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Procedia Structural Integrity 28 (2020) 1827–1832

Structural Integrity Procedia

www.elsevier.com/locate/procedia

1st Virtual European Conference on Fracture

# FEM simulation of welded joint geometry influence on fatigue crack growth resistance

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**Abstract**

Fatigue behaviour of welded joints is investigated, in terms of welded joint geometry and the fatigue crack position. It is based on previous work which involved numerical simulation of fatigue crack growth in a welded joint made of micro-alloyed, low-carbon pressure vessel steel P460NL1, with the main focus on fatigue crack growth rate through different welded joint regions. The goal here was to change the size of the heat affected zone, as the region in which the fatigue crack initiated, and to compare the results obtained for new crack length values with the original ones, obtained by creating numerical models based on experimental data. A number of models were created, some of which simulated the case with a bigger heat affected zone (and, consequently, a smaller crack length in the weld metal), and other which simulated the case with a smaller heat affected zone. Due to the micro-structural differences between these two welded joint regions, noticeable differences appeared in the numbers of cycles obtained for each zone with varying fatigue crack lengths, as well as in the total number of cycles for both zones through which the crack propagated.



*Keywords:*Finite element method, welded joint regions, fatigue crack growth rate, Paris law

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10.1016/j.prostr.2020.11.005

## 1. Introduction

Due to the heterogeneous nature of welded joints, which always consist of a number of regions with different micro-structures and resulting mechanical properties, extensive research on how these differences affect the growth of a fatigue crack located in the heat affected zone were performed [1,2].

Results obtained by these experiments were then used for the purpose of developing numerical models, which would also take into account the heterogeneity of welded joints. After it was shown that the slope of the stable part crack growth rate vs. SIF threshold curve changes when the fatigue crack transitions from one region to another, the following question was asked: What would happen if the size of these regions was different, and the crack length through the HAZ was longer/shorter? It was expected that the fatigue life of the specimen would increase if the crack took longer to reach the weld metal region (since it had noticeably lower resistance to fatigue crack growth), but another goal was to determine to what extent these changes in geometry would affect the number of cycles, i.e. how much they could increase/decrease the fatigue life. Numerical simulations, performed in ANSYS R19.2, were confirmed as a simple and effective way of getting the results, without the need to repeat the experiments, which would involve unnecessary complications with welding of joints with slightly different geometries every time.

## 2. Materials and FEM input parameters

Material properties that were of importance for these simulations were obtained from various experiments, and are given in table 1 below. In addition, Paris law coefficients that were adopted for the simulations are shown in table 2. These coefficients varied significantly between different welded joint regions, which justified the need to determine them experimentally for each specimen [5]. The welded joint itself was made of micro-alloyed low carbon ferritic normalised high strength steel P460NL1, with VAC 65 used as filler material. The motivation behind investigating the fatigue properties of a pressure vessel steel (a rarely encountered scenario in practice) lies in the fact that this material is used in manufacturing of transportation tanks (especially for ammonia [6]), and as such is actually subjected to cyclic loading.

Table 1. Mechanical characteristics of welded joint regions through which the fatigue crack propagated

| Region | Yield stress [MPa] | Tensile strength [MPa] |
|---|---|---|
| Heat affected zone | 568 | 829 |
| Weld metal | 460 | 690 |

Table 2. Paris coefficients C and m for welded joint regions through which the fatigue crack propagated

| Region | C | m |
|---|---|---|
| Heat affected zone | 2.01e-11 | 3.40 |
| Weld metal | 2.87e-08 | 2.05 |

As for the geometry of the models, it was defined according to the dimensions of the standard Charpy test specimen with dimensions of 10x10x55 mm [7]. The notch was located in root side of the heat affected zone, and this was also the location of the fatigue crack, which was defined with an initial length of 0.2 mm. This was done due to ANSYS requirements, since a fatigue crack had to be included in the model (although it was not present in the experimental specimen at the beginning of the pure bending experiment [2], which was used as the base for numerical simulations).

## 3. Finite element method simulation

As was previously mentioned, numerical simulation were performed in ANSYS version R19.2. Finite element method is a commonly used method for simulating a wide variety of problems, in numerous fields including fracture mechanics, biomedicine, aerospace engineering, etc. [8-10], due to its accuracy, effectiveness and repeatability. There are several ways in which fatigue behaviour can be simulated using FEM, and the simplest and fastest one involves the use of Paris law, which requires two coefficients, C and m.

