01 Jan 2002

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Recommended Citation

G. Chen et al., "Forensic Investigation of Failed Mast Arms of Traffic Signal Supported Structures," *Transportation Research Record*, vol. 1814, pp. 9-16, National Academy Press, Jan 2002.
The definitive version is available at https://doi.org/10.3141/1814-02

Forensic Investigation of Failed Mast Arms of Traffic Signal Supported Structures

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In Missouri, 11 traffic signal mast arms fractured at the arm-post weld connection in 7 years. To reduce this fatigue failure, the Missouri Department of Transportation developed a fatigue-resistant weld profile that increases the weld leg and reduces the slope of the weld at the toe. This study investigated causes of the failed arms, compared performance of new and old weld profiles, and suggested retrofitting measures for further investigation. The scope included a metallurgical investigation of one failed field mast arm, laboratory fatigue testing of five prototype mast arms (two new and three old profiles), and laboratory failure analysis of one arm tested to cracking. Metallographic and fractographic analyses indicated that the fatigue crack in the failed mast arm initiates near the weld toe of the arm due to undercutting, creating a sharp local toe angle. Location of undercutting at the heat-affected zone of the base material, where the material is softest, further contributed to early fatigue failure. Tests showed that the new weld profile does not consistently increase fatigue strength. Premature fracture surfaces of one tested arm indicated that the fatigue cracks initiate in an area at the weld toe as observed in the failed mast arm. Therefore, changing the weld profile alone is unlikely to increase mast arm fatigue life. Pinning the weldment surface at the weld toe of mast arms is suggested to increase the life of mast arms.

Several states, including Missouri, Wyoming, California, Texas, Illinois, and New York, experienced fracture failures of signal mast arms in recent years. In Missouri alone, there were 11 incidents since 1995 that concerned the Missouri Department of Transportation (MoDOT). The latest incident occurred on an urban highway in October 2000. Although these failures constitute a small percentage of the total inventory of more than 6,000 mast arms, their occurrence on urban and suburban highways posed a real threat to public safety. Due to the failure of the mast arms, MoDOT recently developed a new weld profile that calls for an increased weld leg and decreased profile slope near the weld toe. The main objectives of the research program were to investigate the causes of the failed arms, to compare the performance of mast arms supplied by three manufacturers (called "J-Company," "U-Company," and "V-Company"), and to verify whether the new weld profile indeed enhances the performance of mast arms against fatigue failures. Three of the research tasks of the program included the failure analysis of a failed mast arm, laboratory tests of five prototype arms manufactured by the three vendors, and failure analysis of a test-to-cracking arm in the laboratory.

Multiple cantilevered signal mast arms have failed in the St. Louis region (R. E., Bennett Interoffice Memo, Missouri Department of Transportation, May 27, 1997) Of the 10 failures before 1998, 60% were manufactured by J-Company. Excluding the two mast arms that have lasted longer than 20 years, the proportion of failed mast arms manufactured by J-Company increases to 75%. The remaining mast arms were produced by U-Company and V-Company. In each of the failures (except for a failure of a signal supported structure with two arms), cracking initiated near a weld that connects the mast arm to the base plate. The mode of cracking was reported to be fatigue.

Using ultrasonic inspection, an additional 35 arms were found to contain a flaw near the mast arm–base plate connection. However, no details about the technique used were provided, and no inspection criteria were provided. In fact, no detection thresholds exist for this weld configuration. An independent testing laboratory—St. Louis Testing, St. Louis, Missouri—examined the weld of a new replacement signal mast arm section from J-Company. This weldment was examined by ultrasonic testing and by a metallographic section through the weld (L. Hillner, Interoffice Memo, Missouri Department of Transportation, May 13, 1997). The laboratory also cited the existence of an ultrasonic indication. However, it could not interpret the results because of the lack of inspection criteria. The metallographic section showed nonfusion and poor penetration of the weld metal.

On the basis of these findings, a series of design recommendations was made (P. Porter, Interoffice Memo, Missouri Department of Transportation, July 8, 1996) to the Signal Mast Arm Standard Drawing (Missouri Highway and Transportation Department 902.40). These recommendations included

- A decrease in the permissible stresses from 140% to 133% of the allowable stresses (dead load + wind load or dead load + ice load + 0.5 wind load);
- An increase in the minimum wind design speed from 129 to 145 km/h (80 to 90 mph);
- Use of American Welding Society D1.1-96 Structural Welding Code;
- Magnetic particle inspection of the weldments; and
- Use of a more fatigue-resistant weld profile.

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PROBLEM AREA

In the state of Missouri, traffic sign and signal supported structures are typically constructed with cold-formed steel. They are cantilevered structures consisting of a vertical post and a horizontal mast arm. The post is typically octagonal in shape, and a solid steel plate is welded on the side of the post for connection with the horizontal arm, as shown in Figure 1. The mast arm comes with either circular or octagonal shapes. It is attached to a base plate with two fillet weldments around its circumference. The first weld is on the outside and would be visible when the mast arm assembly is in service, as pointed out in Figure 1. The second weld is at the end of the arm and on the inside of the hole on the base plate that was cut to mate the octagonal shape of the arm. A schematic diagram showing a cross-sectional view of the mast arm assembly and the locations of the two weldments is presented in Figure 2 (shown in 90° rotation counterclockwise from Figure 1). Note that the end of the arm is not flush with the surface of the base plate. The post and arm are individually prefabricated in the factory and are assembled in the field with four bolts, as observed in Figure 1.

