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Fatigue life prediction of casing welded pipes by using the extended finite element method

Ljubica Lazić Vulićević, Aleksandar Rajić
High Technical School of Professional Studies, Đorđa Stratimirovića 39, Zrenjanin, Serbia

Aleksandar Grbović
Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade, Serbia

Aleksandar Sedmak
Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade, Serbia
asedmak@mas.bg.ac.rs

Živče Šarkočević
High Technical School of Professional Studies, Zvecan, Serbia

ABSTRACT. The extended finite element (XFEM) method has been used to simulate fatigue crack growth in casing pipe, made of API J55 steel by high-frequency welding, in order estimate its structural integrity and life. Based on the critical value of stress intensity factor K_{Ic}, measured in different regions of welded joint, the crack was located in the base metal as the region with the lowest resistance to crack initiation and propagation. The XFEM was first applied to the 3 point bending specimens to verify numerical results with the experimental ones. After successful verification, the XFEM was used to simulate fatigue crack growth, position axially in the pipe, and estimate its remaining life.

KEYWORDS. XFEM; Seam casing pipes; Axial surface crack; Fatigue crack growth; Remaining life.

INTRODUCTION

In order to keep pipeline safe and reliable in operation, its fatigue life estimation is of utmost importance, [1]. Toward this aim, extensive experimental and numerical investigation is needed. In this paper the extended finite element method (XFEM) has been used for modeling and analysis of crack propagation in a seam casing pipe made of API J55 steel by high-frequency (HF) contact welding, but only after its verification, based on the comparison of the xFEM results with experimental results obtained on the standard three-point bending specimen.

RESISTANCE TO CRACK GROWTH OF API J55

Modified CT specimens with thickness d = 6.98 mm (equal to the pipe wall thickness) have been used to evaluate critical values of fracture mechanics parameters (J_{Ic}, K_{Ic}), and the critical crack length, a_c, as shown in more details in [2] for new and exploited pipes. Here only results obtained for exploited pipe are shown in Tab. 1.

Specimen	Temperature [°C]	J_{Ic} [kN/m]	K_{Ic} [MPa√m]	a_c [mm]
BM-NR-E		35.8	91.4	14.4
HAZ-NW-E	20	48.5	106.4	19.6
WM-NW-E		45.7	103.3	18.5

Table 1: The values of J_{Ic} K_{Ic} and a_c - pipe taken from service.

Based on the obtained values of K_{Ic} for the base metal (BM), heat-affected-zone (HAZ) and weld metal (WM), one can conclude that the BM has the lowest resistance to crack initiation and propagation.

VERIFICATION OF THE METHOD USING EXPERIMENTAL RESULTS OBTAINED ON STANDARD SPECIMEN

The XFEM is relatively new method of numerical simulation and it has to be verified by experimental results, [3]. For this purpose the results from experimental testing and from numerical simulation using XFEM, both carried out on the standard Charpy specimen, were compared. The specimen is made of API J55 steel, the same steel as the pipe is made of.

The three-point-bending test was conducted on standard Charpy specimen made from BM, since it has the lowest resistance to crack initiation and propagation. The test was conducted on high-frequency pulsator RUMUL-CRACKTRONIC at the room temperature providing relation between the crack length, a, and the number of cycles N.

A finite element model of the Charpy specimen was created using the Abaqus software. Mesh was refined around the initial crack, as shown in Fig. 1.

