11.7 BEAM TENSION FLANGE CRACKING

The initial fabrication of the support structure included angles that connected the bottom flanges of the parallel W-sections. These transverse attachments were fillet welded to the bottom flanges with a 10-cm long fillet weld for stability during transport. The angles were removed in the laboratory once the support structure was set in place. The area of connection was roughly ground smooth at three locations, while the fourth location was left with a flame-cut section of angle remaining.

Late in the testing, a faulty wire gave erratic signals to one of the actuators. When this happened, control devices in the system would abruptly stop the testing, resulting in a slight impact loading to the testing setup. The problem could not be immediately identified, and the impact loading continued sporadically over the course of one million cycles. This impact loading caused fatigue cracks at the locations where the fillet welded attachments previously existed. In fact, at one location over 60 percent of the tension flange of the W12x72 beam had cracked. The crack had penetrated 18-mm up the beam web as well. This crack may be seen in Figure 11-30 and in Figure 11-31.

The procedure for repair was performed exactly as illustrated before. Figure 11-32 shows where the tip of the crack in the beam flange was replaced with a drilled hole. Similarly, Figure 11-33 shows the tip in the beam web drilled out.

Figure 11-30: Crack in beam tension flange due to abrupt stops in loading.

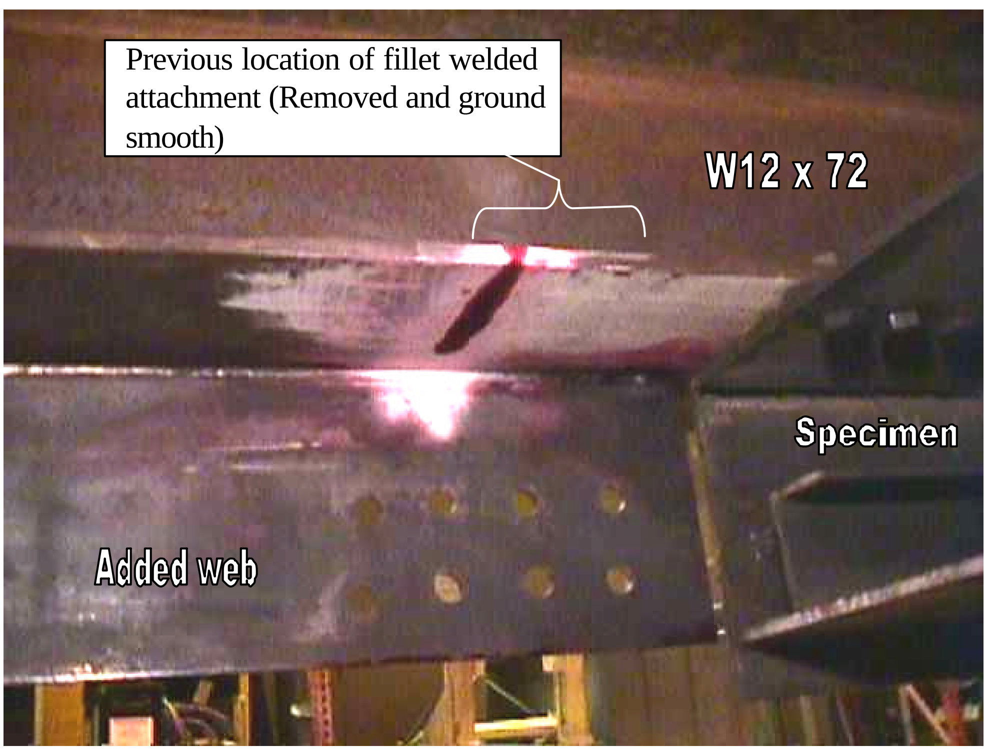


Figure 11-31: Bottom view of cracked beam flange.

