Example - SAE Welded Square Tube

The Strain-Life and Fracture Mechanics Method

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The SAE Fatigue Design and Evaluation Committee coordinated a series of experiments and analysis to compare fatigue analysis techniques used by various industries to assess the durability of welded structures. Two steel tubes were welded into a T shape to simulate the production component taken from the structure shown in Figure 1. This is a common weld configuration found in agricultural equipment.

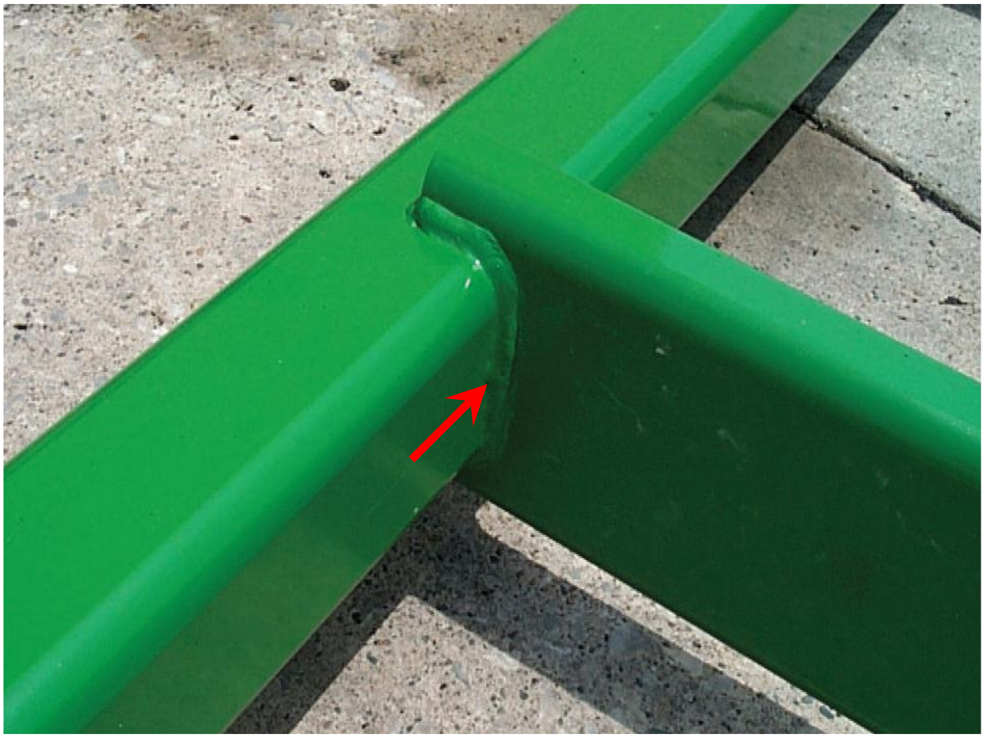

Figure 1. Typical weld detail found in agricultural equipment

This joint is subjected to combined bending and twisting loads. This detail served as the basis of a laboratory specimen that could be easily tested. The specimen, Fig. 2, is fixed on two ends and forces are applied through a lever arm attached to the third end. This design produces both bending and torsion stresses in the square tube. The distance from the force to the weld toe in bending is 271.5 mm (10.7") and the distance of the applied force to the centerline of the square tube is 317.5 mm (12.5").

The specimen is manufactured from a 4" (101.6 mm) square structural steel tube and a 2" x 6" (50.8 x 152.4 mm) rectangular tube, both with a 0.312" (7.9 mm) wall thickness. The partial penetration fillet weld is the same size as the tube wall thickness and was manufactured with the MIG welding process.

