H2 and Tables H1 and H2. Photographs of the welds are given in Figs. H3 and H4. In Fig. H2 the depth of penetration and heat input are plotted against cathode vertex angle. With helium shielding gas, the maximum penetration occurred at a CVA of 30° and decreased as the CVA increased. With argon shielding gas, peak penetration occurred at a CVA of 60° and also decreased as CVA increased. Examination of the depth of penetration data for the two shielding gases shows that the maximum penetration with helium is 43% greater than the maximum penetration with argon and that the average penetration of the helium arc is 100% greater than that of the argon arc for the range of CVA's tested. It also should be noted that the variation in penetration with CVA for helium is less than with argon. For example, between a CVA of 30° and 120°, the variation with helium is .015 in. (.38 mm) while for argon it is about .045 in. (1.14 mm). This is important because variation in the CVA, will cause a smaller change in depth of penetration with the helium arc than with the argon arc.

-H3-
Heat input is also plotted against CVA in Fig. H2. For a constant current, shielding gas, travel speed, and electrode to work distance, the heat input might be expected to be constant. This is not the case, however, because the voltage changes with changes in the CVA. This is illustrated in Fig. H5 where the voltage is plotted against CVA. For both gases, the voltage decreased as the CVA increased. Therefore, for the same current and travel speed, heat input decreased as CVA increased. This is one of the reasons for decreased penetration at larger angles.

An explanation for the voltage change has been proposed. If the current density is assumed to be constant for all values of CVA (assuming constant current), the cathode area must therefore be the same. When the CVA is small, the arc must travel further up the electrode to maintain the same area as an electrode with a large included angle. This makes the "effective" arc length of a small angle electrode longer than that of a large angle electrode even though both have identical cathodes to work distance.

Figure H4 shows the change in width of the weld bead with CVA for each shielding gas. Note that the bead width for the argon arc is greater than the helium arc over the whole range of cathode angles.

The effect of GTA torch orientation on penetration at the fillet weld toe is shown in Figs. H6 and H7. When a fatigue crack develops at the weld toe, it usually grows perpendicular to the
flange or at an angle of 5° or 10° from perpendicular in the direction of the weld root. For maximum effectiveness, it is necessary to place the maximum penetration of the TIG melted zone directly over the work. In Figs. H6 and H7 the intersection of the vertical scribed line with the plate surface represents the fillet weld toe. In Fig. H6 the top specimen shows the results of argon shielding gas and 10° torch orientation. Maximum penetration occurs beyond the weld toe. In this case even if the crack was shallow enough to be repaired with the argon arc, there is a good chance of not completely melting it because the melted zone is in the wrong place. The lower specimen in Fig. H6 shows a torch orientation of 20°. It is apparent that the melted zone is effectively placed with respect to the crack. Fig. H7 shows the effect of torch orientation with helium shielding gas. Both the 10° and 20° torch orientation effectively place the remelted zone over the expected crack. This is the result of the more directional and forceful helium arc. The argon arc is not as forceful and tends to spread excessively near the surface. Therefore, when argon is used, more care is required in positioning the torch than when helium is used.

3. Conclusions

The conclusions to be drawn from this study are that both the choice of shielding gas, and the cathode vertex angle significantly affect penetration. The helium shielded arc is seen to be
producing 40% deeper penetration than the argon arc, and that penetration from the helium arc is less sensitive to changes in CVA than the argon arc. It is recommended that in order to obtain maximum weld penetration, helium shielding gas should be used, and that the electrode be ground to a conical point with an included angle of 30° to 60°.
Fig. H1 Method of Locating Original Weld Toe After TIG Remelting
Fig. H2 Effect of CVA on Depth of Penetration and Heat Input for Argon and Helium Shielding Gas
Fig. H5 Effect of CVA on Arc Voltage
Fig. H3 Cross-Sections of Bead on Plate Tests for Argon (top) and Helium (bottom) Shielding Gas Showing Weld Penetration for Different Cathode Vertex Angles
Argon Shielding

Helium Shielding

Fig. H4  Bead Width Variation with Cathode Vertex Angle for Argon (top) and Helium (bottom) Shielding Gas
Fig. H6  Effect of Torch Orientation on Remelt Penetration for Argon Shielding Gas
Fig. H7 Effect of Torch Orientation on Remelt Penetration for Helium Shielding Gas
### TABLE H1: RESULTS OF PENETRATION TEST FOR ARGON SHIELDING GAS

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<td>Current (amps)</td>
<td>Voltage (volts)</td>
<td>Heat Input (kilojoules/in.)</td>
<td>Penetration (in.)</td>
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