11 Appendix A: Support Structure Cracking and Repair Methods

11.1 INTRODUCTION

Cracks occurred in a variety of locations during the testing of the specimens. These cracks provide additional information about welded and bolted details outside the scope of the original project. Many of the cracks started at discontinuities in the support structure, such as the cover plate termination. Other cracks starting due to rubbing, improper bolt tightness, and weld defects. All of these cracking incidences required repair in order to continue testing. These repairs were observed for effectiveness and crack recurrence.

This appendix details a number of cracks, the repairs made and their general effectiveness. When possible, a detailed account of the repair is made through illustrations and photographs. The overall setup may be seen in Figure 11-1. Particularly sensitive details are pointed out for later reference.

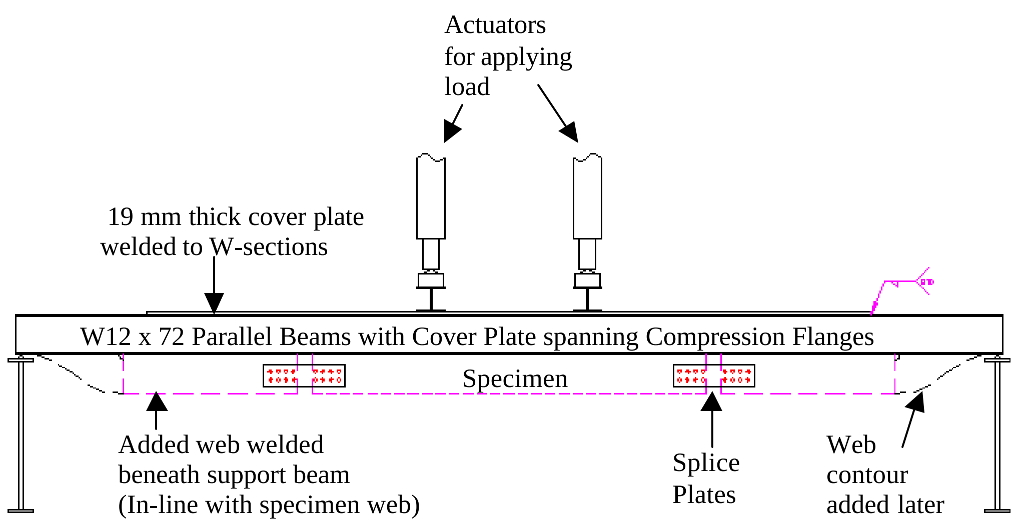

Figure 11-1: Testing setup with problem fatigue areas indicated.