In this case, fatigue crack growth was simulated in the following way:

- two pairs of models were made, one for each zone (with corresponding material properties and Paris coefficients), since fatigue crack growth through regions with different properties is still not possible to simulate.
- In the first model of the HAZ, the crack propagated from 0.2 mm to a length of 1.9 mm, and in the case of its corresponding WM model, it propagated from the length of 1.9 mm to 5 mm (final crack length for all models), thus its total length in the WM was 3.1 mm
- In the second pair of models, HAZ fatigue crack length was 2.45 mm, and the corresponding WM model had a crack length of 2.5 mm.

As can be seen from the above description, in the first case the crack length through the HAZ was less than the example from [1], wherein this length was 2.2 mm. This implies that a smaller heat affected zone was assumed in this case. As a result, the crack length within the weld metal increased, since total crack length was kept at 5 mm. In the second case, fatigue crack length in HAZ was greater compared to the literature (heat affected zone was assumed to be larger), and consequently the WM crack length was shorter (compared to its original value of 2.8 mm).

The geometry used for all four models can be seen in figure 1 (including the mesh), and the boundary conditions and loads are shown in figure 2. One end of the Charpy specimen was fixed, and the opposite end was subjected to a bending moment which corresponded to the moment produced by the device used for the pure bending experiment. The value of this bending moment load gradually decreased, to better simulate the real test conditions, wherein the load also decreased, in order to account for the reduction of the load-bearing cross-section, due to fatigue crack growth. As can be seen in figure 1, the mesh uses finer elements around the crack tip, in order to improve the accuracy and achieve the appropriate convergence (which took several iterations with slightly different element sizes).

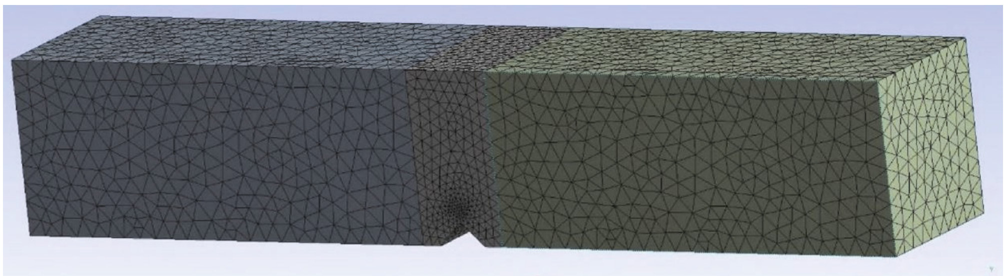

Figure 1. Specimen model geometry and the finite element mesh.

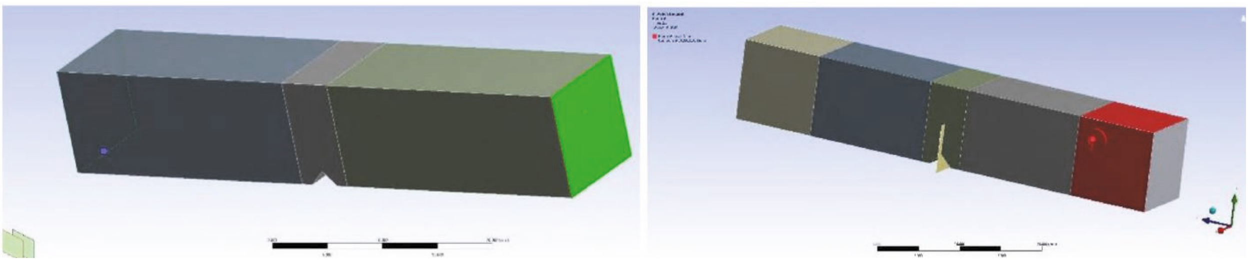

Figure 2. Boundary conditions – fixed support (left) and loads – bending moment (right) used in the models

## 4. Results and discussion

This section of the paper contains the obtained results for all models, in terms of the number of cycles. It should be noted that in the case of heat affected zone specimens, the total number of cycles was obtained by taking the number from the simulation, and combining it with the number of cycles that the specimens had shown for a crack length of 0.2 mm, since this was the necessary minimum fatigue crack length for the simulation and the experimental specimens did not have a crack to begin with (it initiated during the loading). Thus, a number of cycles equal to 136 000 was added to obtain a more realistic result, and account for the “missing” part of the fatigue crack growth (from zero to 0.2 mm). There was no need to do this for weld metal specimens, since their initial crack length corresponded to the length achieved by the crack during its propagation through the previous zone (3.1 and 2.5 mm for two WM models).

