Automatic fatigue crack propagation calculation on welded high strength steels

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R. Baptista[1,2*], V. Infante[2], J. Marques[3]

[1] CDP2T, Department of Mechanical Engineering, ESTSetúbal, Instituto Politécnico de Setúbal, Campus do IPS, Estefanilha, 2914-761 Setúbal, Portugal

[2] LAETA, IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1, 1049-001 Lisboa, Portugal

[3] Instituto Superior Técnico, ULisboa, Av. Rovisco Pais 1, 1049-001, Lisboa, Portugal

(*)***Email:*** **ricardo.baptista@estsetubal.ips.pt**

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ABSTRACT

The demand for high strength steels is increasing. Understanding the fatigue behaviour of these materials is crucial for design and development of high performance products. The problem is even more complex when components are made of welded parts and the material parameters change as the crack propagation develops. To assess welded high strength steel fatigue behaviour, different welded CT specimens were tested. The Paris law material constants were obtained for the base material, the heat affected zone and the weld material. Fatigue life predictions were made using the obtained parameters and different automatic techniques for fatigue crack propagation. ABAQUS extended finite element method was tested, but as the implementation of the Paris law is not straight forward, to many conversions must be made and the results are too computer intensive. Therefore, a more simple and intuitive Python algorithm was developed, to directly use the experimental material parameters to predict the crack propagation path. The obtain results show a good agreement with both the experimental Paris curves, and the analytical solution.

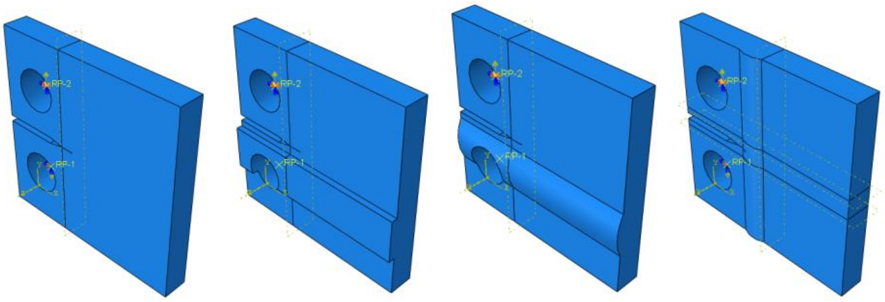
Keywords: Fatigue, Crack Propagation, High Strength Steel, Mixed Mode.

INTRODUCTION

As the demand for high strength steels (HSS) increases, so does the necessity to understand these materials behaviour. When considering welded materials, the problem is even more complex, as Maier et al. [1], showed that the fatigue crack propagations properties are influenced by the material microstructure of the heat affected zone (HAZ). Qiang et al. [2] also showed that the mixed mode fatigue crack propagation of welded HSS is not clear, as the welded material actually has a better fatigue behaviour justified by the more favourable microstructure. Our work intends to study the fatigue behaviour of HSS welded specimens (Figure 1), while using a newly developed algorithm for fatigue crack propagation. This algorithm can use any type of Finite Element Method (FEM) model to automatically calculate the Stress Intensity Factor (SIF) on the crack front and use the Paris Law to predict the elapsed number of cycles for a constant crack increment. The crack propagation direction is predicted using the Maximum Tangential Stress criterion, using the same methodology as Ayatollahi et al. [3]. Our algorithm also allows to use or determine the direct Paris Law material parameters, unlike the ABAQUS implementation of eXtended Finite Element Method (XFEM), which forces parameters conversions and is also a very computer intensive solution, with a advantage of not requiring the remeshing of the model, Singh et al. [4].

RESULTS AND DISCUSSION

The crack propagation algorithm was tested with three different FEM models. A 2D plane strain model, enabling to simulate de normal CT specimen and the CT specimen with a longitudinal weld. A 3D model using the contour integral for calculating the SIF on a normal CT specimen and the welded specimens. Finally, a 3D model using XFEM to calculate the fracture mechanics parameters on the three before mentioned specimens. The SIF value was used to preform a mesh convergence study. As one can see on Table 1, for the normal CT specimen it is possible to use a lower mesh density. Longitudinal or transversal welded specimens require a higher mesh density. A free mesh technique was always used, to allow for automatic mesh creation. Comparing the 3D models, one can see the XFEM models does not allow the use of quadratic elements, therefore the overall number of nodes is lower.



a) b) c) d)

Figure 1. Different CT specimens used, a) normal 2D and 3D specimen, b) 2D specimen containing a longitudinal weld, c) 3D specimen containing a longitudinal weld, d) 3D specimen containing a transversal weld.