The cracks on almost all the failed mast arms are located at the connection of the arm to the base plate. They were observed to initiate on top of the arms and are primarily associated with the bending effect of the mast arms in the vertical plane.

METALLURGICAL ANALYSIS OF IN-SERVICE FAILED ARM

To better understand the causes of failure, the results for one analyzed failed octagonal mast arm are presented in this paper. The arm and the fracture surface were visually examined first. Four sample specimens were prepared, and then both metallographic and fractographic analyses were conducted to determine the reasons for their cracking.

Visual Examinations on Failed Mast Arm

The mast arm examined is octagonal and similar to the one shown in Figure 1. Close-up views of the arm from various angles are shown in Figure 3. The appearance of the weld bead indicated that welding was discontinuous, with each flat of the mast arm tube welded individually. There was some attempt to tie in the welds on the other flats.

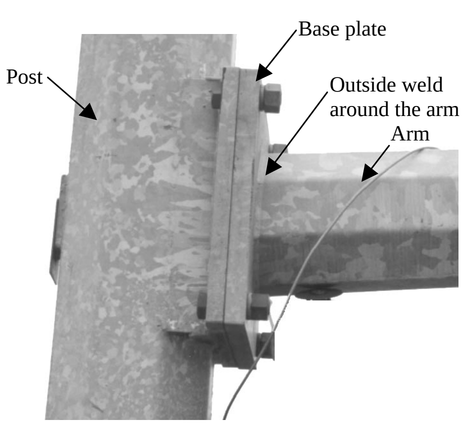


FIGURE 1 Arm-to-post connection.

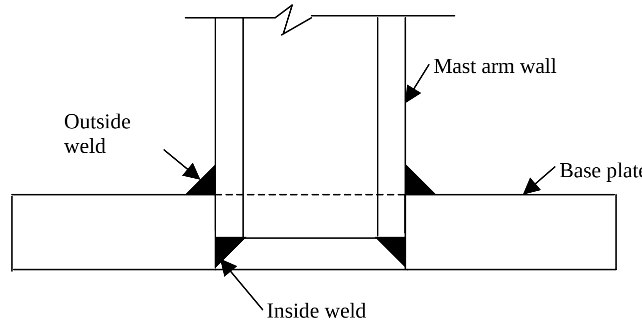


FIGURE 2 Cross-sectional view of a mast arm and base plate.

The progression of the weld solidification pattern indicated that welding was performed in a single direction. The weld on each flat ended at the corner of the flats. No evidence appeared of "buttering back" to prevent crater cracks. At the toe of the weld, undercutting was evidenced on both the signal mast arm and the base plate, as seen in Figure 3. It appeared to be more severe on the side of the mast arm. The shape of the weld bead was convex in relation to the fillet.

A cursory visual examination of a signal mast arm failure was also performed. The fracture showed lack of fusion in several places and had the characteristic blue temper colors showing exposure to heat. Several locations on the fracture had a morphology that suggested fatigue had initiated at multiple locations on the outer surface at the toe of the weld. Initiation and propagation of cracking were through the base metal. No beachmarks were observed, although this is not unusual in weldments.