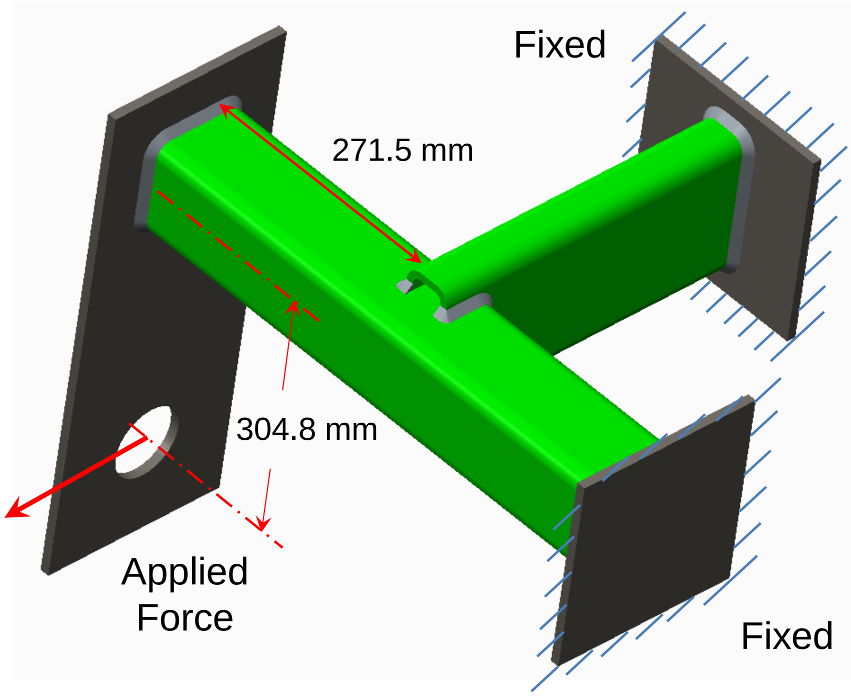

Figure 2. Test specimen

Test setup is shown in Fig. 3. Specimens are typically painted white to aid in visual crack detection. Fatigue tests were conducted with a completely reversed load (R = -1) of 4000 lb.

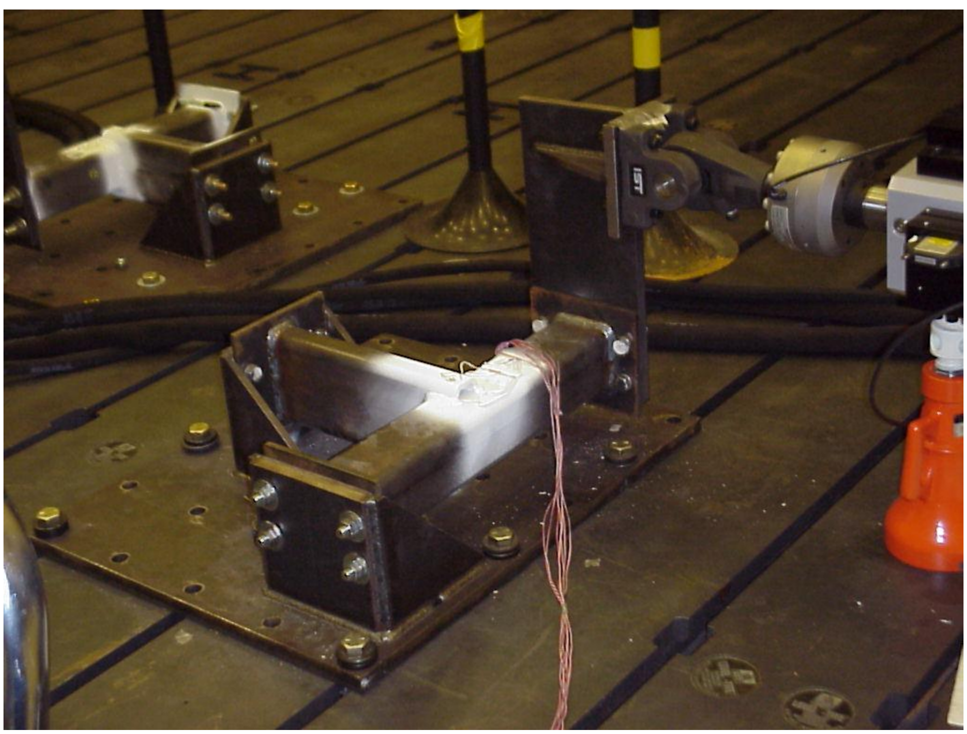

Figure 3. Test fixture

The weld geometry

The dimensions of the weld at the critical location were (see slides No. 55 and 56 in the notes on weldments or in the paper quoted above):
$t = 0.32in$, $t_p= 3t = 0.936in$, $h= 0.312in$, $h_p= 0.312in$, $r = 0.0312$, $\theta=45^o$.
The stress concentration factors determined for those dimensions were:
$K_t^m = 1.784$ and $K_t^b = 2.203$.