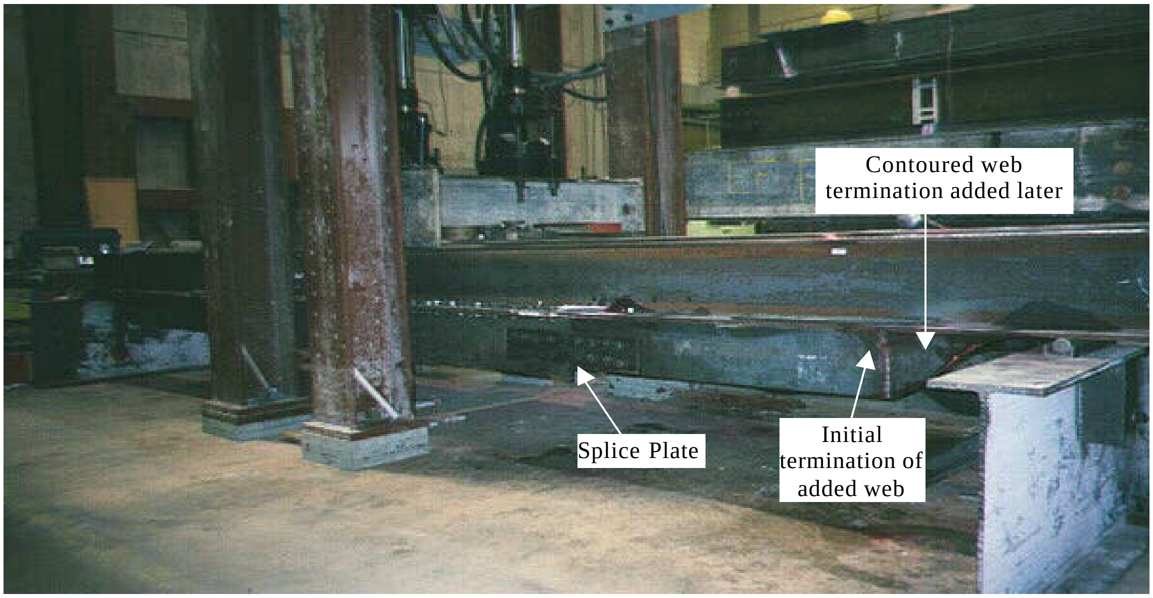

Figure 11-2: Testing setup with structural details clarified.

An actual photo of the experiment is seen in Figure 11-2. The splice plates bridge the gap between the added web and the specimen. The thickness of the added web and each splice plate was 13-mm. Each added web was attached to the W12x72 beams by 8-mm double-sided fillet welds. These welds were made with the flux-core arc welding (FCAW) process and terminated approximately 3-cm from the end of either side of the added web. The web was tack welded at either side prior to making the full longitudinal fillet welds.

Eight A490 bolts, each 22-mm in diameter, were tightened to 75% of the yield strength of the bolt to provide a slip critical connection in the splice plates. The capacity of this bolt setup was considered highly conservative. However, variations in web placement in the specimens created alignment problems with web permanently mounted below the beam support structure. Spacer plates were used to provide smooth, aligned surfaces that the splice plates could be fastened to. The spacer plates, though, reduced the capacity of the connection and slippage was noticed if the bolts were not torqued to at least 80% of the nominal yield strength. An example of the spacer plates is seen in Figure 11-3.

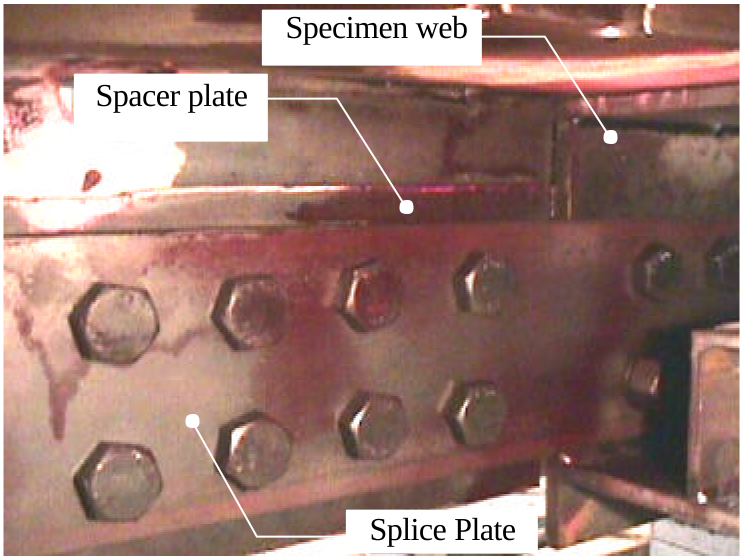

Figure 11-3: Spacer plates used to line up added web and specimen web.

Further detail will be now shown in outlining the cracking incidences.

11.2 FILLET WELD TERMINATION CRACKING

The first incidence of cracking was observed when webs were added below the W12x72 beams in line with the specimen webs. Splice plates connected the webs to each specimen as seen in Figure 11-4. The web and splice plate addition was made to promote force transfer to the composite section of the specimen and the support structure. These modifications, however, initially caused high stresses to be located in fatigue-sensitive areas, such as the added web termination.

Initially there was no smooth contour used to gradually taper the added web. Excluding the taper caused a high stress concentration at the fillet weld terminations. These fillet weld terminations were located 20-cms from the support. It was thought that the net section stress at this point would be below the S-N fatigue limit for fillet weld terminations, a Category E detail in the AISC Steel Design Manual. The stress ranges exceeded the constant amplitude fatigue limit (CAFL), however, and cracking ensued at all four corners. The figure below illustrates the point of cracking.