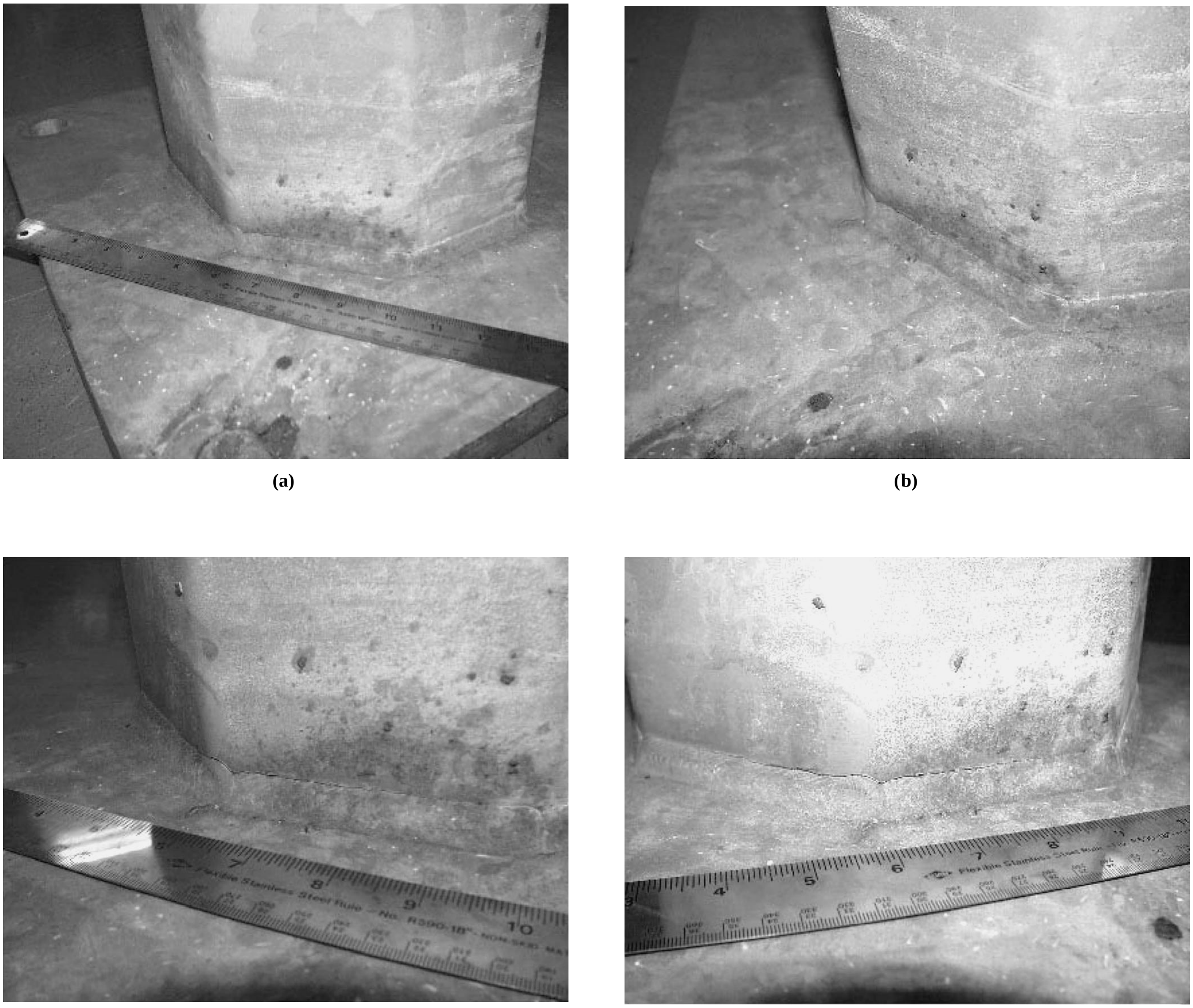
Failure Analysis

Procedure

Fractographic analysis was carried out first for the determination of crack initiation sites. It was followed by the metallographic evaluation of the weld metal, base plate materials, and features of the weldment such as the heat zone, fusion line, grain-refined region, and degree of penetration of the weldment. To observe a fracture surface, the surface was opened on the mast arm in two steps. The first step was to oxyacetylene cut a relatively large piece from approximately 50 mm (1.97 in.) ahead of the cracked portion of the weldment. The second step was to cut the "flame cut" piece in an abrasive saw to remove specimens small enough to be used in metallographic analysis. In addition, the metallographic specimens were sufficiently removed from the heat-affected zone from the flame cutting operation to reveal the as-received microstructure.

Metallographic Examination of Failed Arm

Four specimens were taken from locations in the mast arm assembly. Specifically, in reference to Figure 2, two specimens were cut from the outside weld in cracked and uncracked regions, which are respectively designated "CT" and "ET." The other two specimens were cut from the inside weld in cracked and uncracked regions, respectively denoted as "BC" and "BE." The resulting sections are shown in Figure 4. The sections were prepared metallographically using standard practice and were then etched using 2% Nital (2 ml HNO_3, 98 ml CH_3OH) to reveal the microstructure.



(a) (b) (c) (d)

FIGURE 3 Views of the typical outside weld on the luminary stanchion: (*a*) overall view of the stanchion, (*b*) and (*c*) views showing extent of undercut on multiple faces, (*d*) cracking evident at the undercut of the weld.

Examination of these sections showed a lack of fusion in all metallographic sections. There was no evidence of any weld preparation. On the inside weld (Specimen BE), the weld beads at three locations presented in Figure 5 show a typical microstructure of acicular ferrite. The zone-in picture at location A_1 gave a more detailed view of the microstructure. The heat-affected zone showed evidence of banded spherodized pearlite. The base material was also banded and exhibited distinct regions of very fine pearlite. This structure is not unusual for A36 steel that has been cold formed. The radius at the toe of the weld is sharp. A sharp undercut of the weld is also evident. The undercut is approximately 50 to 100 μm (1.97×10^{-3} to 3.94×10^{-3} in.) deep and 200 μm (7.87×10^{-3} in.) wide. This is a very sharp notch and occurs where the base material is the softest and least resistant to fatigue.

On the outside weld (Specimen ET), the weld beads at three locations, shown in Figure 6, presented evidence of undercutting at the site of crack initiation of the fracture surface. The close-up view at location C_1 confirmed the cracking. The small size of the shear lip indicates that the stress levels were small in comparison with the overall section size. At the region of the root of the fillet, evidence of porosity, and cracks linking regions of porosity, were observed. This probably occurred by overload, possibly during the final failure. This is indicated by the direction of cracking, perpendicular to the fracture. However, this also could have occurred because of residual stresses in the weld.