The FE stress analysis

The solid model of the entire set-up is shown in Figure 4. Tests were carried out at the John Deere Co. (USA) laboratory and more details concerning the tests and material properties can be found in the reference - ***A. Chattopadhyay, G. Glinka, M. El-Zein, J. Qian and R. Formas, Stress Analysis and Fatigue of Welded Structures, Welding in the World, (IIW), vol. 55, No. 7-8, 2011, pp. 2-21.***

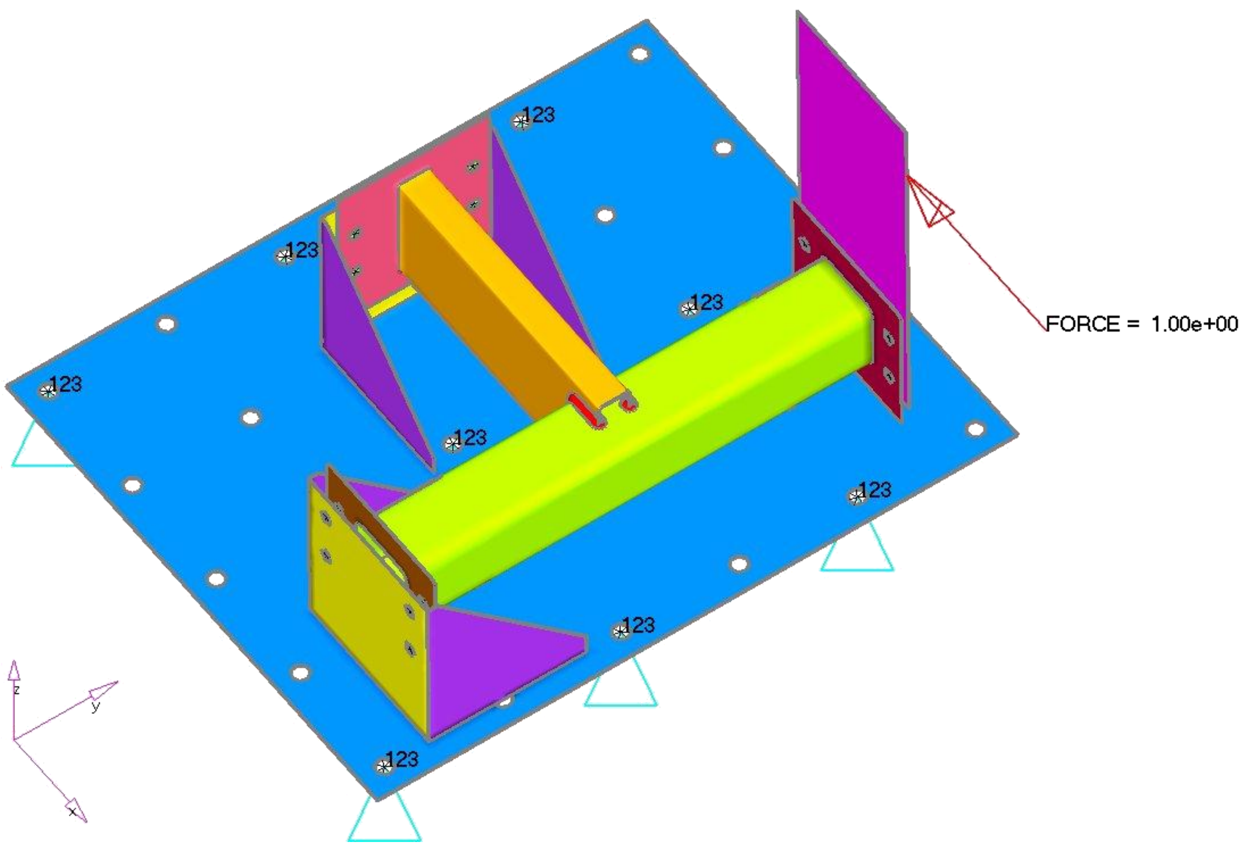

Figure 4. Solid model of tested structure

The structure was analyzed first with the FE-Abaqus package using the shell methodology described earlier.

