Fatigue Crack Paths in a Welded Structure

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ABSTRACT. *In the present paper, different fatigue crack paths and fatigue properties in a welded structure have been investigated. The investigated object is a link from a bulldozer, which is exposed to variable amplitude loading in operation. The analysis is based on a global FE-model and a number of sub-models. In the FE-analysis the automatic crack propagation program FRANC2D is used to simulate different crack paths. The investigation covers cracks initiating from weld toes, roots and base material. Fatigue tests were performed to verify life and crack paths. The crack path simulations showed good agreement with test while the fatigue life showed some deviations between predicted and tested.*

INTRODUCTION

In the present investigation, a link from a bulldozer is analysed. The link is a part of the lifting framework, see Figs 1 and 2. The function of the link is to transfer force from a hydraulic cylinder into the bucket, which cause fatigue loads. The link is manufactured from five gas-cut plates in high strength steel, see Table 1. The overall length is about 1200 mm. Figure 2b shows the different types of welded joints in the link and all welds will be analysed in several positions. Some of the links were TIG-treated in position W2 and all links were shot blasted after welding. Shot blasting, performed in the actual manufacturing unit, gives normally residual stresses in compression at the surface at the same level as controlled shot peening, see Samuelsson [1]. There are approximately 9x2 (2 according to the symmetry condition) critical points (toes, corners and roots) were fatigue cracks can start from. The hydraulic cylinder generates forces with variable amplitude in the link between +900 and -700 kN.

Figure 1. Bulldozer.

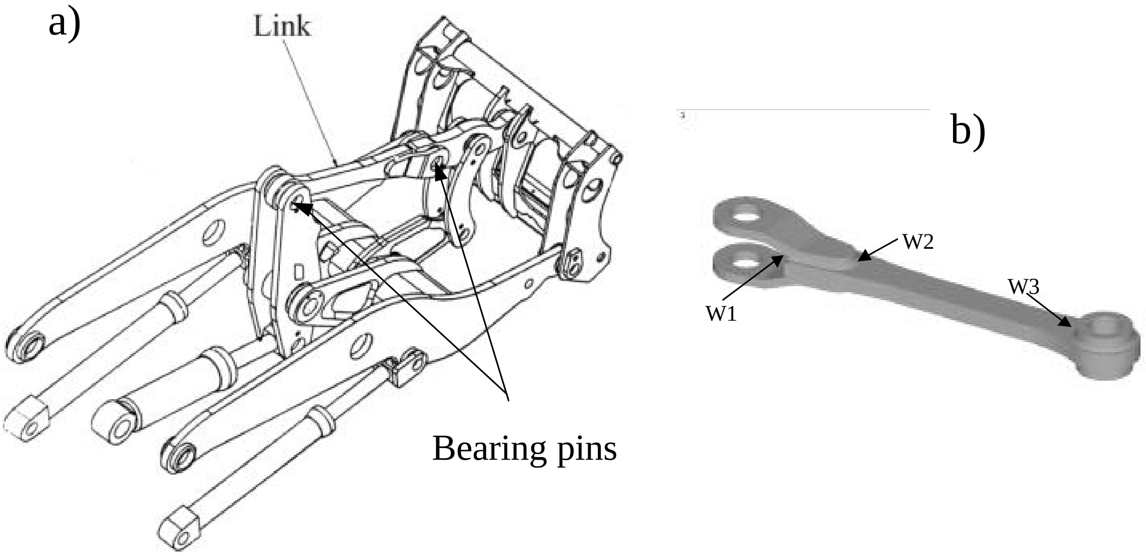

Figure 2. Schematic picture of the placement of the link and the critical welds. W1-W3 are the welds that will be investigated according to fatigue.

Table 1. Properties of material in the link.

Steel	σ_y R_{EH} (MPa)	σ_b R_M (MPa)
EN10113-2 (SS2144 Swedish stand.)	420	480

The fatigue properties of the link were earlier investigated in Martinsson and Samuelsson [2]. In [2] four different fatigue design methods, as nominal stress, geometric stress, effective notch stress and LEFM were applied and evaluated on the link. The LEFM calculations were made by using weight function solution of a semi-elliptical crack, see Fett et al. [3]. The crack was assumed to grow normal to the first principal stress. The aim of this paper is to compare simulated fatigue properties and crack paths in FRANC2D (FRacture ANalysis Code 2D) with test.