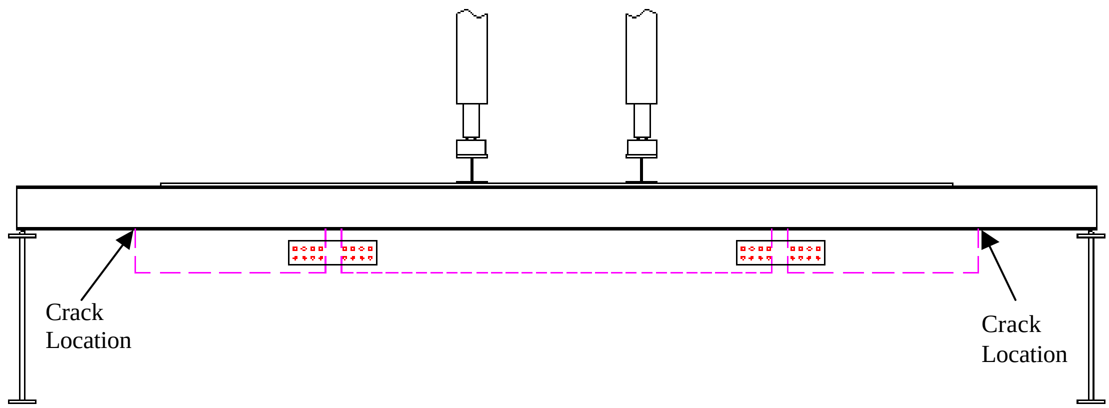

Figure 11-4: Initial testing setup with abrupt web terminations.

A typical crack may be seen in Figure 11-5. These were relatively long, through-thickness cracks that had not yet entered the beam web. Although the cracks were located at all four corners of the structural setup, they were not noticed until a detailed inspection was performed. An appreciation for the difficulties of field inspection may developed from this experience. Tabe 11-1 displays the monitored development of the cracks and corresponding repair procedure.

Table 11-1: Initial cracking in added web fillet weld terminations.

Crack Description	Corner Location/Through -thickness final length (mm)	Estimated Stress Range	Estimated Number of Cycles	Repair Method (More detail follows)
Fillet weld termination	SE: 100 NE:105 SW: 110 NW: 45	39 MPa	$1.2x10^6$	Remove part of added web, drill out crack tips, butt weld crack in flange between drill holes, add contoured web