At the fillet of the weld opposite the primary fracture, a small secondary crack approximately 125 μm (4.92×10^{-3} in.) long was observed, propagating parallel to the primary fracture. This crack was observed to be propagating from a region of undercut, at the toe of the weld. The radius of the weld bead to the base material was also sharp. This indicates a substantial stress concentration. The straight nature of the crack is indicative of a fatigue crack. The presence of a small

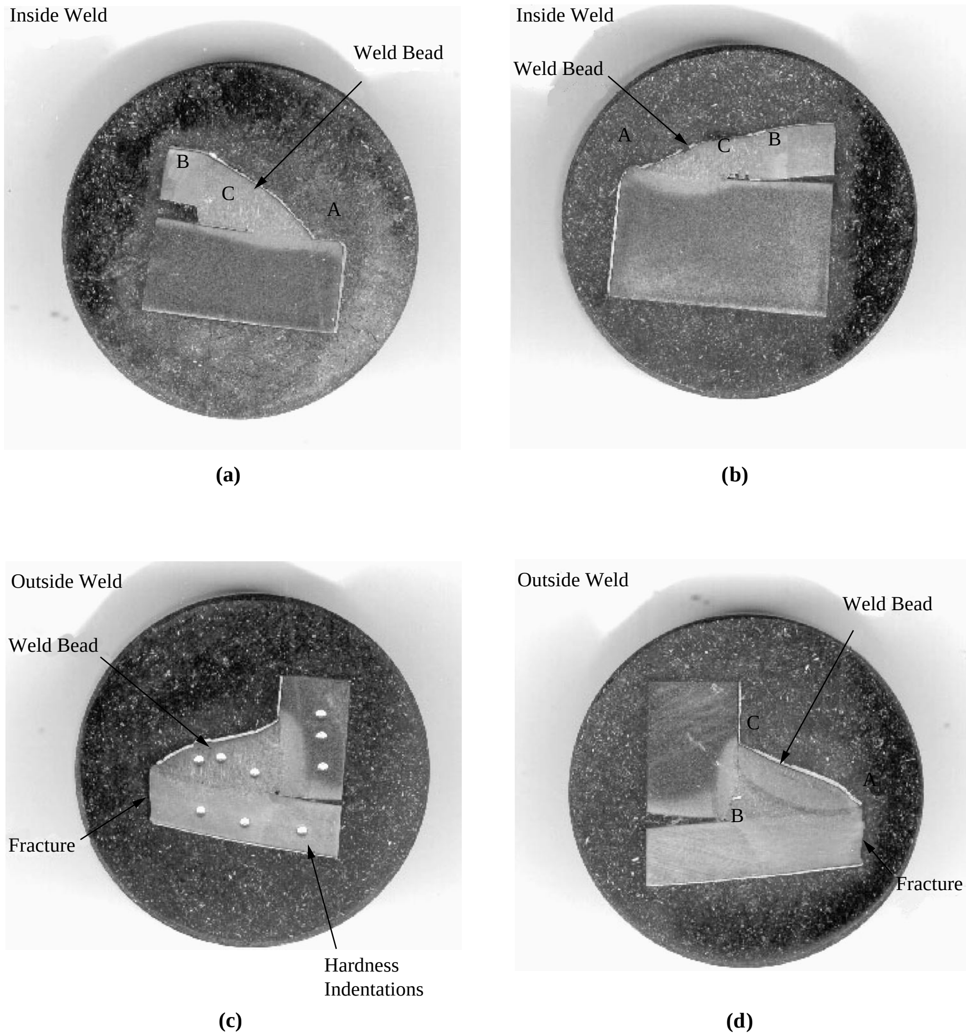


FIGURE 4 Metallographic specimens examined: (*a*) Specimen BC, (*b*) Specimen BE, (*c*) Specimen CT, and (*d*) Specimen ET.

fatigue crack at the toe of the weld at the base plate, parallel to the primary fracture, shows that failure was not limited to crack initiation at the weld toe on the side of the signal mast arm.

Discussion of Results

It is clear that the weld quality is poor, with a lack of fusion and lack of penetration. This can be improved by proper joint preparation and preheating the weld. Better penetration of the weld could be achieved by creating a small, 45° bevel at the edge of the base plate where the mast arm meets the base plate. This bevel could readily be achieved by grinding immediately before welding. This would improve the amount of weld fusion and penetration. It would also provide a concave weld-bead shape that is more conducive to fatigue service. This would reduce the sharp radius produced by the convex weld shape, decreasing the high stress concentration.

However, failure of the mast arm did not result from poor penetration or lack of fusion. Failure occurred in the base metal. Even these poor welds were adequate to hold the base plate and the mast arm together. Failure initiated at a region of undercutting at the toe of the weld. This was aggravated by the undercutting in the region of the heat-affected zone, where the base metal is softest and least able to resist fatigue. The presence of undercutting and the resultant large stress concentration factor are likely the source of premature fatigue-crack initiation. Several factors—including excessive current, too long an arc, too large an electrode, and the incorrect electrode angle—cause undercutting at the toe of a weld bead. It is symptomatic of poor welding procedures or inexperienced welding operators. Pinning is suggested to reduce the undercutting effect.