Table 1. Element types and mesh densities used on FEM simulations.

Specimen	Element Type	Nodes	Average element size [mm]
Normal	2D Quadratic 8 nodes	14520	1.0
Longitudinal Weld	2D Quadratic 8 nodes	21300	.75
Normal	3D Quadratic 20 nodes	68500	2.0
Longitudinal Weld	3D Quadratic 20 nodes	73400	1.5
Transverse Weld	3D Quadratic 20 nodes	78000	1.5
Normal (XFEM)	3D Linear 8 nodes	40000	1.5
Longitudinal Weld (XFEM)	3D Linear 8 nodes	31600	1.5
Transverse Weld (XFEM)	3D Linear 8 nodes	25900	1.5

The FEM models were used to obtain the SIF along the growing crack. When compared with the ASTM-E647 results, one can see on Figure 2, all the models predict a higher SIF. For cracks lengths inferior to 25 mm the difference increases as the crack length decreases. For crack lengths superior to 25 mm the differences remain constant. The 2D model maximum difference was 9% and for cracks lengths superior to 25 mm the difference is negligible. 3D models show higher differences, with the XFEM model resulting in a minimum difference of 4.5%, 1% higher then the contour integral model. These results are in line with the ones obtained by Shi et al. [5].

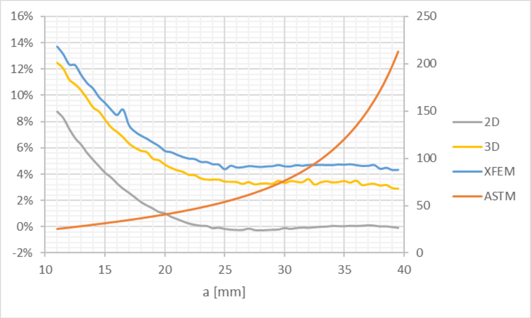
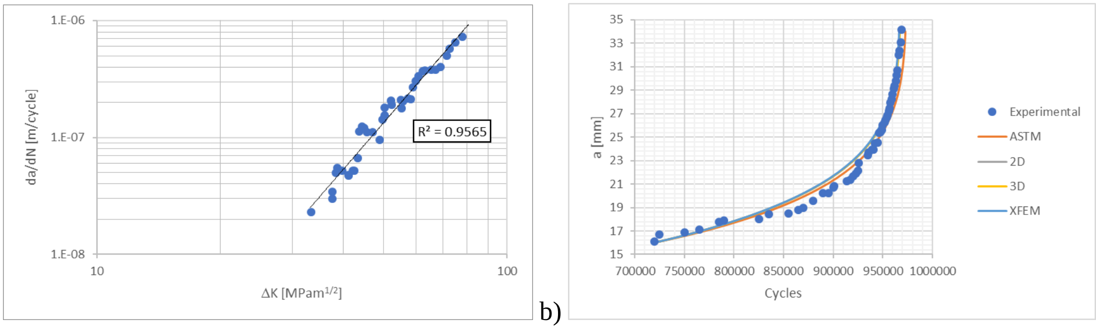


Figure 2. Stress intensity factors vs crack length and obtained differences between ASTM and FEM models.

These differences are important when predicting fatigue life crack propagation. Higher SIF will predict a lower number of elapsed cycles for the same crack increment. To accurately predict crack propagation, using different models the Paris law material constants must be corrected for the appropriate model. Figure 3 a) show the data fit for the material parameters obtained using the ASTM-E647 standard, while Figure 3 b) show the crack propagation simulation using different models and the experimental base results. As one can see there is no difference between the different models, and the results map accurately to the experimental results for crack lengths higher than 25 mm. The Paris Law parameters were corrected for the different models. As the predicted SIF increases, the C parameter decreases, and the m parameter increases. The XFEM model predicted a 4.5% higher SIF, resulting in a 45% lower C parameter and a 2.3% higher m parameter.