FRANC2D is a 2D finite element based simulator for curvilinear crack propagation in planar (plane stress, plane strain, and axisymmetric) structures developed at Cornell University by the Cornell Fracture Group [4]. The finite element mesh is locally regenerated after each step of propagation by means of a remeshing algorithm. The propagation process is driven by linear elastic fracture mechanics concept which are used to calculate mixed-mode stress intensity factors, predict incremental changes in trajectory, and assess local crack stability. It should also be mention that there is a 3D version called FRANC3D available from the Cornell Fracture Group. The 3D version is far more complex and as a first step the more simple 2D could be a reasonable choice.

FINITE ELEMENT MODELS

In [2] a global model of the link was made in a 3D CAD program and imported to ANSYS 5.6 where the finite element calculations were made. Due to the symmetry of the link only a quarter of the model was used in the FE. The elements used were 20 node brick and 10 nodes tetrahedral element for the structure and contact elements to model the contacts between the cylinders and the link. As input for FRANC2D a 2D model of the investigated welds with a rather fine mesh are needed. Figure 3 shows a schematic picture of the link and the refined mesh 2D sub-models at the welds W1-W3.

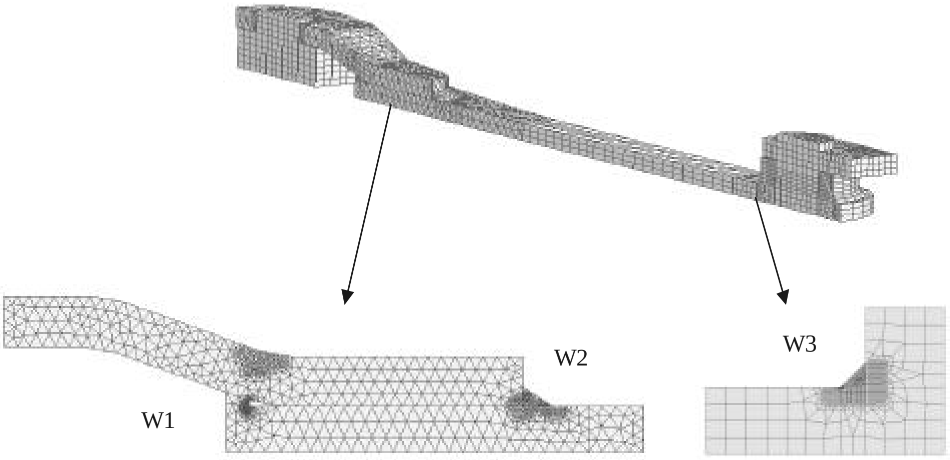

Figure 3. Schematic picture over the link and the 2D sub models. The arrows show the locations of the sub models.

The 2D sub-models were also made in ANSYS. A compiler was used to transfer the FE-mesh and the applied boundary conditions into FRANC2D.

FATIGUE TEST ON COMPONENTS

Five links were fatigue tested until fracture or large cracks occurred, see Martinsson & Samuelsson [2]. The applied load time history was measured in field with a range of +900 --700 kN. The fractures occurred in W1 and W3. No fractures were recorded at W2. There were also small cracks starting from the gas cut edges in the fork but the major fracture occurred in W1 and W3. The test resulted in failures after 150-300 test hours with a mean value ~210 hours for W1 and W3. One test hour contained about 6000 load-cycles with a convex distribution of the range pair exceed count histogram.

RESULTS AND DISCUSSIONS

Table 2 shows max and min stress for the applied range and the predicted fatigue life of the welds W1-W3. In case of crack propagation from the weld toe, a 0.1 mm crack has been used as initial crack [1,5]. The inbuilt fatigue calculation mode in FRANC2D only takes consideration to ΔK_I as the crack driving force. Due to the large values of ΔK_{II}, especially at the root side of the investigated welds ΔK_{eq} was used instead. In Socie and Marquis [6], three different formulas for calculating ΔK_{eq} are mentioned:

Table 2. Predicted life in hours.