FATIGUE TESTING OF LABORATORY SPECIMENS

To determine the fatigue strength of a typical weld connection as shown in Figure 1, five prototype mast arms were tested in the laboratory. They include products from three manufactures and two arms with a new fatigue-resistant weld, as sketched in Figure 7. Clearly, the new weld profile extends the weld leg and reduces the slope at the toe of the weld. Numerical simulations in Chen et al. (*1*) demonstrated that the new weld profile may extend the crack propagation life because of the longer leg of the weld. The question of whether

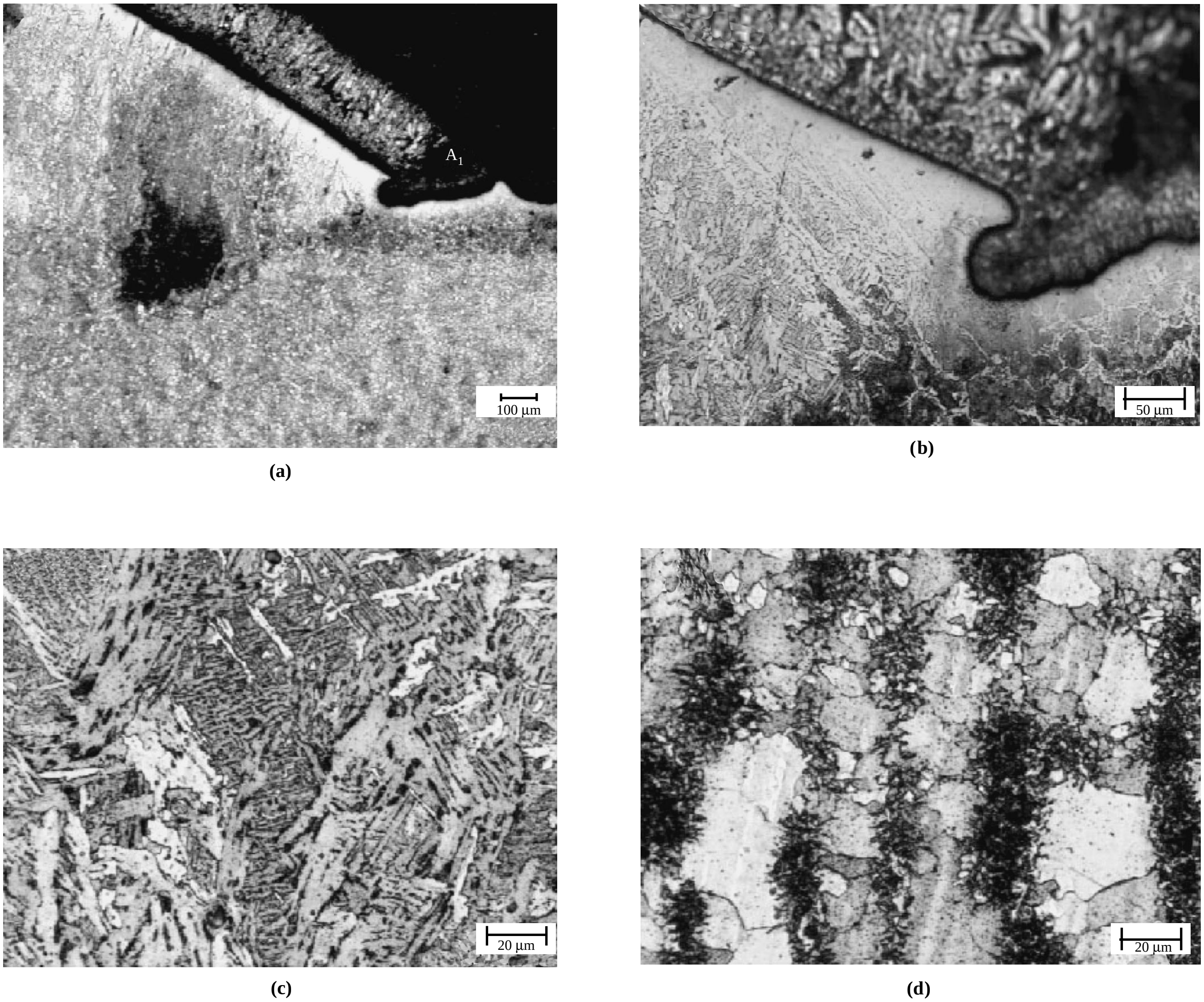


FIGURE 5 Selected photomicrographs from Specimen BE: (*a*) Location A, (*b*) Location A_1, (*c*) Location B, and (*d*) Location C.

the new weld profile is able to delay the initiation of cracking remains to be addressed.