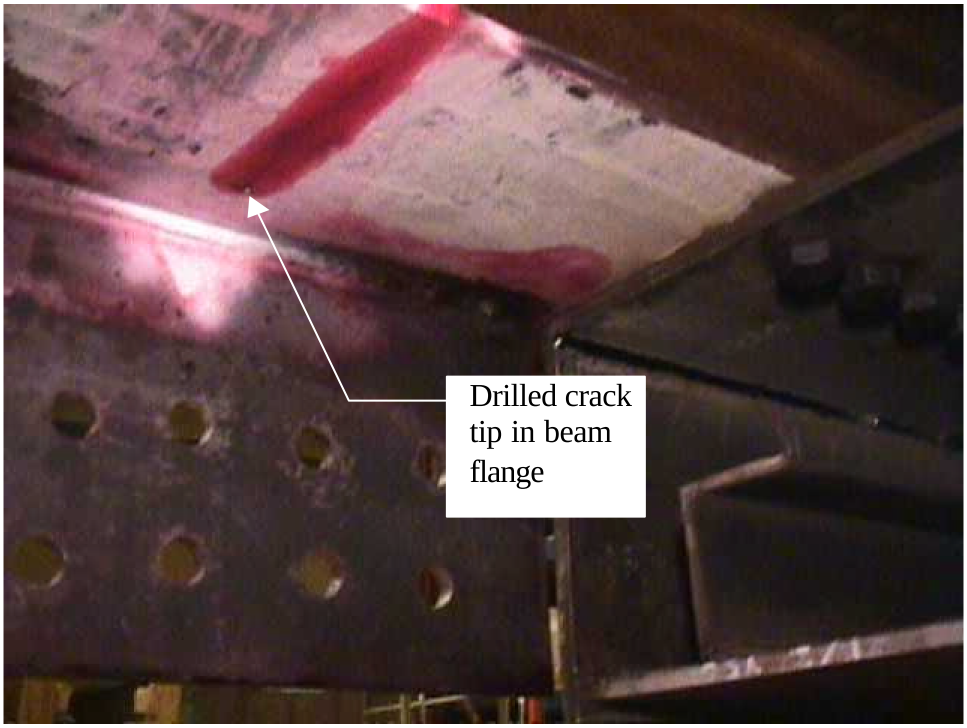


Figure 11-32: Crack tip in tension flange drilled out.

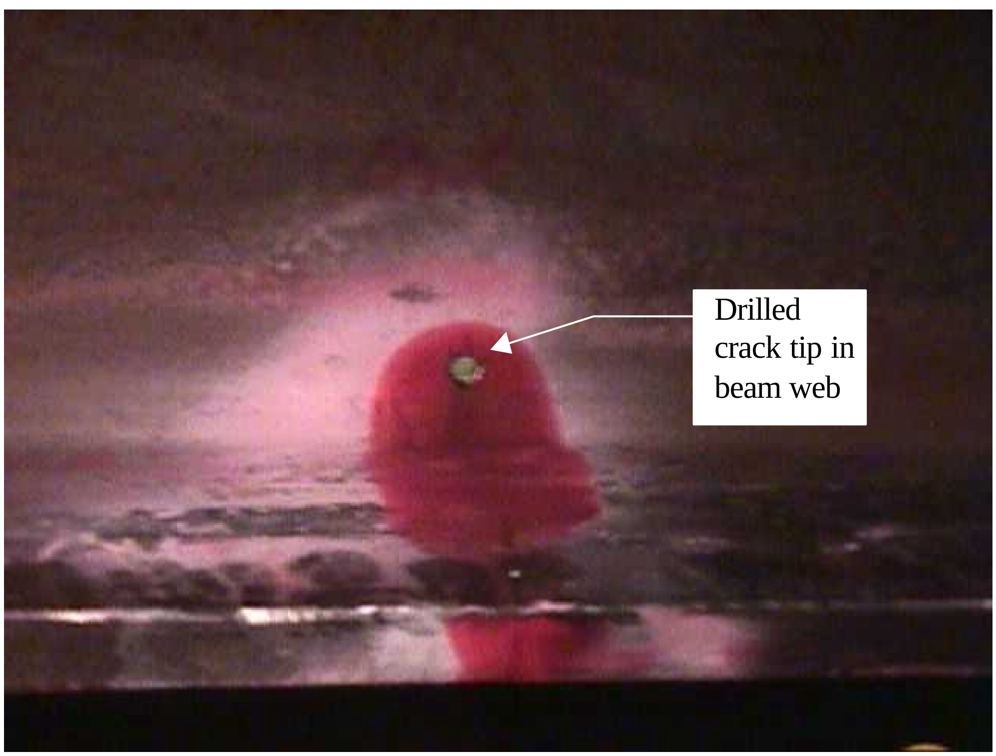


Figure 11-33: Crack tip in beam web drilled out.

To illustrate the importance of making sure the crack tip has been drilled out, Figure 11-34 shows a first attempt at drilling out the crack tip. After drilling the hole, the red dye penetrant is re-used to make sure the crack terminates in the hole that was drilled. On this occasion, the crack tip was missed by the drilled hole and a larger hole became necessary, as seen in Figure 11-35. Note that these holes are not intended to arrest the crack. They are merely placed to remove the crack tip and provide a guide on the extent of the crack faces in welding.

Figure 11-34: Initial hole drilled which missed the crack tip.

Figure 11-35: Enlarged hole captures the crack tip.