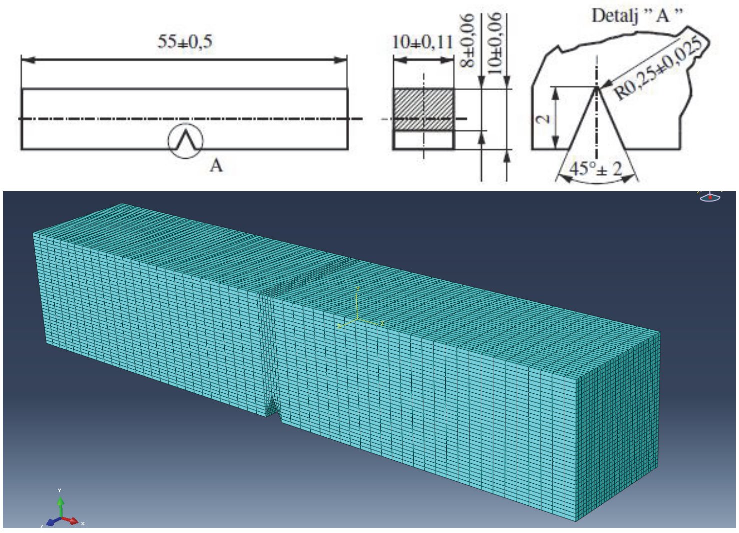

Figure 1: Standard Charpy specimen: dimensions of the specimen and 3D model obtained using Abaqus software.

The crack growth to its critical size was simulated by using Paris equation:

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C_p (\Delta K)^{m_p} = C_p \left(1.12 \cdot \Delta\sigma \cdot \sqrt{\pi \cdot a}\right)^{m_p}$$

where da/dN [m/cycles] is the fatigue crack growth, ΔK [MPa√m] the stress intensity factor range, C_p and m_p material parameters, which have the following value in this paper: $C_p = 2.11 \cdot 10^{-15}$, exponent $m_p = 6.166$, [2].

The initial crack length used in the analysis was 2 mm. The growing crack was incremented at steps of 0.16 mm (chosen by the software) and 28 steps were performed. The first step in 3D analysis using XFEM was crack "opening" (Fig. 2). In this step stresses in the specimen are obtained, as well as stress intensity factors (SIFs) at the crack tip. Based on that, Morfeo/Crack for Abaqus, computes the SIFs for mode I, II and III, for every step of the crack propagation, and the corresponding crack growth. Fig. 2 shows crack at beginning (1st step- crack opening), Fig. 3, after 8th step, while Fig. 4 shows the crack after the 27th step.

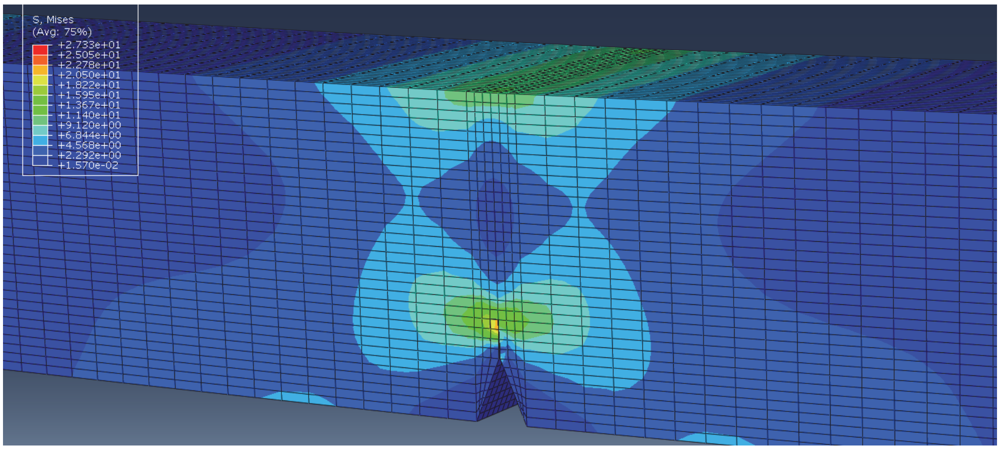

Figure 2: Step one - crack opening and Von Mises stresses at crack tip.

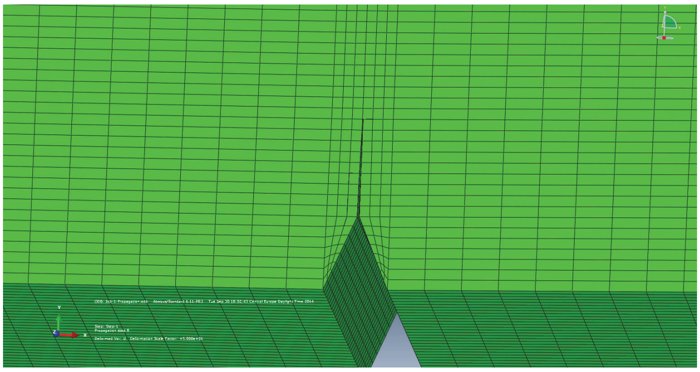

Figure 3: Crack length after 8th step.