Weld	Äó$_{max}$ (MPa)	Äó$_{min}$ (MPa)	Prediction on life in hour	
			No Relax	Relax
W1	450	-350	40	116 (-0.8)
W2 (toe)	844	-621	26	75 (-0.8)
W2 (root)	817	-608	16	46 (-0.8)
W3 (toe)	703	-789	105	354 (-1.0)*
W3 (root)	492	-712	77	260 (-1.0)*

$$\Delta K_{eq} = \left(\Delta K_I^4 + 8\Delta K_{II}^4\right)^{\frac{1}{4}} \qquad \text{“Crack tip displacement”} \qquad (1)$$

$$\Delta K_{eq} = \left(\Delta K_I^2 + \Delta K_{II}^2\right)^{\frac{1}{2}} \qquad \text{“Strain energy release”} \qquad (2)$$

$$\Delta K_{eq} = \left(\Delta K_I^2 + \Delta K_I \Delta K_{II} + \Delta K_{II}^2\right)^{\frac{1}{2}} \qquad \text{“Cross product”} \qquad (3)$$

In the present paper, Equation 1 has been used.

The da/dN curve values are taken from IIW and have the following values, m=3 and C=1.5e-13 (units in Nmm$^{-3/2}$ and mm) recalculated for a failure probability of 50%, [7]. In the fourth column in Table 2 the total stress ranges have been used to calculate life. In that case the assumption is made that the max and min applied stresses do not relax the residual stress fields. In the fifth column effective stress intensity factor ΔK_{eff}, based on the estimated R-value have been taking into account by using Eq. 4, see Maddox [8]:

$$U = 0.72 + 0.28 \cdot R \qquad (4)$$

$$\text{where } R = \left(\frac{s_{\min}}{s_{\max}}\right) \text{ and}$$

$$\Delta K_{eff} = U \cdot \Delta K_{eq}.$$

The R-value of –0.8 in W1-W2 is due to the applied strange of +900 --700 kN and the assumption of that the residual stress is fully relaxed. This simple assumption regarding the relaxation of residual stresses is based on the max and min effective notch stress method performed in the earlier investigation of the fatigue properties of the link in Martinsson & Samuelsson [2]. Because of the vicinity of the non-linear contact between the bearing pin and the link of weld W3 the relation between applied load and stress is not linear resulting in an R-value, respectively, -1.1 and –1.5 for the weld toe and root. The ´*´ in the fifth column is set to –1 due to the limits of the range of the equation.

The long predicted life of the weld toe at W3 is due to the faster growth of the root side, which causes a redistribution of the stress at the weld toe.

The need of simulate the crack path from the weld toe is often unnecessary because of the well-defined crack path. Instead the weight function technique could be used [8]. An exception is if there is redistribution of the stress while the crack grow as in the case of W3. The benefit of using weight function technique at the weld toe is the easy to use, the possibility of using 2D cracks i.e. an semi elliptical crack, which normally is the case in larger welded structures.

Figure 4-6 shows the simulated and tested crack paths of the investigated welds W1-W3.

The FE calculations showed large stresses at the two locations at W1 shown in Fig. 4. The stresses were, respectively, 50 MPa and 43 MPa for the two locations at +100 kN. The agreement between test and simulation showed good agreement.