Once the crack tips had been drilled out, a one-sided butt weld was made with a backing bar in place (See Figure 11-36). The completed butt weld was then ground smooth to allow for redundant bolted plates to be used. The ground butt weld and bolting pattern may be seen in Figure 11-37. The bolted plates were included as an additional precaution as this location was a critical region of the support structure. Although the bolted plates were designed as a slip-critical assembly, it was projected that slip-critical connection should only be relied upon as a safety measure in the event of full flange cracking. In other words, the slip-critical connection was projected to not be effective in preventing future crack initiation.

Figure 11-36: Completed butt weld with backing bar in place.

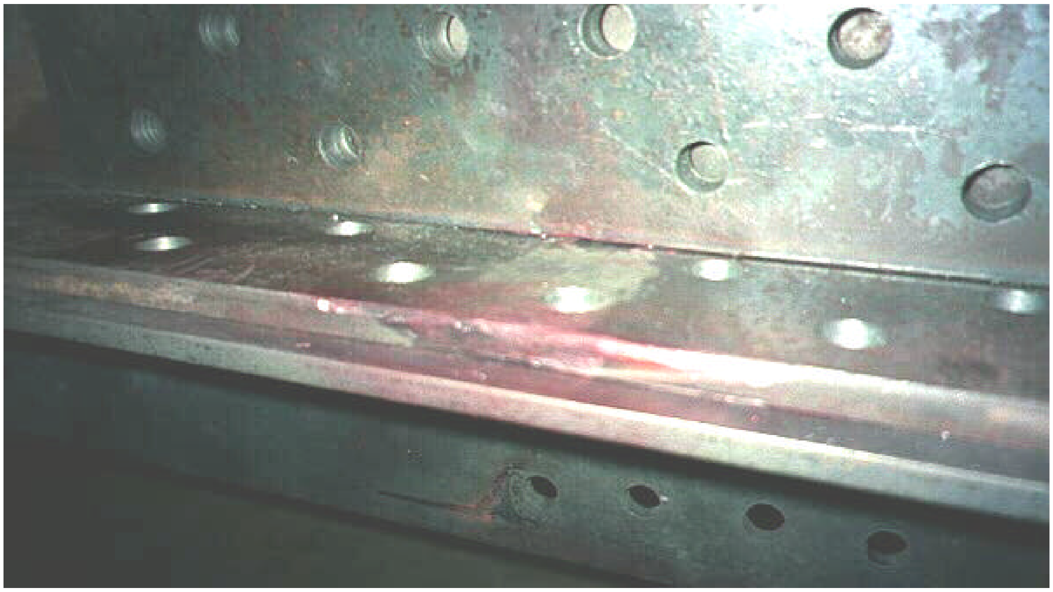


Figure 11-37: Ground butt weld with bolt pattern drilled for adding redundant plates.

The full repair is shown in Figure 11-38. The redundant plates have been placed above and below the previously cracked flange. A spacer plate was required on the lower side of the beam to provide a level surface with the specimen. Eight A490 bolts having a 22-mm diameter were used on either side of the former crack location. In the other three corners of the support structure, only small cracks were found (< 19-mm). Drilling a hole through the crack tips successfully stopped these cracks for the remainder of the testing.

Figure 11-38: Final repair of cracked beam tension flange.

11.8 FINAL COMMENTS ON HOLE DRILLING SUCCESSES

Drilling out the crack tip has been repeatedly shown to be successful in stopping a crack. Figures 11-39 and 11-40 present a final illustration of the exceptional success common to this repair technique. The photo shows a location where a fatigue crack had grown to a through-thickness crack in the beam tension flange. This crack had propagated to within 50-mm of the flange edge prior to hole drilling, and a large 29-mm hole was necessary to capture the crack tip and arrest the crack. To quantify the stress in the remaining tension strip, a strain gage was mounted mid-way between the hole edge and the free edge of the flange. Strain gage readings indicated large stress ranges of 108 MPa were present. Furthermore, a noticeable dip at this location was observed during testing, indicating the area had tolerated a significant amount of stress fluctuations throughout testing. Surprisingly, after eight million cycles at this stress range no further cracking was observed. For this reason, the practice of hole drilling is highly advocated as an effective fatigue repair.

Figure 11-39: Several cracks arrested by hole drilling.