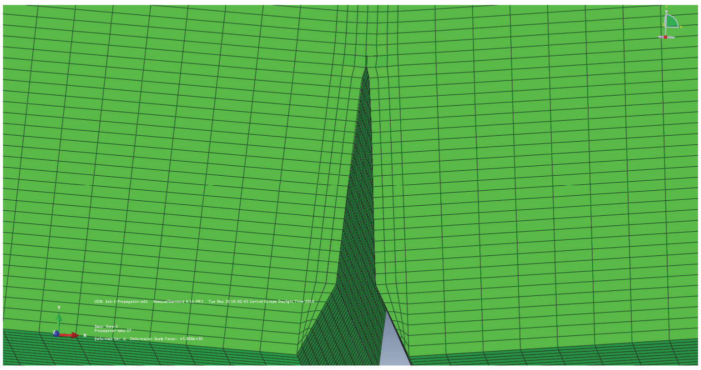

Figure 4: Crack length after 27th step.

The SIF values at the crack tip determine the appropriate crack growth increment. This procedure was performed in 28 steps in order to simulate incremental crack growth. Values obtained in Abaqus for the 16th crack growth step are shown in Tab. 1, indicating SIF values K_{eq}, K_I, K_{II}, and K_{III}) in the last four columns. As expected, crack growth was characterized by K_I, since values of K_{II} and K_{III} are negligible. Therefore, data for all crack growth steps is given only for

K_I, Tab. 2, including its average, minimum and maximum values along the crack front. Tab. 2 also shows number of point in each crack growth step, being between 66 and 68.

Curvilinear abscissa along the crack front [mm]	*x* front coordinate [mm]	*y* front coordinate [mm]	*z* front coordinate [mm]	K_{eq} [MPa√m]	K_I [MPa√m]	K_{II} [MPa√m]	K_{III} [MPa√m]
0.000	0.033	0.781	0.035	67.4	67.3	-0.1	0.8
0.151	0.031	0.791	0.187	67.4	67.3	-0.1	0.7
0.293	0.028	0.801	0.328	67.4	67.4	-0.1	0.7
0.445	0.025	0.815	0.479	67.5	67.4	-0.1	0.6
0.585	0.023	0.828	0.618	67.5	67.4	-0.1	0.5
0.716	0.021	0.841	0.749	67.5	67.4	-0.2	0.5
0.855	0.018	0.853	0.887	67.5	67.4	-0.2	0.4

Table 2: Values for K_{eq}, K_I, K_{II}, and K_{III} in the 16th crack growth step.

			SIF for mod I, K_I [MPa√m]		
step	Crack length *a* [mm]	Number of points of the crack front	max	min	average value
1	2.00	66	28.09	26.34	27.60
2	2.15	68	29.63	27.93	29.08
3	2.31	66	30.97	29.50	30.60
4	2.47	68	32.44	31.46	32.16
5	2.65	68	34.34	33.81	34.04
6	2.84	66	36.42	35.82	36.22
7	3.03	68	37.84	37.39	37.68
8	3.22	68	40.22	39.77	39.99
9	3.42	66	42.97	42.62	42.82
10	3.61	68	44.93	44.58	44.83
11	3.80	68	47.99	47.49	47.75
12	3.96	66	51.62	51.19	51.46
13	4.19	68	54.40	54.15	54.30
14	4.39	68	58.43	57.91	58.17
15	4.58	66	63.43	63.07	63.25
16	4.78	68	67.45	67.19	67.33
17	4.98	68	73.02	72.59	72.80
18	5.18	66	80.30	79.84	80.10
19	5.38	68	86.26	85.91	86.11
20	5.58	68	94.77	94.09	94.40
21	5.78	66	106.00	105.16	105.58
22	5.98	68	115.78	115.07	115.48
23	6.18	66	129.66	128.21	128.72
24	6.37	66	148.40	146.73	147.56
25	6.58	68	165.09	164.01	164.37
26	6.78	68	190.23	187.30	188.21
27	6.98	66	225.71	222.78	223.74
28	7.18	68	261.11	257.68	258.90

Table 3: Values for K_I for all steps (28) growth.