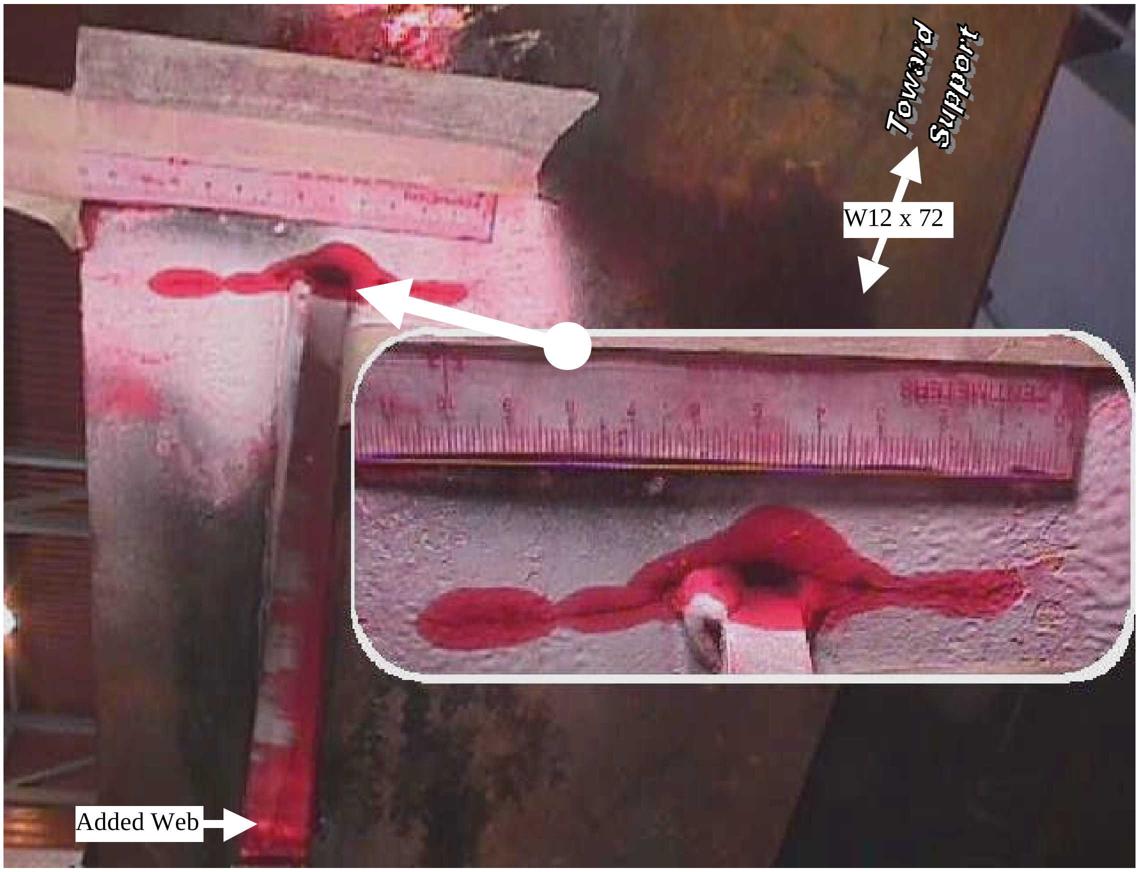

Figure 11-5: Typical crack at fillet weld termination of added web.

The dye in Figure 11-5 is used to help visualize the extent of cracking in the lower flange of the I-beam. Notice the offset of the added web from that of the flange centerline. The eccentricity of the added web was necessary to maintain alignment with the specimen webs.

At this point one might question the design W-sections, but these were painstakingly chosen for their dimensions. A brief aside will be used to justify the design and provide insight into the beam size selection. It is presented here because the consequences of the design are most pronounced in the fatigue problems that are presented in this appendix. The beam size of W12x72 was chosen for several reasons:

- First of all, a greater depth beam would reduce the stresses available in the stiffened panel for testing. Since the composite section (i.e. Support beams and test specimen) has a large section modulus, the overall depth of the structure had to be minimized to reach the desired stress levels in the stiffened plate of the specimen.
- Secondly, the beam flanges had to be wide enough to accomodate the bolt-up assembly of the specimens. Bolting patterns were detailed to provide the easiest assembly possible considering both bolt strength requirements and the feasibility of tightening the bolts to slip-critical specifications.
- Finally, the capacity of the actuators and laboratory was a factor in developing a specimen the optimized the use of transverse width limitations.

The experimental testing could not proceed without repair of the cracks at these loacations. The repair of the cracks will be detailed through the use of photographs and accompanying description.

The first step in rhe repair was to locate the crack tips. This was performed with the red penetrating dye previously discussed in this report. A 19-mm hole was drilled at the crack tips once they were located. A photograph of one crack tip being drilled out may be seen in Figure 11-6.

Figure 11-6: Drilling out the crack tips.

Drilling out the crack tips removes any existance of a sharp notch that might promote further cracking. A typical location with holes drilled at the crack tips may be seen in Figure 11-7. With the crack tips drilled out, a 10-cm portion of the added web was removed to increase accessability to the cracked region. A recipricating saw was used as seen in Figure 11-8.