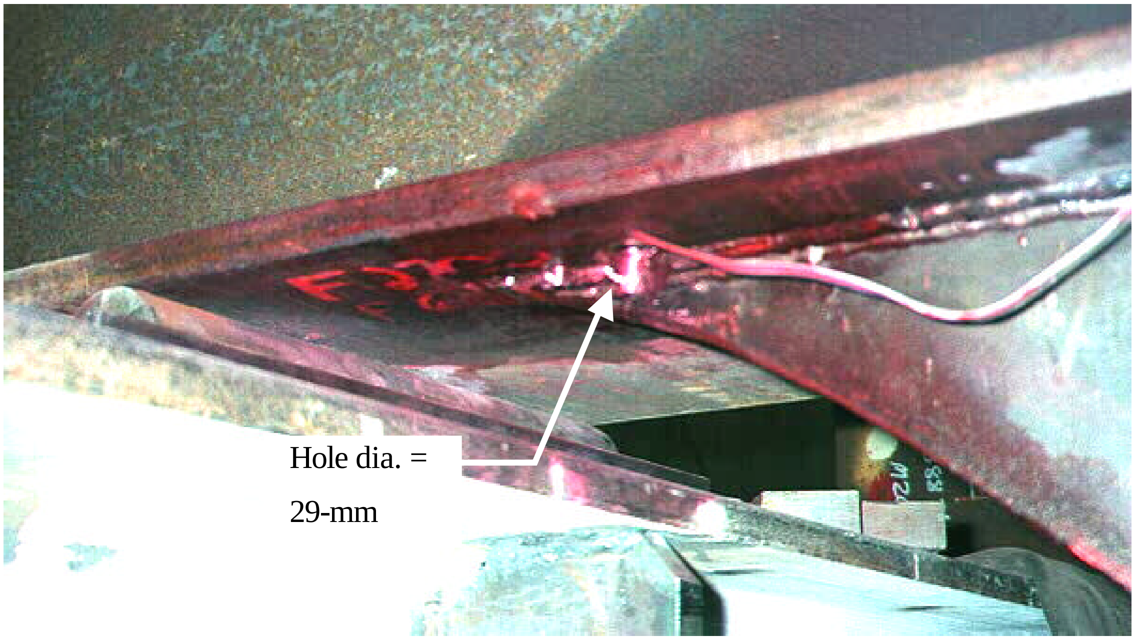
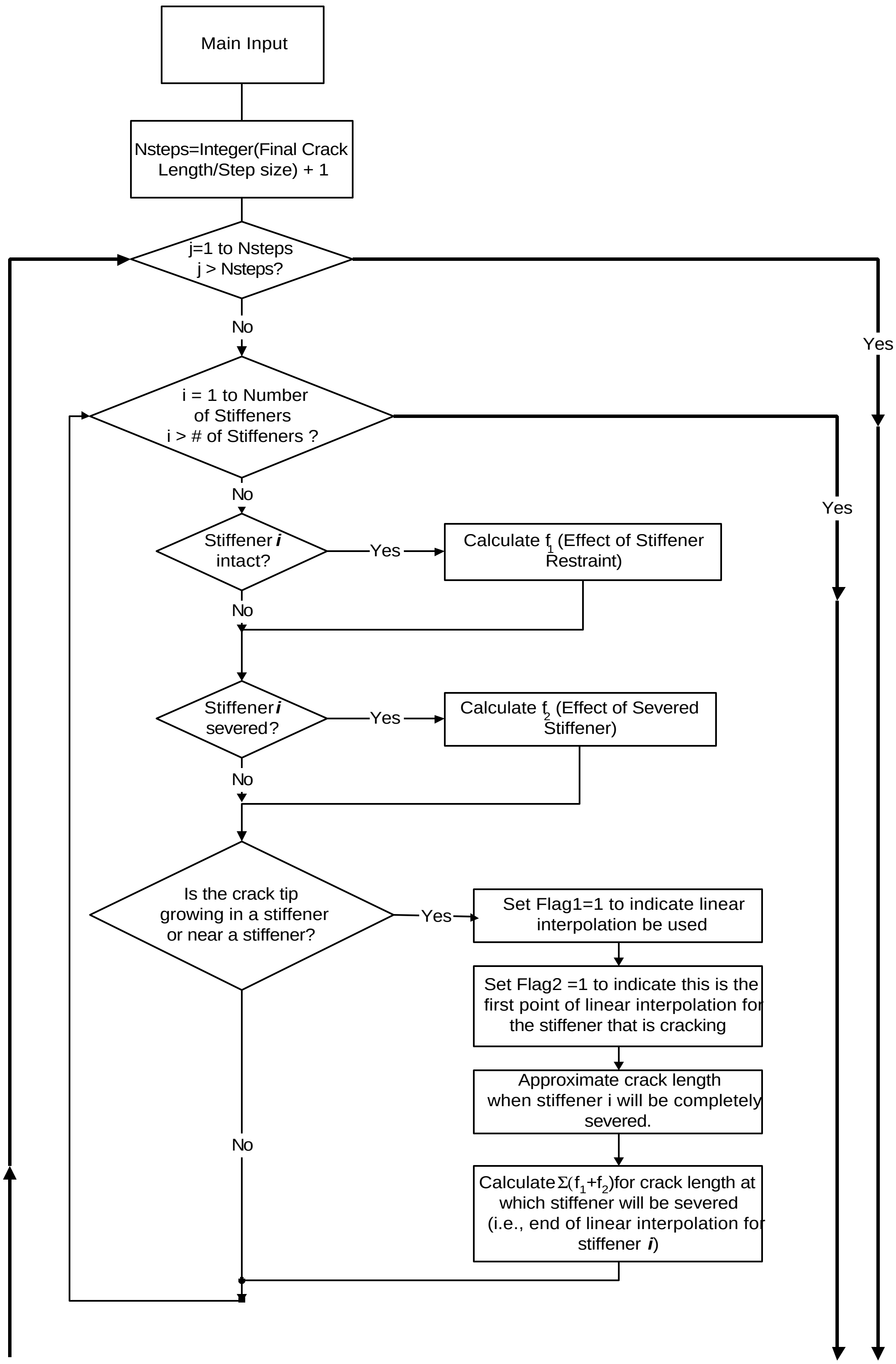