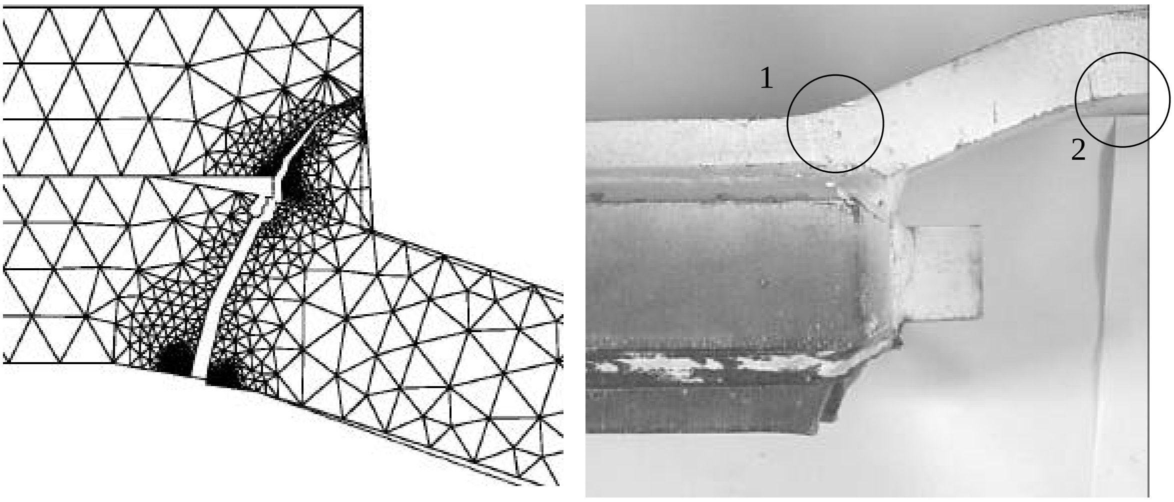

Figure 4. Comparison between simulated and test of crack paths in W1.

No fracture occurred in W2. One link was cut up to be able to investigate the root side of W2. Small cracks were found at the root side. Figure 5 show simulated and predicted crack paths at the root side. The 1 mm crack corresponds to the positive part of the stress range (0-900 kN) while the 2.5 mm corresponds to the negative stress range (0--700 kN). As shown in Fig. 5, the simulated crack paths agreed well with test. Due to the predictions both the toe and root side of W2 should be fatigue critical locations. A possible reason for the underestimate of the life of W2 could be that the residual stress in the weld around the fork are in tension which causes compression on the contact area between fork and the major plate. The occurrence of compressive residual stress in a similar joint was shown in Hansen [9]. The compressive residual stresses locally reached a value of -130 MPa. The compression in combination with friction between the bar and the fork will change the load transfer in the joint and reduce the local stress in W2.

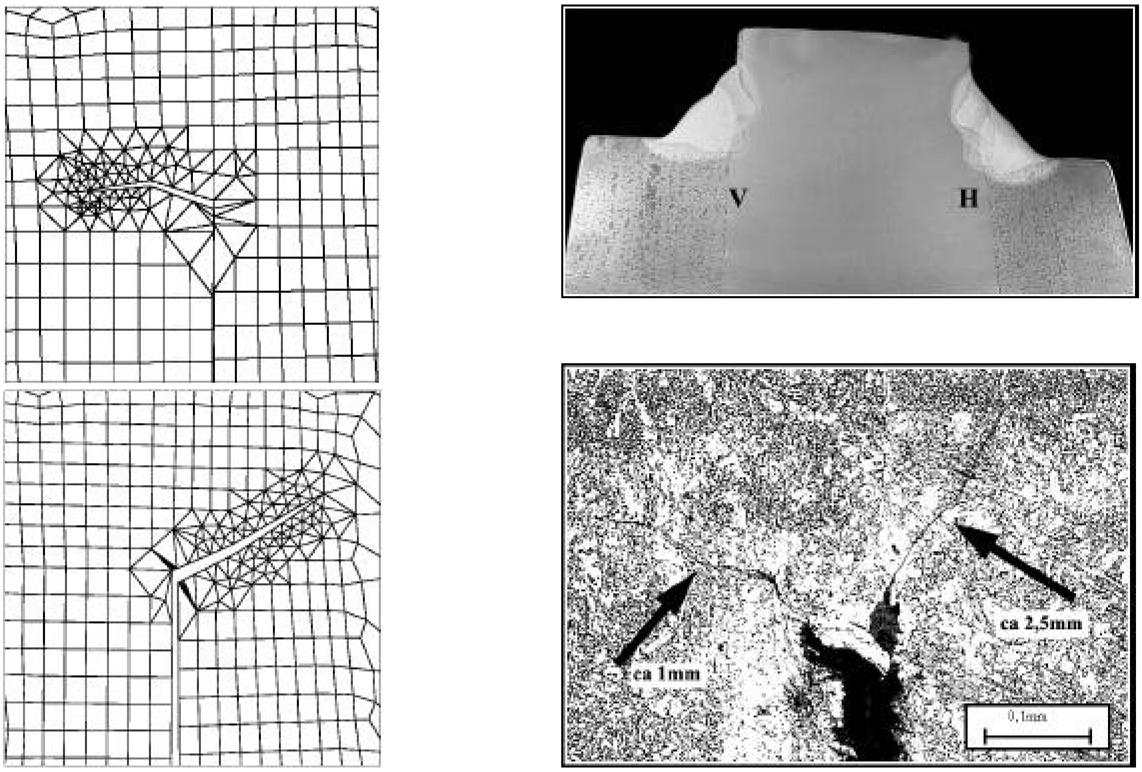

Figure 5. Comparison between simulated and test of crack paths in W2.