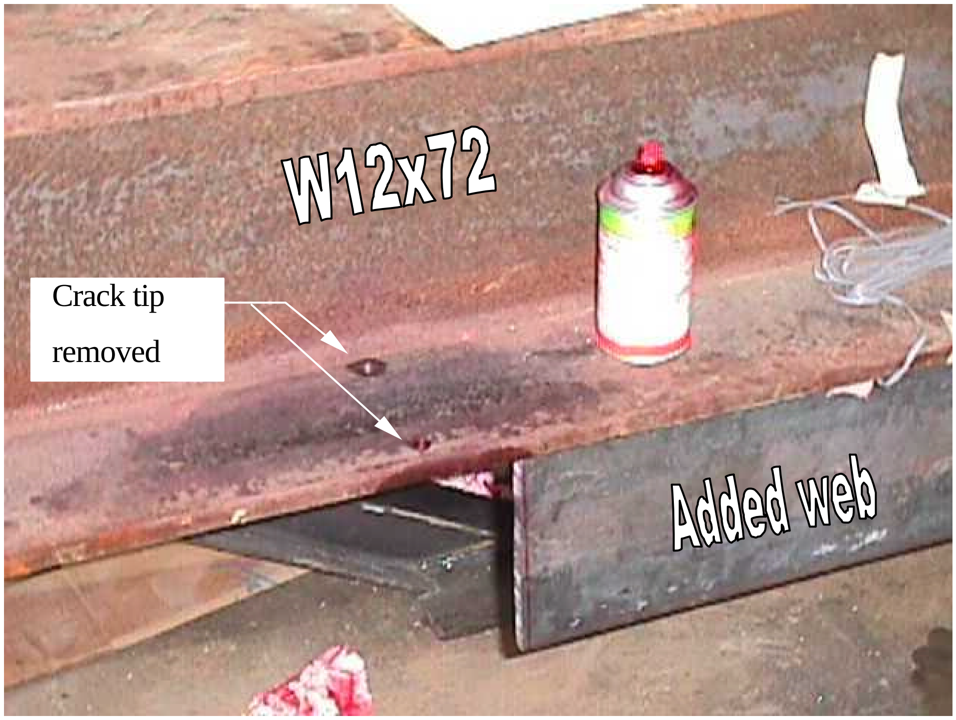

Figure 11-7: Drilled out crack tips in beam flange.

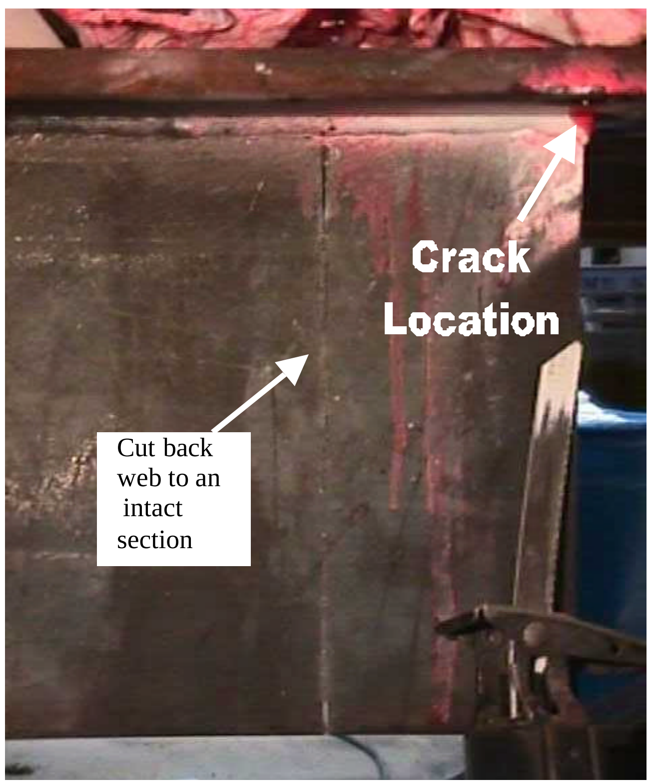

Figure 11-8: Increasing accessibility for weld repair.

Figure 11-9: Resultant weld between drilled-out crack tips.