The FE model and the FE mesh are shown in Figure 5. The stress levels denoted with various colors are shown in Figure 6.

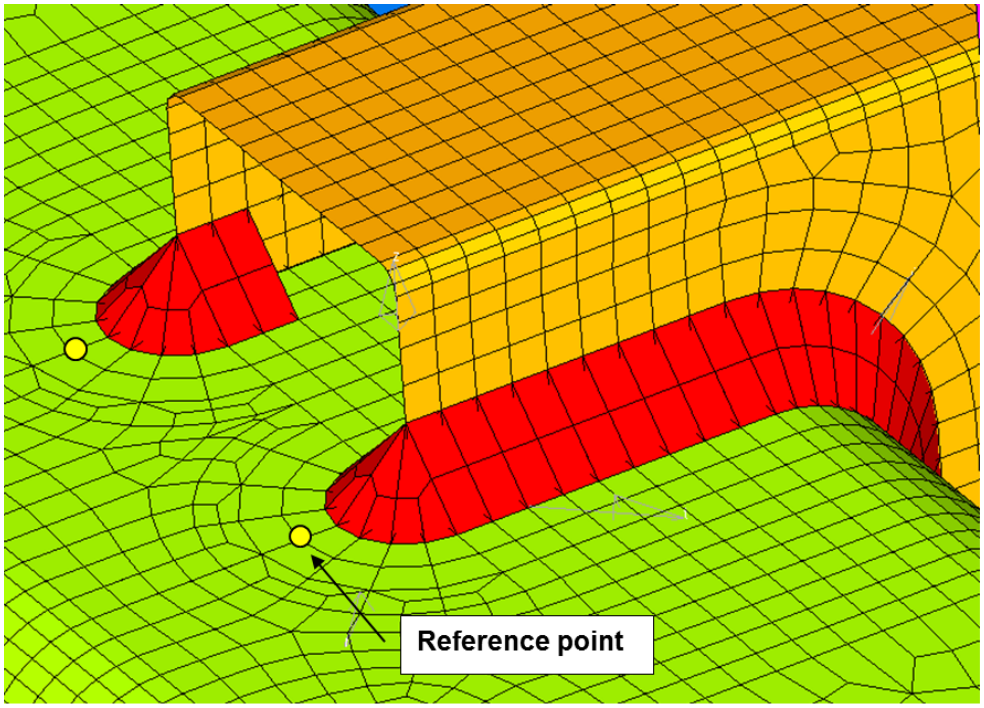

Figure 5. The FE shell model of the structure

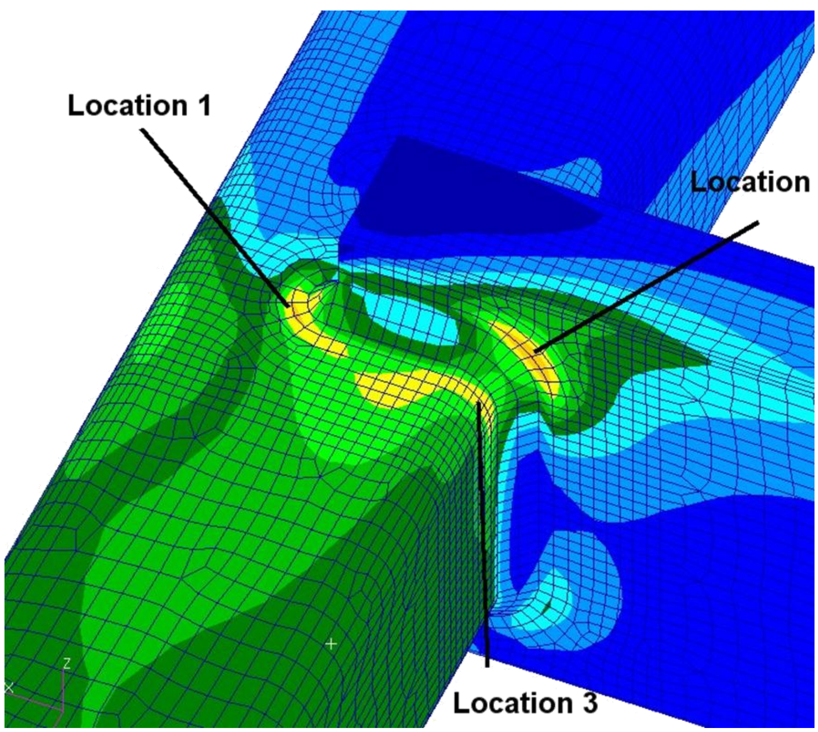

Figure 6. Location of critical regions

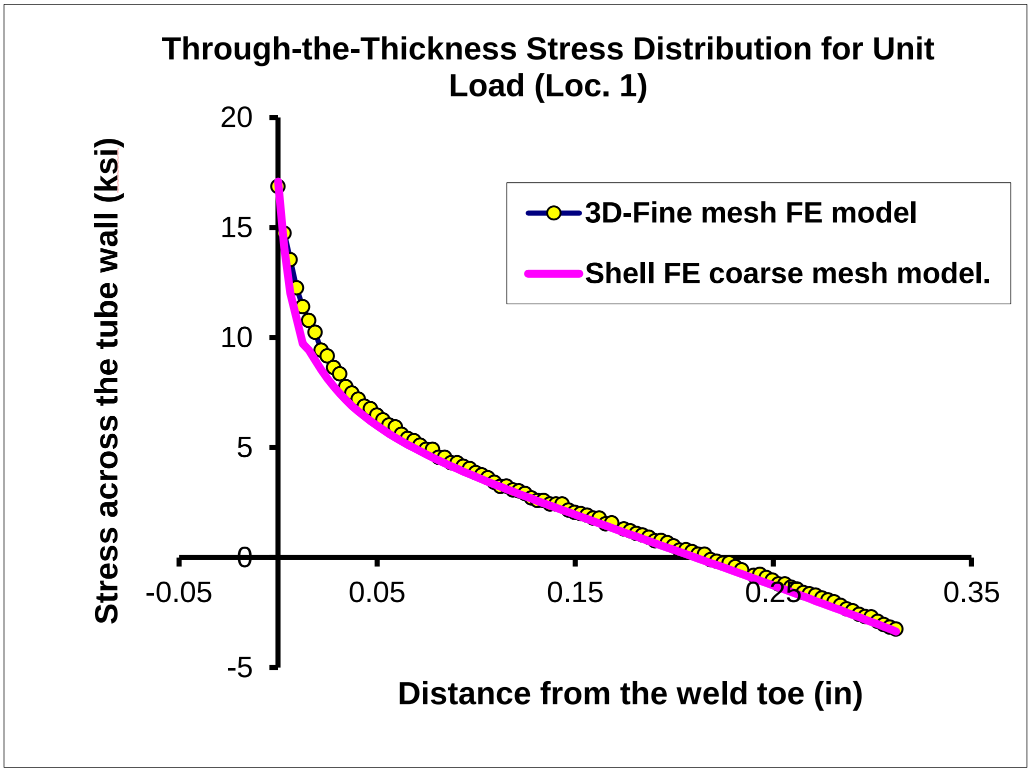

Figure 7. Through thickness stress distribution at the critical location

The highest stress induced by the reference load of F=1000 lb was found in Location 1 and therefore this region was analyses from the fatigue durability point of view.

The shell stresses induced by the reference load force of F=1000 lb on both sides of the plate at the critical location were: σ^1_{hs}= 8.25 ksi and σ^2_{hs}= - 3.05 ksi. Therefore the membrane and bending stress contributions were:

$$\sigma^m_{hs} = \frac{\sigma^1_{hs} + \sigma^2_{hs}}{2} = \frac{8.25 + (-3.05)}{2} = 2.6\,ksi$$

$$\sigma^b_{hs} = \frac{\sigma^1_{hs} - \sigma^2_{hs}}{2} = \frac{8.25 - (-3.05)}{2} = 5.65\,ksi$$

Therefore the peak stress at the weld toe induced by the reference load of F=1000 lb was determined as:

$$\sigma_{peak} = \sigma^m_{hs} K^m_{t,hs} + \sigma^b_{hs} K^b_{t,hs} = 2.6 \times 1.784 + 5.65 \times 2.203 = 17.089\ ksi\ .$$

This peak stress can be finally scaled according to the applied load.