Chart in Fig. 5 shows very similar behavior of experimentally tested specimen and its 3D numerical simulation. Beyond 10^6 cycles very small number of cycles to collapse is left, and in this area two curves are exactly the same. Generally speaking, one can say that experimental and numerical results agree well, with some differences which require further investigation.

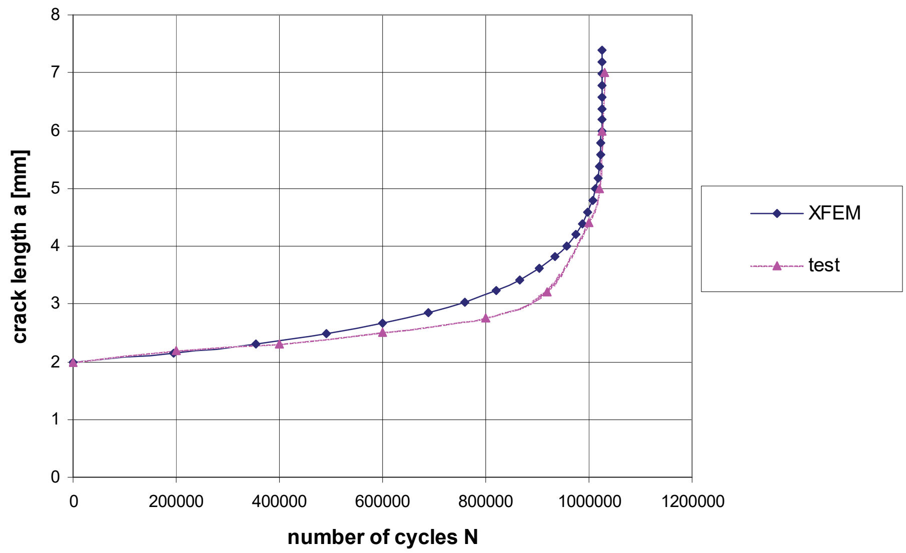

Figure 5: Comparing curves from experiment and 3D simulation.

FATIGUE LIFE PREDICTIONS OF PIPES WITH AXIAL SURFACE CRACK

The main technical characteristics of the oil rigs from where the observed pipe are as follows, [4]:

- layer pressure (Kp-31): maximum=10.01 [MPa], minimum=7.89 [MPa],
- layer temperature: T=65 [°C],
- number of strokes of pump rod: n_{PR}=9.6 [min^{-1}].

The geometry used in simulations is pipe with axial surface crack in the base metal (BM), Fig. 6. The pipe is made of API J55. On the outer surface of the pipe there is an initial axial surface crack with dimensions: a=3.5 mm and 2c=200 mm. The wall thickness is 6.98 mm.

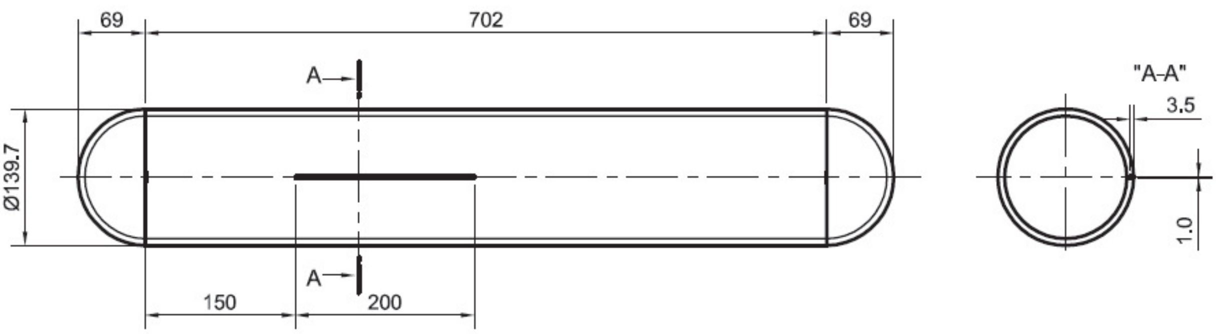

Figure 6: Geometry of pipe.