Figure 3 shows the crack length vs. number of cycles (a-N) curves for the first pair of models – HAZ fatigue crack length of 1.9 mm, and the corresponding WM crack length of 3.1 mm. Figure 4 shows the second pair, with a longer HAZ crack (due to assumed increased HAZ size) of 2.45 mm, and a shorter WM crack, with the length of 2.5 mm. It should be noted that the crack length was controlled by defining the number of substeps in the second load step, since larger number of substeps means longer cracks. Due to this, it was not possible to achieve perfectly accurate lengths of fatigue cracks for all models.

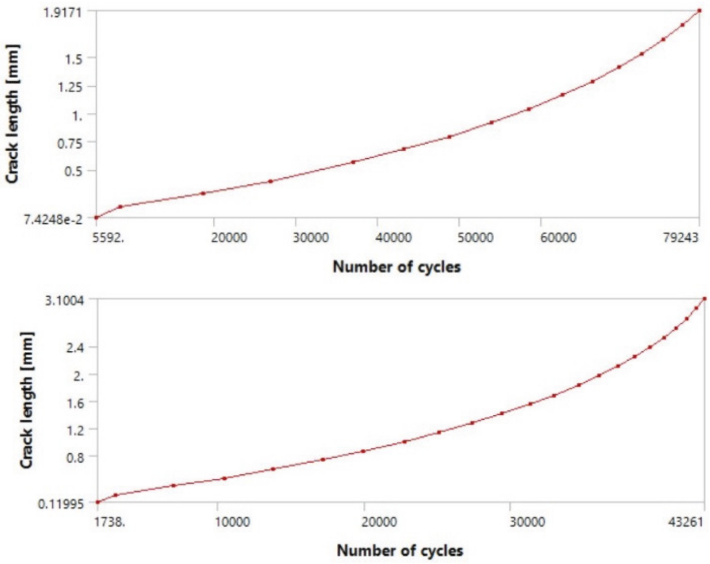


Figure 3. Numerically obtained a-N curves the models with 1.9 mm HAZ crack (upper) and 3.1 mm WM model (lower) crack

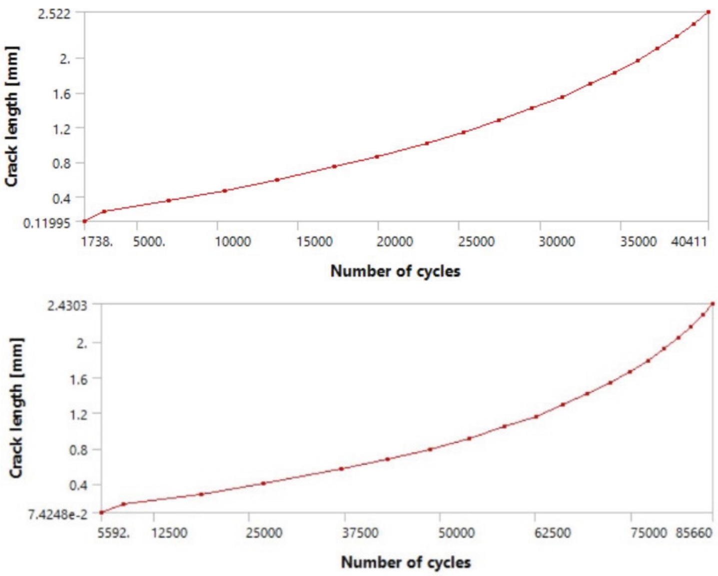


Figure 4. Numerically obtained a-N curves the models with 2.45 mm HAZ crack (upper) and 2.5 mm WM model (lower) crack

Once the results were obtained (after determining the appropriate number of substeps for each models), the next stage involved the comparison of the total numbers of cycles for both pairs with the original values (2.2 mm HAZ + 2.8 mm WM). As expected, models with increased crack length (3.1 mm WM and 2.43 HAZ models) had a slight increase in the number of cycles, and at the same time, the other two had slightly lower value. The goal was to see how these changes affected the overall fatigue life, and if any significant differences were made, since there was a realistic possibility that the increase in the number of cycles in one region would compensate the decrease in the other, and vice-versa. Table 3 shows the comparison of total number of cycles for the referent model [1] and the two pairs analysed as part of this research.