Based on the geometrical parameters of the weld and the stress data above the Monahan equations were used in order to determine the through thickness stress distribution at the critical location (see slide No.41, 42 and 77 – notes on welded structures).

The through the thickness stress distribution induced by the reference load F=1000 lb is shown below. This stress field is to be used for the fatigue crack growth analysis.

Residual stresses

In addition to stresses induced by the applied load additional stress field i.e. residual stresses introduced by the welding process have also been found. Measurements of residual stresses with the help of X-ray technique made it possible to construct approximate residual stress field shown in Figure 8. The effect of the residual stress field is to be demonstrated in due course.

Material Properties

Structural steel tubes are specified as the dimension on the outside thus - a 4” square tube measures 4” on the outside. The corner radius is typically equal to the thickness on the inside and twice the thickness on the outside. The tubes were made (John Deere Co. notation) of A22-H steel material. Properties of this material are given below.

Table 1 - Monotonic mechanical properties of the A22-H steel material

Ultimate strength (S_u)	Yield strength (S_y)	Elastic modulus (E)
79.0 (ksi)	68.89 (ksi)	29938 (ksi)

Table 2 - The cyclic and fatigue properties of the A22-H steel material

Fatigue strength coefficient (σ'_f)	169.98 (ksi)
Fatigue strength exponent (b)	-0.12
Fatigue ductility coefficient (ε'_f)	0.648
Fatigue ductility exponent (c)	-0.543
Cyclic strength coefficient (K')	155.2 (ksi)
Cyclic strain hardening exponent (n')	0.187

The fatigue crack growth data was given in the form of the Paris equation:

$$\frac{da}{dN} = C\left(\Delta K\right)^m$$

Where: m = 3.02 and C = $2.9736 \cdot 10^{-10}$ for ΔK in [ksi√in] and da/dN in [inches] and R=0.
The threshold stress intensity factor and the critical stresses intensity factor were assumed as ΔK_{th}=3.19 ksi√in and K_c = 72.81 ksi√in.