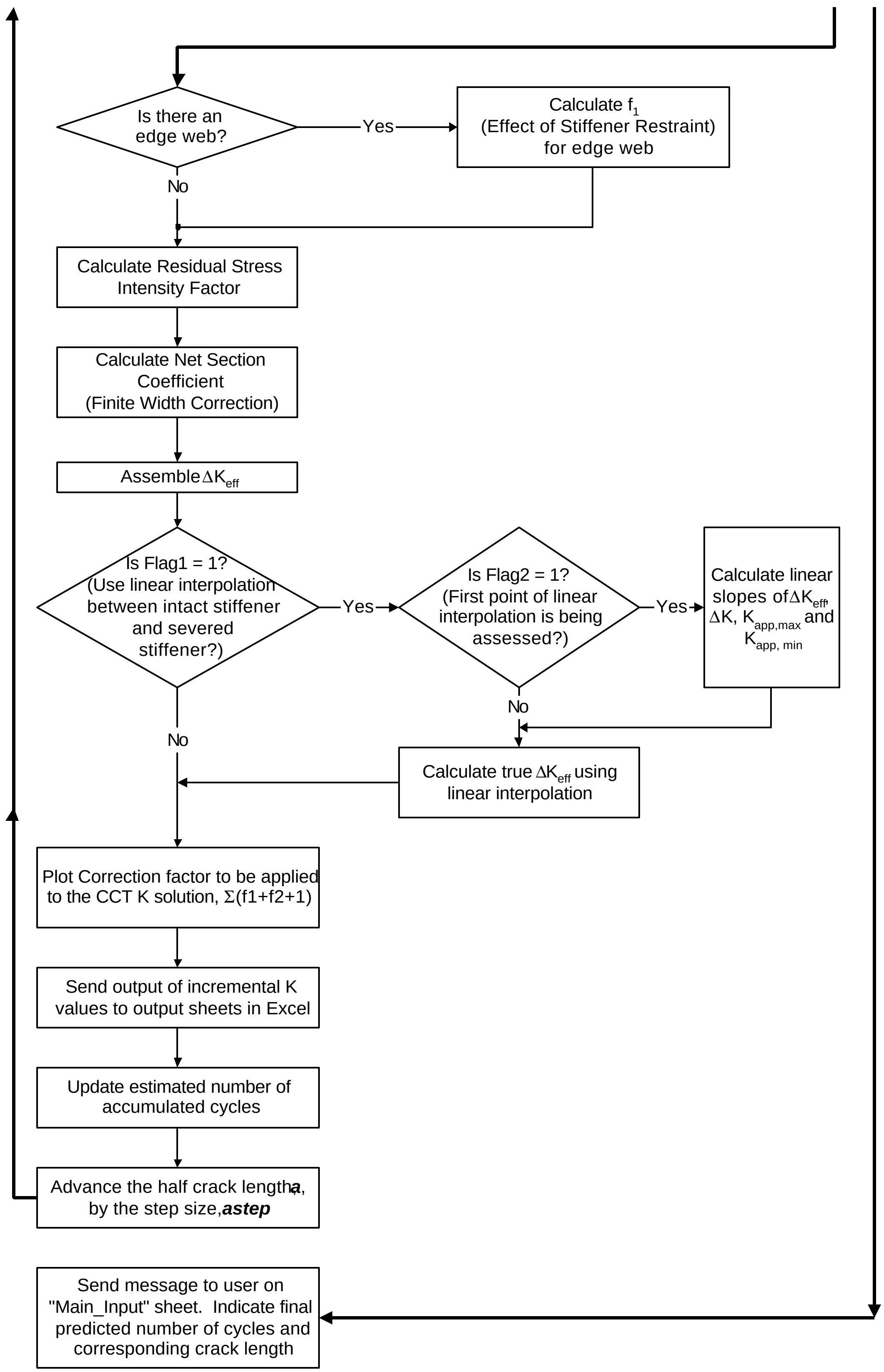