Increased accessibility to the crack allowed a complete penetration weld to be made between the drilled holes. The end result may be seen in Figure 11-9. Normally one should not weld the drilled holes shut as this creates an area of high constraint once the weld cools. Instead, the weld should be made between the holes and the holes should be enlarged to remove any roughness that might exist at the weld termination.

After repairing the cracks in the beam flanges, an overall improvement to the added web termination was necessary. The abrupt termination of the added web was replaced with a contoured web. The addition of the contoured web termination may be seen in Figure 11-10.

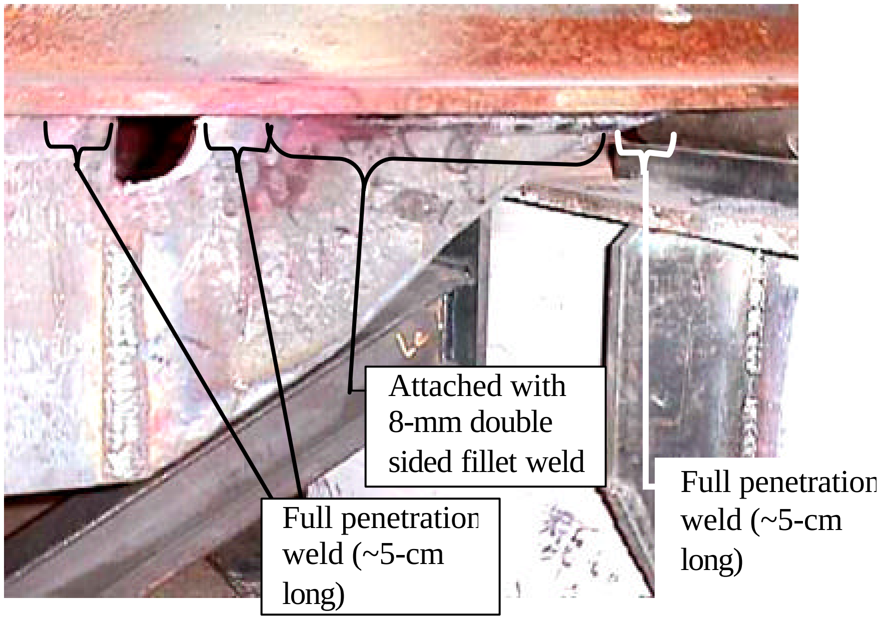

Figure 11-10: Attachment of contoured web to existing web.

It was predicted that adding the contoured web would gradually transfer the force from the web into the support beam. For increased fatigue resistance, the terminations of the added web were made with full penetration welds. The remainder of the contour was attached with 8-mm double sided fillet welds.

The contour web addition was made to all four corners of the support structure. A picture of the resultant repair may be seen in Figure 11-11.

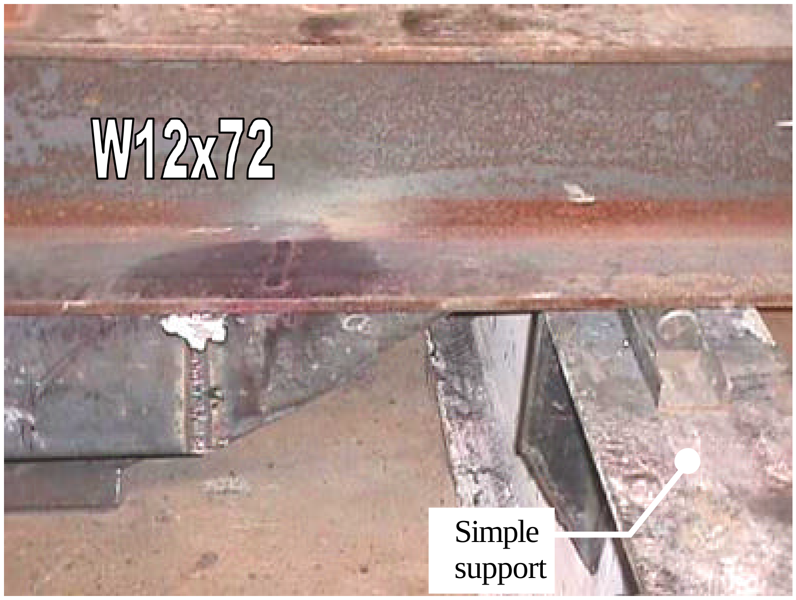

Figure 11-11: Typical repair for web terminations at four corners.