Test Setup and Plan

Each mast arm was set up as a cantilever beam. A single load was applied at 2.032 m (6.67 ft) from the fixed end of the beam. The fixed end represents the location of the arm-to-plate weld joint, as pointed out in Figure 1. A hydraulic actuator was used to provide a superimposed dead and cyclic load that corresponds to the stress range from 68.95 MPa to 124.1 MPa (10 to 18 ksi) at the top of the arm and 100 mm (3.94 in.) from the weld. The average stress of 96.53 MPa (14 ksi) was determined to be representative of the dead-load stress experienced by mast arms in service, as observed from the field-instrumented Stadium & Forum arm and the Providence & Green Meadows arm (*1, 2*). The stress range of 55.16 MPa (8 ksi) represents the wind- or truck-induced load for the evaluation of fatigue strength. This number was chosen by using the design curve for a Category E connection detail (*3*). Considering the mean value of test data, it was determined that a 55.16-MPa (8-ksi) stress range would cause a detectable crack at 1.6 million cycles. This number of cycles was practical. It would not require months of testing for each specimen, yet would not be of such short duration that comparisons could not be made. The sinusoidal loading was applied at the rate of 2 Hz for all tests. This frequency was low enough so that heat buildup at the weld would be negligible but sufficiently high to apply 1.6 million cycles in approximately 10 days, including downtime to check for cracks.

All tests were conducted with a Machine Testing Systems (MTS) closed-loop system under a load-control condition. A load cell was used to measure the force applied on the actuator and a linear variable differential transformer was used to measure the movement of the actuator or the deflection of the cantilevered arm at the load point. Strain gauges were placed in the longitudinal orientation of each specimen 100 mm (3.94 in.) from the weld, as they were on the field-instrumented mast arms (*1, 2*). For most of the tests, they were placed only on the top and bottom faces of the specimen. The load was set so that the top strain gauge was measuring the desired stress range,

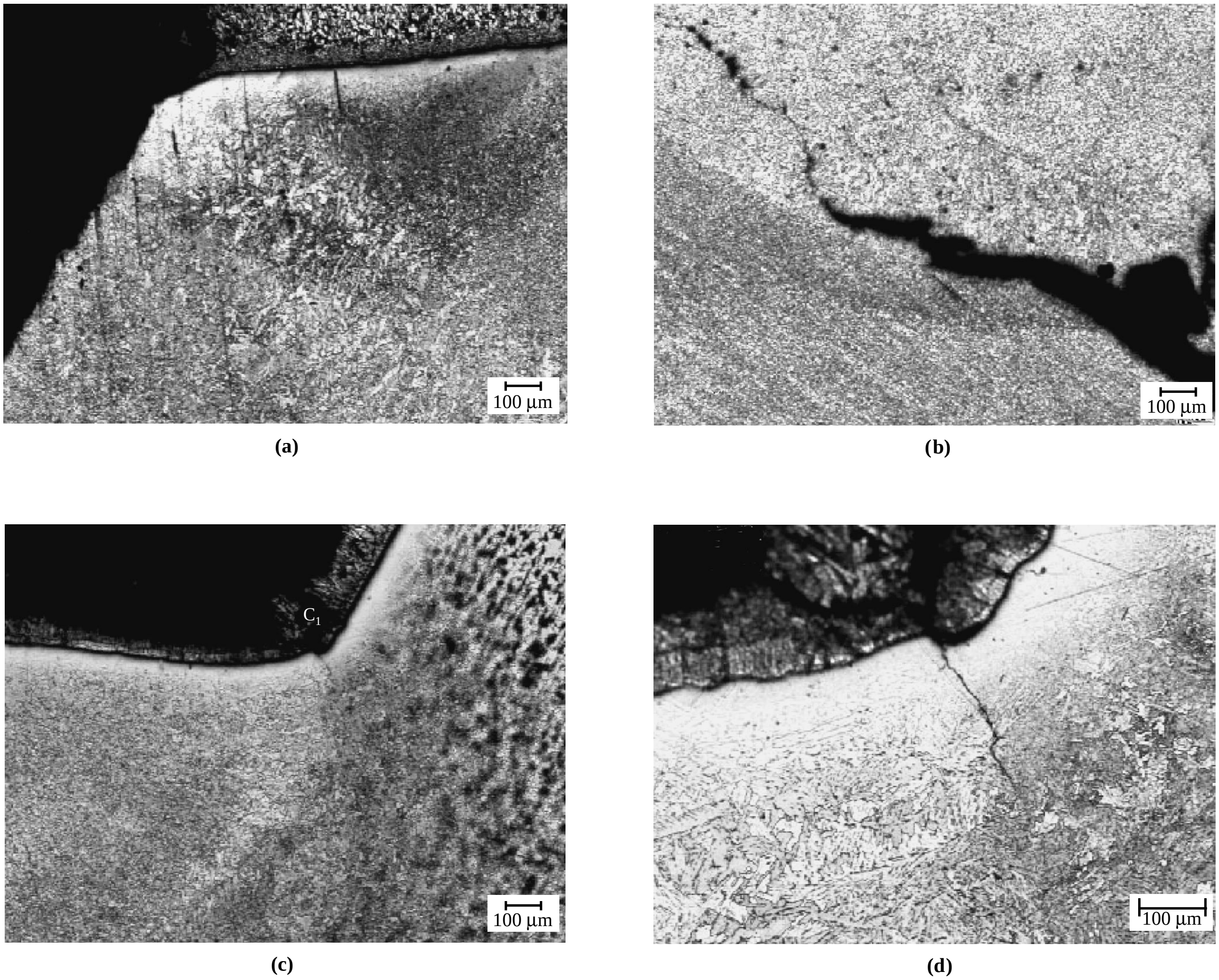


FIGURE 6 Selected photomicrographs from Specimen ET: (*a*) Location A, (*b*) Location B, (*c*) Location C, and (*d*) Location C_1.