No fracture occurred at the weld toe of W3. As shown in Fig. 6, the simulated crack paths agreed well with test. The agreement between fatigue test and predicted life was also very satisfying. This is however not obvious. Based on the underestimate of the life of W2 where compressive residual stresses may have increased the fatigue properties the same phenomena would arise at the root side of W3 too. A possible explanation to the better agreement of W3 could be due to the high compressive bending stress due to the cylinder pressure of the wall of the ring when a negative force is applied, see Figure 7. This leads to a residual stress relaxation and the crack will grow faster. Another aspect of the residual stress distribution is that W2 is welded with three runs while W3 is welded with one run.

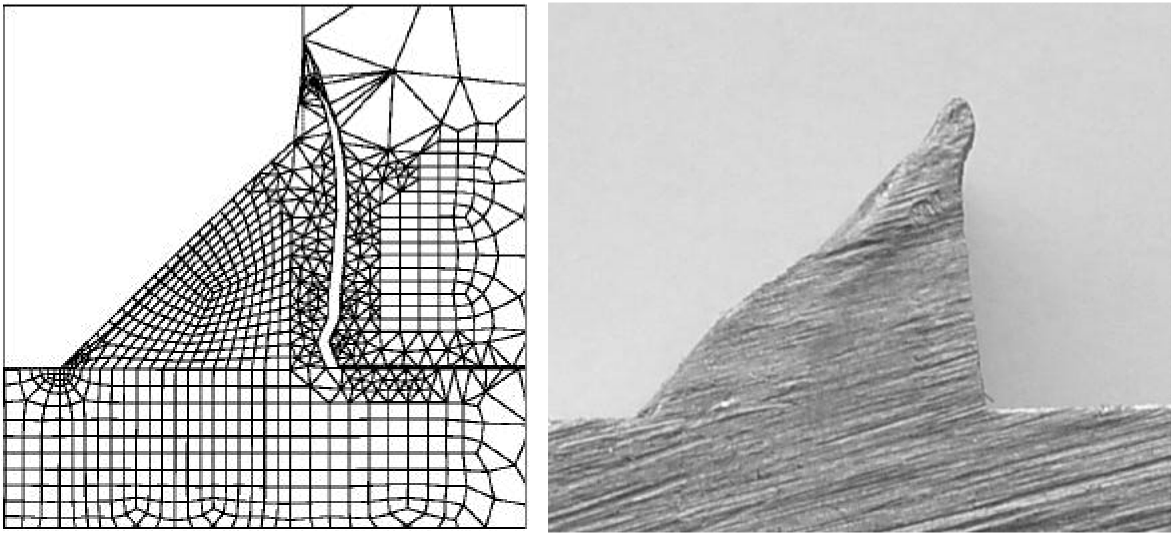

Figure 6. Comparison between simulated and test of crack paths in W3

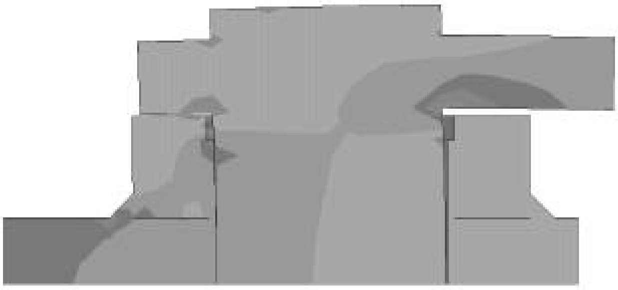

Figure 7. Bending stress due to the cylinder pressure of the wall of the ring.

CONCLUSIONS

- The simulated crack paths agreed well with test.
- The life prediction of FRANC2D is most suitable for crack growth from the root side.
- The residual stress distribution is important and strongly affects the predicted life.

FURTHER WORK

- Evaluate FRANC3D or similar 3D crack propagating programs.
- Residual measurements or simulations of the welds.

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