11.3 CRACKING IN FULL PENETRATION WELD AND BASE METAL

Modifying the abrupt termination of the added web was originally predicted to solve the fatigue cracking issue at these locations. It was soon found, however, that the state of stress was high enough even near the support to induce fatigue cracking. Fatigue cracks developed at both the contour web terminations and the weld access holes. All of these locations had been improved with a full-penetrations weld. Several small defects, however, were noticed in the welds. Fatigue cracks initiated at these flaws as well as in the base metal of the added web. These cracks had grown to an average length of 15-mm within $1.5x10^6$ cycles. Parallel cracks were noticed at several corner locations indicating that a large amount of stress existed in the region. The crack tips were immediately drilled out once the crack had progressed into the beam flange. Figure 11-12 and Figure 11-13 show a pair of cracks emanating from the end of the contoured web termination with the crack tips already drilled out.

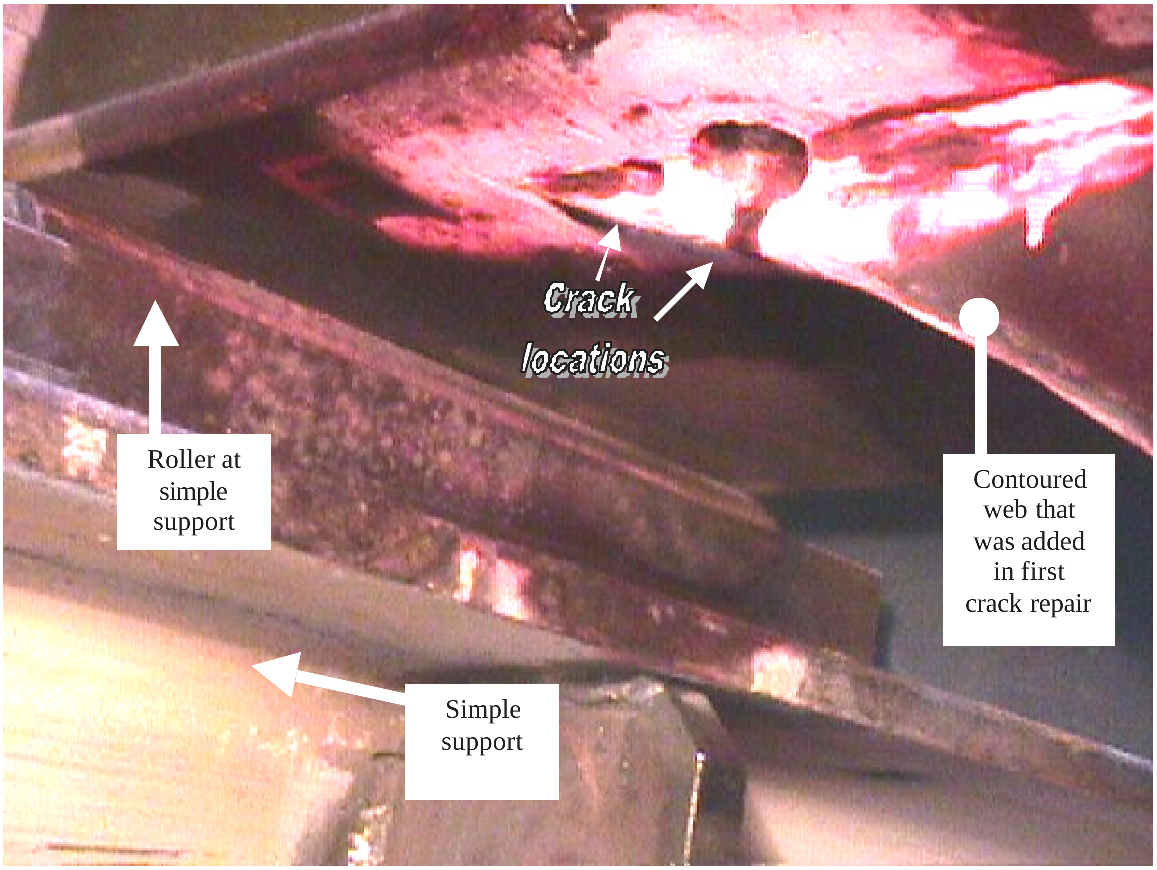

Figure 11-12: Cracking in full penetration weld after contour repair was made.