68.95 to 124.1 MPa (10 to 18 ksi). Every 4 to 6 h, data were collected to ensure the stresses were within an acceptable range of the desired values. If the stresses were greater than $\frac{1}{10}$ of 6.90 MPa (1 ksi) from the desired values, the loading was adjusted on the MTS machine.

Magnetic particle testing was used to detect cracks. Such a test was performed every 200,000 cycles or if it was believed a crack had formed. Crack initiation was verified with the sudden change of the applied load. The formation of a crack on the top face of the specimen released the local stress at the top. To maintain the desired stress, the applied load must be increased in a short time. Although slight modifications of the load were necessary during the testing period, an obvious trend of increased loading indicated the initialization of a crack.

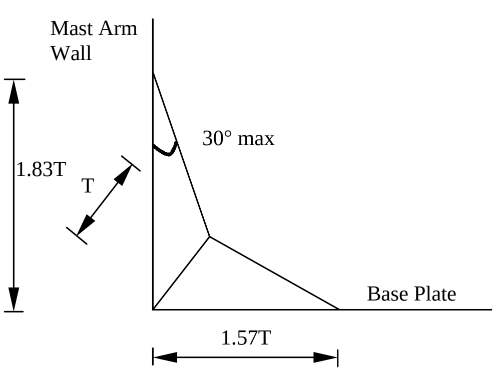


FIGURE 7 Fatigue-resistant weld profile.

Test Results

A summary of the fatigue test results of the five specimens is presented in Table 1. The first two mast arms performed satisfactorily for Category E details, and of the two, the new weld profile did perform better than the old weld profile. However, the third arm, also with the new weld design, experienced premature cracking. The results of the three V-Company arms indicate that the new weld design does not consistently improve the fatigue performance of mast arms. The last two arms also were well below the mean fatigue curve. They had questionable weld qualities based purely on visual inspection, which may have been the cause of the premature failures. All the failures occurred at the top of the arm at the toe of the transverse fillet

TABLE 1 Summary of Fatigue Test Results

Arm	Manufacturer	Weld Profile	Cross Section	No. of Cycle at Failure	Comments
254682	"V-Company"	Old	Circular	1.8 million	None
BB34970	"V-Company"	New	Circular	2.1 million	None
CB12917	"V-Company"	New	Circular	0.4 million	Possible lack of fusion of weld
88791	"U-Company"	Old	Octagonal	0.5 million	Flaw detected by magnetic particle testing prior to loading
9539 CL54	"J-Company"	Old	Octagonal	0.0 million	Flaw detected by naked eye prior to loading

weld. The U-Company arm was the only one that did not crack through the thickness of the tube. This arm had the thickest section. Even though the crack had not propagated through the thickness, there was an obvious decrease in stiffness at the top of the tube and a visual crack. Therefore, it was definitely failed by the criteria of these tests. The J-Company mast arm was certainly flawed before fatigue testing. This arm was the only one that was recalled from the field. The cause of this flaw is unknown, but it was consistent in appearance with the fatigue cracks produced during testing. The cracks also occurred at the corners of the octagon, locations of high stress concentration.

The complete description of the five arms and their test results can be found in Alderson (*2*). Only the results for Specimen CB12917 are explained in greater detail below. This circular arm with the new weld design has a section modulus of 3.02×10^5 mm^3 (18.4 $in.^3$). A load of 20.91 kN (4.7 kips) is necessary to produce 96.53 MPa (14 ksi) at the top strain-gauge location, and a load range of ±5.52 kN (1.24 kips) was applied to produce the required stress range. The specimen was magnetic particle tested before fatigue testing, and no flaws were detected. However, it appeared to have a lack of fusion of the weld joint.

Specimen CB12917 failed at 0.4 million cycles. This was 75% earlier than anticipated. Figures 8*a* and 8*b* show the variation in displacement and load range for this arm. These two figures suggest crack initiation between 0.3 million and 0.4 million cycles, which was confirmed by magnetic particle testing at 0.5 million cycles. Figure 8*c* shows the crack on the outside of the arm.

METALLURGICAL ANALYSIS OF LABORATORY TEST FAILED ARM

Specimen CB12917 was analyzed for the cause of its premature failure. It was metallographically examined to determine the morphological features associated with the weldments and the crack initiation site. The same procedure used in preparing the specimens of the in-service failed mast arm was followed to make two specimens from the cracked sections. Both fractographic and metallographic analyses were conducted on the specimens. The fracture surfaces indicate that the fatigue crack in both specimens initiated in an area at the weld toe of the mast arm. Classic features of fatigue fracture are present.