A finite element model of the pipe was created using the Abaqus software. The initial crack length used in the analysis was 200 mm, and it was 3.5 mm deep (the wall thickness is 6.98 mm). Mesh was refined around the initial crack, and a uniform template of elements was used. The growing crack was incremented at steps of 0.2 mm. The first step was crack opening, and after that, the crack was growing through the inner side of wall, in radial and axial direction, while, in 7th step, it becomes through-wall crack. Fig. 7 shows the crack growth at beginning (1st step - crack opening), whereas Fig. 8 shows crack growth after 7th step when the crack "breaks" through the wall. Afterwards, crack grows in axial direction only through inner side of the wall, and "outer" initial crack remains the same as it was in the beginning of simulation, until 64th step, when "inner" and "outer" crack become equal, 200 mm long, and it has become complete through-wall crack, Fig. 9. Further crack growth is in axial direction until the final step of 3D simulation, when the crack is 209.42 mm long. Fig. 10 shows 3D chart of "inner" and "outer" crack growing.

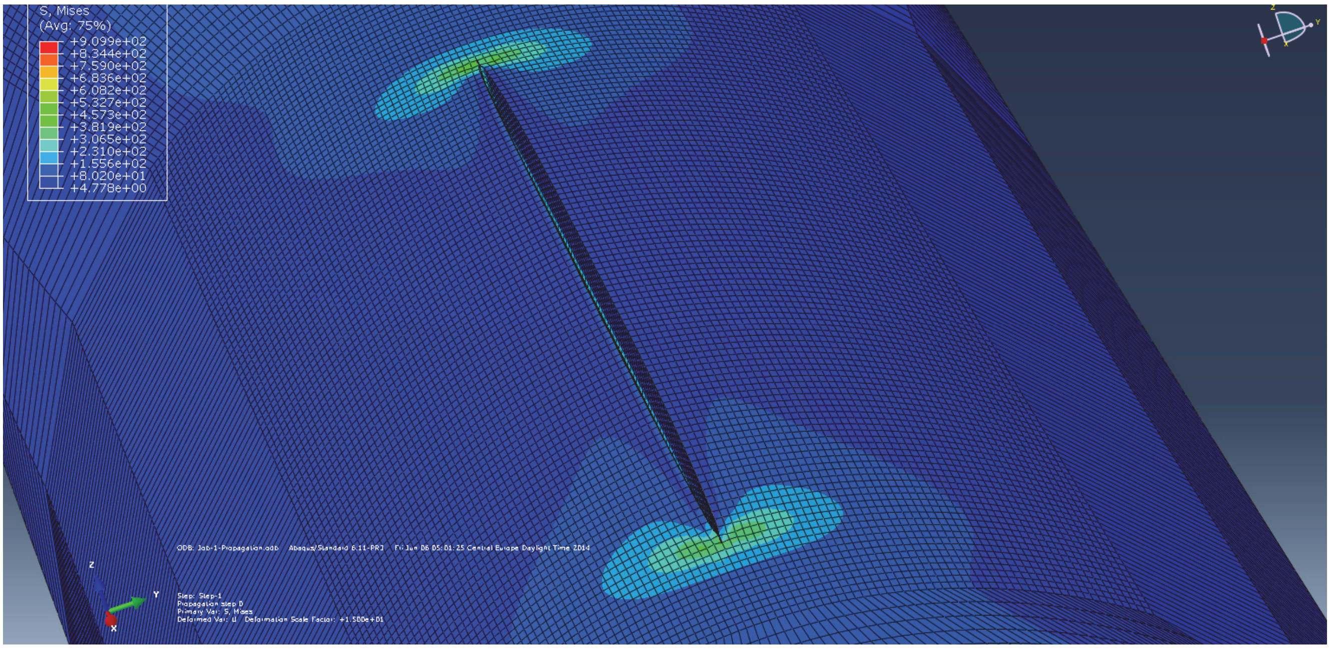

Figure 7: Step 1 - crack opening and Von Mises stresses at crack tips.