Figure 11-40: Large hole used in arresting crack at fatigue sensitive location.

12 Appendix B: Flowchart for Analytical Program




Is there an edge web?
Yes
Calculate f_1 (Effect of Stiffener Restraint) for edge web
No
Calculate Residual Stress Intensity Factor
Calculate Net Section Coefficient (Finite Width Correction)
Assemble ΔK_{eff}
Is Flag1 = 1? (Use linear interpolation between intact stiffener and severed stiffener?)
Yes
Is Flag2 = 1? (First point of linear interpolation is being assessed?)
Yes
Calculate linear slopes of ΔK_{eff}, ΔK, $K_{app,max}$ and $K_{app, min}$
No
No
Calculate true ΔK_{eff} using linear interpolation
Plot Correction factor to be applied to the CCT K solution, Σ(f1+f2+1)
Send output of incremental K values to output sheets in Excel
Update estimated number of accumulated cycles
Advance the half crack length, *a*, by the step size, ***astep***
Send message to user on "Main_Input" sheet. Indicate final predicted number of cycles and corresponding crack length

13 Appendix C: Arbitrary Point Force in Infinite Medium

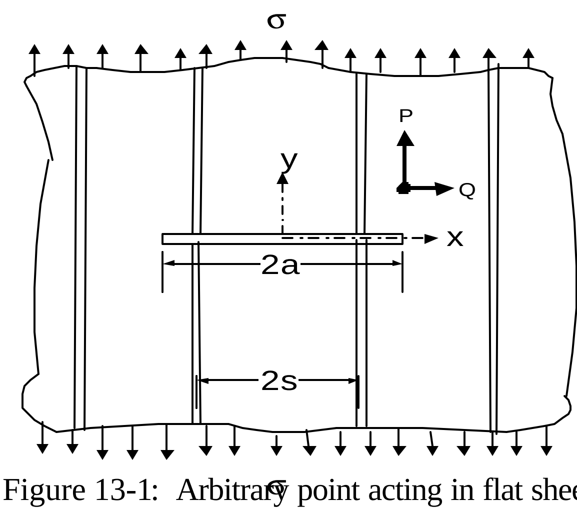


Figure 13-1: Arbitrary point acting in flat sheet.

Two complex functions necessary for arbitrary force stress intensity factor:

(See Compendium of Stress Intensity Factors, Ref. 131 page 1.1.12)

Equation 1

$$H(z) = \frac{a \cdot (zhat - z)}{(zhat - a) \cdot \left(\sqrt{zhat^2 - a^2}\right)}$$

Equation 2

$$G(z) = \frac{a + z}{\sqrt{z^2 - a^2}}$$

where : $zhat = x - i \cdot y$ $\quad z = x + i \cdot y$

The resulting stress intensity factor requires these functions to be broken into four parts:

$G1 = 1 + Re(G(z))$ $\quad H1 = Re(H(z))$

$G2 = Im(G(z))$ $\quad H2 = -Im(H(z))$

Note: There was an error found in the handbook solution for G1 and G2. Originally, the handbook incorrectly stated: G1 = 1 - Re(G(z)) and G2 = -Im(G(z))

Equation 1: Manipulation into separate real and complex parts:

$$H(z) = \frac{a \cdot (zhat - z)}{(zhat - a) \cdot \left(\sqrt{zhat^2 - a^2}\right)}$$

Let $\frac{zhat - z}{zhat - a}$ be part 1,

and $\sqrt{zhat^2 - a^2}$ be part 2

Part one:

$$\frac{\text{zhat} - z}{\text{zhat} - a} = \frac{x - i\cdot y - (x + i\cdot y)}{x - i\cdot y - a}$$

$$\frac{\text{zhat} - z}{\text{zhat} - a} = \frac{x - i\cdot y - (x + i\cdot y)}{x - i\cdot y - a}$$

$$\frac{\text{zhat} - z}{\text{zhat} - a} = \left[2\cdot i\cdot\frac{y}{(-x + i\cdot y + a)}\right]\cdot\frac{(-x - i\cdot y + a)}{(-x - i\cdot y + a)} = \frac{-2\cdot i\cdot y\cdot x - 2\cdot i^2\cdot y^2 + 2\cdot i\cdot y\cdot a}{x^2 - 2\cdot x\cdot a - i^2\cdot y^2 + a^2} = \frac{2\cdot y^2 + 2\cdot y\cdot i\cdot(a - x)}{(x - a)^2 + y^2}$$