The microstructures of both specimens are typical of low carbon steel. The base material is a low carbon ferrite—pearlite steel. The weld metal consists of large, columnar grains containing acicular ferrite with bainite and is consistent with the previous metallographic analysis of the in-service failed mast arm. The heat-affected zone is

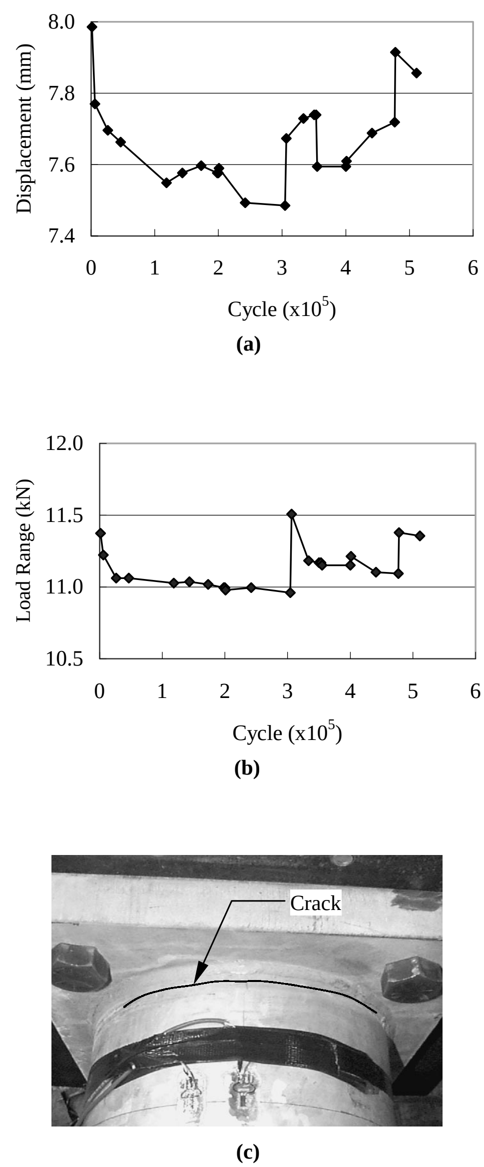


FIGURE 8 Specimen CB12917 test results: (*a*) maximum displacement versus number of cycles, (*b*) applied load versus number of cycles, and (*c*) fatigue crack on outside of the mast arm.

also consistent with the previously reported data. The coarse-grained region adjacent to the fusion line consists of blocky ferrite and bainite with some acicular ferrite. Further removed from the fusion line are the grain-refined zone and finally the base metal.

The toe of the welds appears to have very sharp local toe angles. Although it is not possible to directly measure the toe angle at the fracture initiation site, it is possible to examine the toe of the welds at the opposite side of the site. This examination revealed that the sharp features found in the previous specimens cut from the in-service failed mast arm are nearly exactly reproduced in the two specimens. Both specimens appear to have two-pass weldments. However, the advantages gained by the fatigue-resistant weld are negated due to the sharp features at the toe of the weld. Mast arms manufactured in this manner will continue to have lower-than-expected fatigue life values as long as these sharp features at the toe of the welds are present. Even though the fatigue-resistant welding procedure is used, the sharp features at the toe of the weldments will control the crack initiation or fatigue life.

To eliminate the sharp features of the weld, a thorough investigation of welding parameters must be accomplished. The optimum potential and current must be identified and combined with stringent quality control measures to eliminate these defective features in the weldments. The welds of the mast arm examined appeared to be produced using either the shielded metal arc weld (SMAW) or the gas metal arc weld (GMAW) process. In either case, oxide (rust) must be thoroughly removed from the components before the first weld pass. And any slag (SMAW) or thin oxide layer (GMAW) must be thoroughly removed between passes. In addition, it is very important that the proper welding potential be used (i.e., voltage). In particular, the effect of voltage on weld profile is dramatic. The effect of welding current essentially controls the heat input to the weld and thus the size of the weld.

CONCLUDING REMARKS

Based on the laboratory tests of five mast arms and the failure analyses of an in-service and a laboratory test failed arm, several observations can be made:

- Failure of the signal mast arm was caused by initiated fatigue cracking on the outside weld at the weld toe. Crack initiation was enhanced by the presence of weld undercutting creating a sharp geometrical stress concentration. The location of the undercutting at the heat-affected zone of the base material, where the base material is softest, further contributed to early fatigue failure.
- The welds were of poor quality and exhibited lack of penetration and lack of fusion. However, this lack of penetration and lack of fusion did not contribute directly to the premature failure of the signal mast arms.
- The weldments of the two failed mast arms analyzed have similar sharp features, and their failure mechanisms are thus the same, even though the laboratory test failed arm was designed with the new weld profile. The initiation of crack appears independent of the type of weld profile.
- Laboratory tests indicated that two of the three mast arms manufactured by V-Company performed satisfactorily, whereas both arms manufactured by J-Company and U-Company failed prematurely. Test results also verified that the new weld profile does not necessarily delay the initiation of cracking in mast arms and thus is unlikely to increase the fatigue life of mast arms.
- It is anticipated that the fatigue performance of mast arms can be improved substantially by pinning the weldment surface at the weld toe of the mast arms.

ACKNOWLEDGMENTS

Sincere thanks are due to Vince Imhoff, Tom Allent, and Don Davidson of the Missouri Department of Transportation for their continuing guidance of the research project. The authors also acknowledge the financial and material support from the Missouri Department of Transportation and the U.S. Department of Transportation through the University Transportation Center at University of Missouri-Rolla.

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Publication of this paper sponsored by Committee on General Structures.