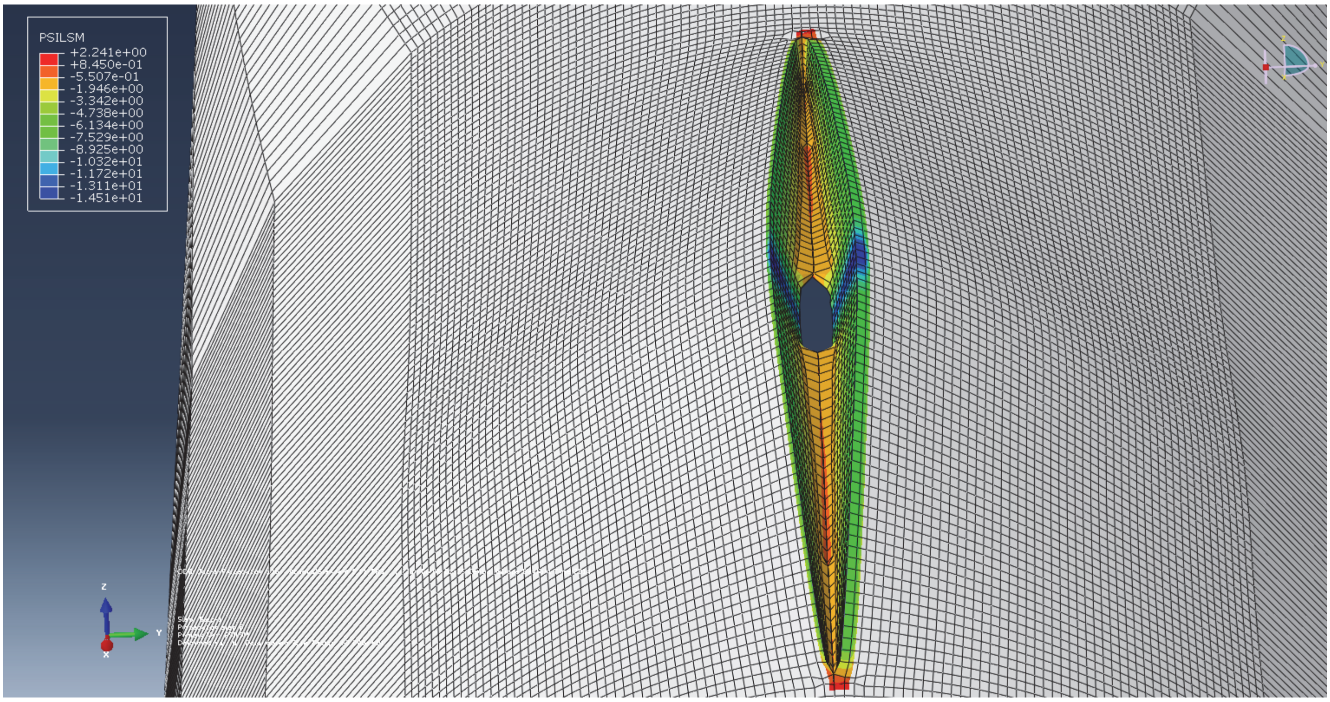

Figure 8: The 7th step – crack became through-wall and stresses around the crack.