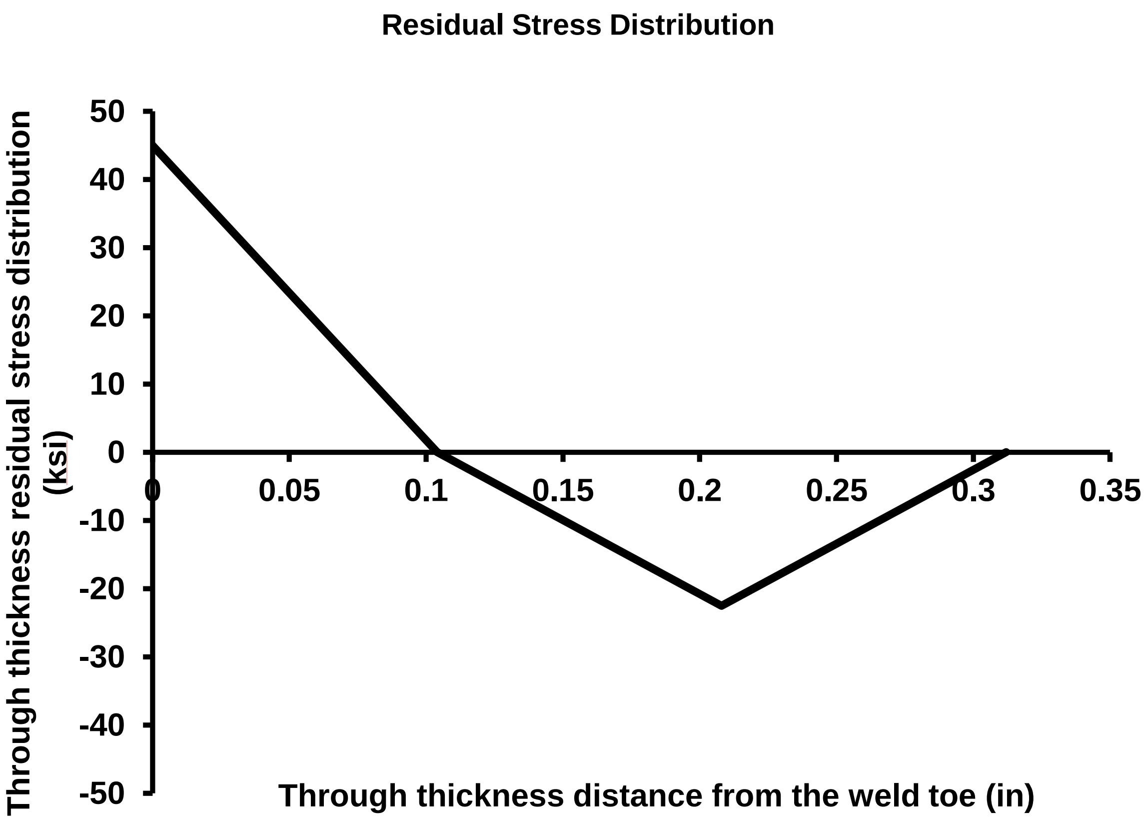

Fig. 8. Through thickness residual stress field

Fatigue analyses

The fatigue analyses are to be carried out with the help of the FALIN and FALPR computer programs to be demonstrated live in the classroom.
Fatigue cracks initiated at the end of the weld (see figures above) and they were growing through the thickness as surface cracks almost-semielliptical cracks as shown in Figure 9.

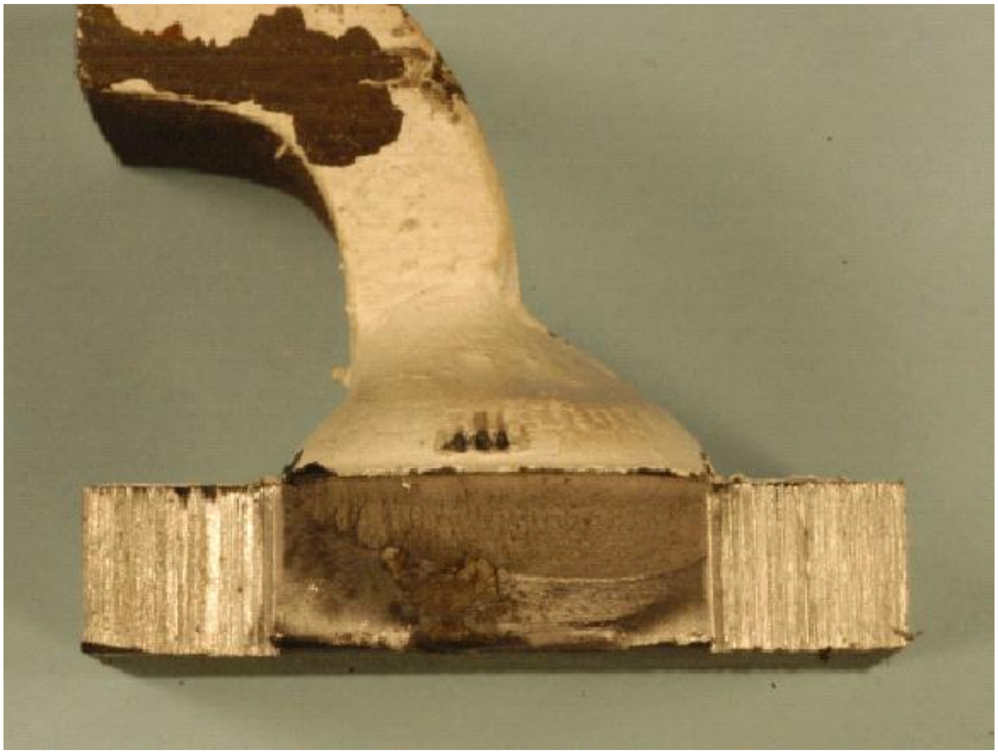

Figure 9. Typical fatigue cracks at the end life of the structure

All input files, based on the supplied data above, are included into the package together with the executable versions of the FALIN and FALPR programs.