Part 2 (denominator):

$$\sqrt{\text{zhat}^2 - a^2} = \sqrt{(x - i\cdot y)^2 - a^2}$$

$$\sqrt{\text{zhat}^2 - a^2} = \sqrt{x^2 - 2\cdot i\cdot y\cdot x + i^2\cdot y^2 - a^2} = \sqrt{\left(x^2 - y^2 - a^2\right) - 2\cdot i\cdot y\cdot x}$$

let:

$$q = x^2 - y^2 - a^2 \qquad r = 2\cdot y\cdot x$$

then

$$\sqrt{\left(x^2 - y^2 - a^2\right) - 2\cdot i\cdot y\cdot x} = \sqrt{q - i\cdot r}$$

Assembling this denominator portion of the fraction:

$$\frac{1}{\sqrt{\left(x^2 - y^2 - a^2\right) - 2\cdot i\cdot y\cdot x}} = \frac{1}{\sqrt{q - i\cdot r}}\cdot\frac{\sqrt{q + i\cdot r}}{\sqrt{q + i\cdot r}} = \frac{\sqrt{\text{denom}}\cdot\left(\cos\left(\frac{\phi}{2}\right) + i\cdot\sin\left(\frac{\phi}{2}\right)\right)}{\sqrt{q^2 + r^2}}$$

where

$$\text{denom} = \sqrt{q^2 + r^2} = \sqrt{\left(x^2 - y^2 - a^2\right)^2 + (2\cdot y\cdot x)^2} \qquad \tan(\phi) = \frac{r}{q} = \frac{2\cdot y\cdot x}{x^2 - y^2 - a^2}$$

Assembly:

$$H(z) = \frac{a\cdot(\text{zhat} - z)}{(\text{zhat} - a)\cdot\left(\sqrt{\text{zhat}^2 - a^2}\right)} = \frac{a\cdot\sqrt{\text{denom}}}{\text{denom}}\cdot\left(\cos\left(\frac{\phi}{2}\right) + i\cdot\sin\left(\frac{\phi}{2}\right)\right)\cdot\frac{2\cdot y^2 + 2\cdot y\cdot i\cdot(a - x)}{(x - a)^2 + y^2}$$

$$H(z) = \frac{a\cdot\sqrt{denom}}{denom}\cdot\left(\cos\left(\frac{\phi}{2}\right) + i\cdot\sin\left(\frac{\phi}{2}\right)\right)\cdot\frac{2\cdot y^2 + 2\cdot y\cdot i\cdot(a-x)}{(x-a)^2 + y^2}$$

$$H(z) = \frac{2\cdot a\cdot y\cdot\sqrt{denom}}{denom\cdot\left[(x-a)^2 + y^2\right]}\cdot\left[y\cdot\cos\left(\frac{\phi}{2}\right) + \sin\left(\frac{\phi}{2}\right)\cdot(x-a)\ ... \atop + i\cdot\left[y\cdot\sin\left(\frac{\phi}{2}\right) + (a-x)\cdot\cos\left(\frac{\phi}{2}\right)\right]\right]$$

Resulting Values:

$$H_1 = Re(H(z)) = \frac{2\cdot y\cdot a\cdot\sqrt{denom}}{denom\cdot\left[(x-a)^2 + y^2\right]}\cdot\left[y\cdot\cos\left(\frac{\phi}{2}\right) - \sin\left(\frac{\phi}{2}\right)\cdot(a-x)\right]$$

$$H_2 = -Im(H(z)) = \frac{-2\cdot a\cdot y\cdot\sqrt{denom}}{denom\cdot\left[(x-a)^2 + y^2\right]}\cdot\left[y\cdot\sin\left(\frac{\phi}{2}\right) + (a-x)\cdot\cos\left(\frac{\phi}{2}\right)\right]$$

Now seperate real and imaginary parts of Equation 2:

Equation 2: $G(z) = \dfrac{a+z}{\sqrt{z^2 - a^2}}$

$$G(z) = \frac{a+z}{\sqrt{z^2 - a^2}} = \frac{a + x + i\cdot y}{\sqrt{(x + i\cdot y)^2 - a^2}} = \frac{a + x + i\cdot y}{\sqrt{\left(x^2 - a^2 - y^2\right) + i\cdot 2\cdot y\cdot x}}\cdot\frac{\sqrt{q - i\cdot r}}{\sqrt{q - i\cdot r}}$$

where

$q = x^2 - a^2 - y^2$

$r = 2\cdot y\cdot x$

$$\tan(\theta) = \frac{-r}{q} = \frac{-2\cdot y\cdot x}{x^2 - y^2 - a^2}$$

Substitution of q and r:

$$G(z) = \frac{a + x + i\cdot y}{\sqrt{q + i\cdot r}}\cdot\frac{\sqrt{q - i\cdot r}}{\sqrt{q - i\cdot r}} = \frac{(a + x + i\cdot y)}{\sqrt{q^2 + r^2}}\cdot\left(\sqrt{q^2 + r^2}\right)^{0.5}\cdot\left(\cos\left(\frac{\theta}{2}\right) + i\cdot\sin\left(\frac{\theta}{2}\right)\right)$$

substitute for q and r with: $\text{denom} = \sqrt{q^2 + r^2}$

$$G(x) = \frac{(a + x + i\cdot y)}{\text{denom}} \cdot \sqrt{\text{denom}} \cdot \left(\cos\left(\frac{\theta}{2}\right) + i\cdot\sin\left(\frac{\theta}{2}\right)\right)$$

$$G(x) = \frac{\sqrt{\text{denom}}}{\text{denom}} \cdot \left[\left[(a + x)\cdot\cos\left(\frac{\theta}{2}\right) - y\cdot\sin\left(\frac{\theta}{2}\right)\right] \ldots \atop + i\cdot\left[y\cdot\cos\left(\frac{\theta}{2}\right) + (a + x)\cdot\sin\left(\frac{\theta}{2}\right)\right]\right]$$

Therefore:

$$G1 = 1 + \text{Re}\,(G(z)) = 1 + \frac{\sqrt{\text{denom}}}{\text{denom}} \cdot \left[(a + x)\cdot\cos\left(\frac{\theta}{2}\right) - y\cdot\sin\left(\frac{\theta}{2}\right)\right]$$

$$G2 = \text{Im}\,(G(z)) = \frac{\sqrt{\text{denom}}}{\text{denom}} \cdot \left[y\cdot\cos\left(\frac{\theta}{2}\right) + (a + x)\cdot\sin\left(\frac{\theta}{2}\right)\right]$$

and

$$H1 = \text{Re}(H(z)) = \frac{2\cdot y\cdot a\cdot\sqrt{\text{denom}}}{\text{denom}\cdot\left[(x - a)^2 + y^2\right]} \cdot \left[y\cdot\cos\left(\frac{\phi}{2}\right) - \sin\left(\frac{\phi}{2}\right)\cdot(a - x)\right]$$

$$H2 = -\text{Im}(H(z)) = \frac{-2\cdot a\cdot y\cdot\sqrt{\text{denom}}}{\text{denom}\cdot\left[(x - a)^2 + y^2\right]} \cdot \left[y\cdot\sin\left(\frac{\phi}{2}\right) + (a - x)\cdot\cos\left(\frac{\phi}{2}\right)\right]$$

These resulting expressions are used to formulate K for a variety of cracks:

For a vertical force P, as shown in Figure 13-1:

$$\frac{K_I}{K_0} = G_2 - \left(\frac{1}{\kappa + 1}\right)\cdot H_2 \quad \text{with} \quad K_0 = \frac{P}{2\sqrt{\pi\ a}}$$

where K_I indicates an opening mode crack

$$\frac{K_{II}}{K_0} = G_1 - \left(\frac{1}{\kappa - 1}\right)\cdot H_1 \quad \text{with} \quad K_0 = \frac{-P}{2\sqrt{\pi\ a}} \cdot \left(\frac{\kappa - 1}{\kappa + 1}\right)$$

where K_{II} indicates an sliding mode crack

Alternatively, if an arbitrary horizontal force Q was applied, the following relations would result:

$$\frac{K_I}{K_0} = G_1 + \left(\frac{1}{\kappa - 1}\right) \cdot H_1 \quad \text{with} \quad K_0 = \frac{Q}{2\sqrt{\pi\ a}} \cdot \left(\frac{\kappa - 1}{\kappa + 1}\right)$$

where K_I indicates an opening mode crack

$$\frac{K_{II}}{K_0} = G_2 + \left(\frac{1}{\kappa + 1}\right) \cdot H_2 \quad \text{with} \quad K_0 = \frac{Q}{2\sqrt{\pi\ a}}$$

where K_{II} indicates an sliding mode crack

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