Table 3. Comparison between the models with varied crack length and the original model [1]

| Model | Number of cycles, HAZ | Number of cycles, WM | Total number of cycles |
|---|---|---|---|
| Specimen 5 (HAZ 5 and WM 5) | 218 800 | 42 000 | 260 800 |
| First pair (shorter HAZ + longer WM) | 214 500 | 43 200 | 257 700 |
| Second pair (longer HAZ + shorter WM) | 224 100 | 40 000 | 264 100 |

It should be noted that, due to the slight differences in the fatigue crack lengths achieved in the models, compared to the desired values (e.g. numerically obtained 2.43 mm vs. assumed 2.45 mm), the values were extrapolated. Since the differences in expected and obtained crack lengths were very small, it was assumed that the actual value of cycles could be obtained by a simple linear extrapolation (by multiplying the number of cycles with the ratio of obtained crack length and the assumed one.

As expected, the case where the fatigue crack "spent more time" in the heat affected zone (the micro-structurally favourable welded joint region compared to the weld metal), had shown slightly better fatigue resistance, i.e. the total number of cycles increased by a small amount – 1.012%. In the case where the heat affected zone fatigue crack length was smaller than the original one, the number of cycles was 1% lower. While these differences do not seem particularly significant, they are still expressed in thousands of cycles.

The results for fatigue life of the two pairs of numerical models provided the expected results, in terms of longer heat affected zone crack length resulting in better behaviour during fatigue crack growth. Since the heat affected zone size differences that were assumed were small, there was no significant change in the number of cycles. The specimen itself had a width of 10 mm, and the fatigue crack length was constrained by the used measuring foils (5 mm), which did not leave a lot of room for welded joint region size variation. For welded joints in thicker plates, bigger differences in HAZ size could be introduced, providing more noticeable differences in fatigue life.

## 5. Conclusions

The goal of this research was to determine how changes in welded joint geometry, in terms of heat affected zone size, would affect its resistance to fatigue crack growth, assuming that this crack initiated in the HAZ, and propagated into the weld metal. Two cases were considered, one where the HAZ was smaller and the crack length through it was shorter, and the other where HAZ was larger, resulting in longer fatigue crack length in it. The numerical models with these crack length were paired with the models simulating crack growth through the WM. Obtained results were then compared with the model from previous work, based on experimentally obtained data.

A certain difference in the number of cycles in both zones was observed, leading to a total number of cycles (combination of number of cycles for each HAZ and WM model) slightly different from the original value (for the model based on pure bending experiment). Increased crack length in the HAZ provided better results, since the HAZ had shown higher fatigue resistance to begin with.

The main advantage of the approach shown in this paper is the possibility of adjusting the geometry of the welded joint with ease, in a numerical model, and completing as many different calculations as possible in relatively short time, without the need to make any significant adjustments to the initial model. Since all of the models are based on the experimentally verified one, there is no need to perform additional experiment, which would be rather complicated to achieve, since it would require welding of several plates with varying parameters, in order to obtain different dimensions of the HAZ.

This method can be applied to different welded joint thickness values, as well as to different groove shapes (V, X, K grooves…), since their geometry also affects the fatigue crack length in the case where the crack propagates through different regions. Another possibility is to consider a case where the fatigue crack is initiated on the opposite side of the weld, which would result in its propagation into the parent material. This would lead to a different situation, since the parent material has better fatigue crack growth resistance, hence a smaller HAZ (shorter crack length in it) would be more favourable in such a case.

## 6. Acknowledgements

The authors of this paper acknowledge the support from Serbian Ministry of Education, Science and Technological Development for the TR 35040 project.

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