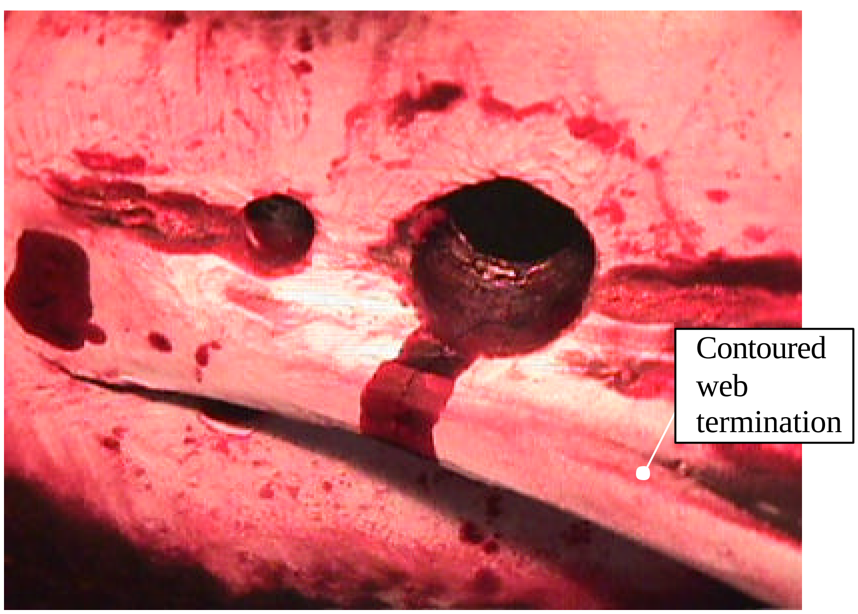

Figure 11-13: Detail of crack occurring in full penetration weld with tips drilled out.

Table 11-2: Cracking in contoured web additions at full penetration weld.

Crack Description	Corner Location/Crack Length (mm)	Estimated Stress Range	Estimated Number of Cycles	Repair Method
Full penetration weld termination	SE: 15 NE:12 SW: 20 NW: 12	55 MPa 55 MPa 55 MPa 55 MPa	$2.5x10^6$ $2.5x10^6$ $2.5x10^6$ $3.0x10^6$	Drill hole at crack tips. Hole diameter ~1/3-1/2 crack length

Table 11-2 presents the crack details and history. The only repair that could feasibly address this problem area was drilling out the crack tips. Hole drilling has been used for years as a crack arrestor. By drilling a hole at the crack tip, two goals are accomplished:

1) The region is made more flexible relieving highly constrained areas.
2) The sharp crack is replaced with a smooth circular profile which readily opens.

New cracks can only develop if a new notch is introduced. With a drilled hole, the surrounding material simply hinges about the hole and new notches cannot be developed. This behavior can be expected provided the hole is large enough. The hole size required to arrest a crack may be determined from the equation:

$$r > \left[\frac{\Delta K}{10.5\sqrt{s_y}}\right]^2 \qquad \text{Eqn. 11-1}$$

where ρ is the required hole diameter in meters, ΔK is the applied stress intensity factor range, and σ_y is the yield stress of the material in MPa. This relation was originally developed by John Fisher to address fatigue cracking in bridge structures. For 350 MPa yield stress, the hole diameter should be approximately 1/3 the total crack length to arrest the crack in a steel structure. Obviously this is not amenable to long cracks, but for instances of distortion-induced cracking such as this one it is exceptionally effective.