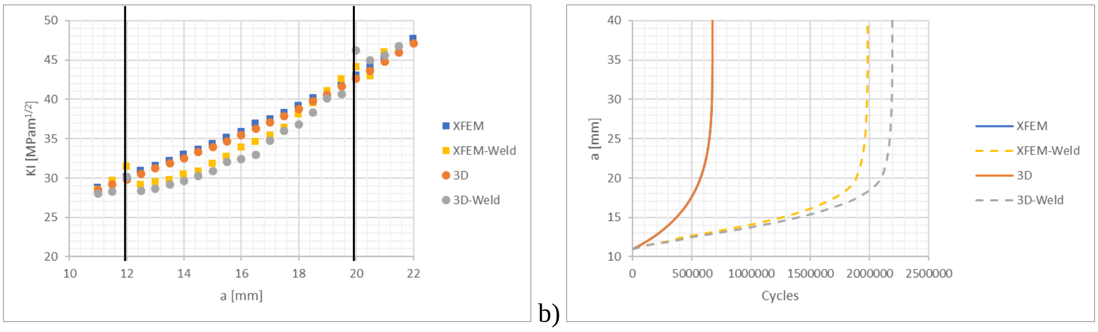


a) b)

Figure 3. Paris Law data fit and crack propagation FEM simulations results.

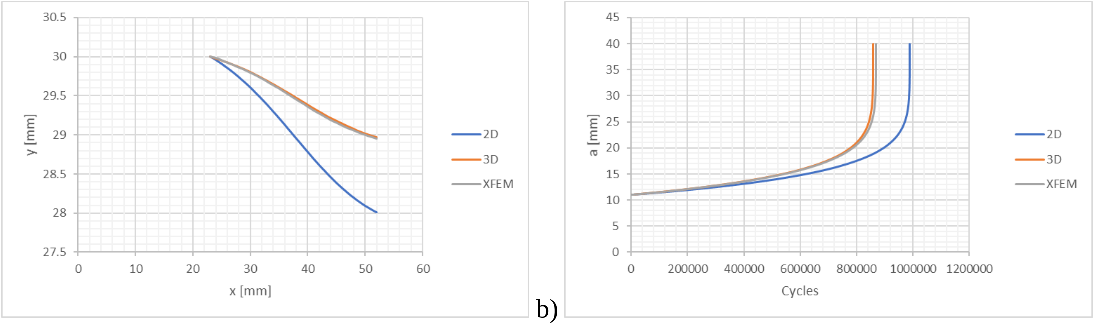
When analyzing the obtained results for the transversal crack, it was possible to use the 3D models to calculate the SIF throughout the welded portion of the specimen. Figure 4 a) show the marked decrease on the SIF from a crack length of 12 mm to 20 mm. These differences are higher for the contour integral model, reaching a maximum of 9.2%, while the XFEM model showed an 8.2% decrease. As the SIF values decrease on the weld zone, the model predicts a higher overall number of fatigue cycles.

Finally, when considering a mixed mode crack propagation example, as the longitudinal weld specimen, Figure 5 a) shows that the model can predict crack deflection. As one can see the 2D model predicts a higher crack deflection, as the SIF for mode II is higher. This is justified by the approximate geometry (Figure 1 b)) generated by this model. The 3D model predicted very close results with the crack deflected by 1 mm for a 40 mm length crack, while the 2D models predicted a 2 mm deflection for the same crack length. The different modeled geometry is also responsible for the different predicted fatigue life, Figure 5 b), as the SIF for mode I are lower on the 2D model.



a) b)

Figure 4. Stress intensity factors and crack propagation curve differences between 3D specimen and transversal weld specimen.



a) b)

Figure 5. Crack propagation curves and crack paths, for crack propagation on a CT specimen with a longitudinal weld.

CONCLUSIONS

- The algorithm accurately predicts crack propagation on the normal CT specimen, and different models can be used to determine the Paris Law material parameters.
- 3D models can be used on more complex geometries, as the transversal welded specimen, and the fatigue life is influenced by the SIF evolution.
- The algorithm can be used to predict mixed mode crack propagation, on the longitudinal welded specimens.

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