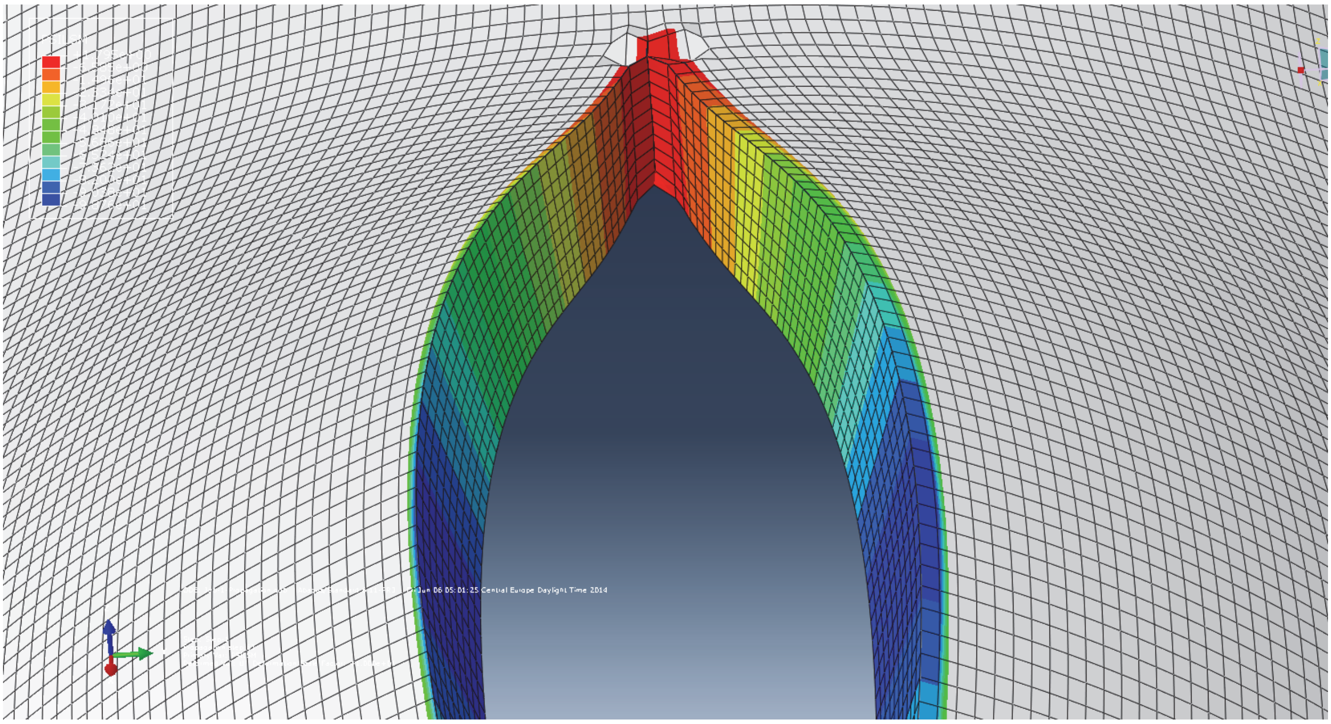

Figure 9: Step 64 when "inner" and "outer" crack going to be equal (crack length is 200 mm) and stresses around the crack.

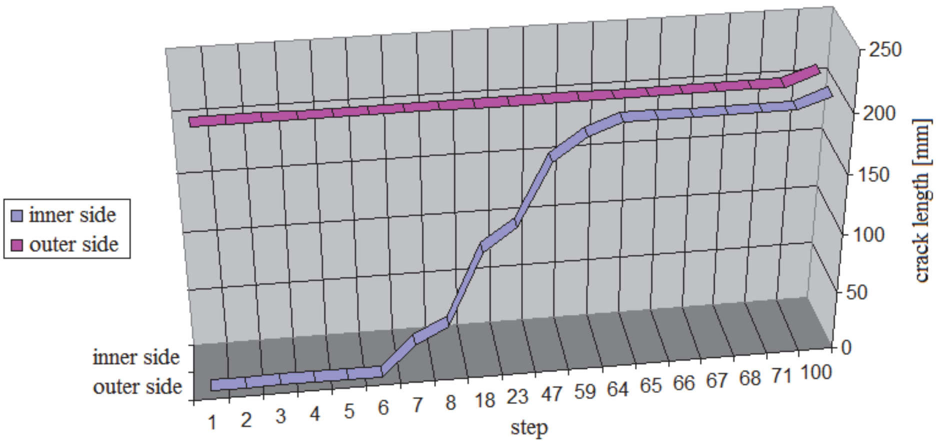

Figure 10: The 3D chart of "inner" and "outer" crack growing.

The prediction of crack growth rate and residual strength of pipe demands accurate calculation of stress intensity factors (SIFs), which determine the appropriate crack growth increment for the crack. This calculation was performed 100 times in order to simulate incremental crack growth. The obtained relationship between equivalent stress intensity factor K_{eq} and crack length a, Fig. 11, shows tendency of increasing K_{eq} with increased crack length a, while the crack was reached up to 210 mm. The fastest increase of K_{eq}, as expected, was before the seventh step, when crack penetrated the pipe wall.

The chart in Fig. 12 shows the obtained relationship between steps and number of cycles. After the 7th step, when the crack penetrates the pipe wall, the number of cycles becomes significantly lower and remains at about the same values until the final step.

The chart in the Fig. 13 shows the obtained relationship between the crack length a [mm] and the total number of cycles N. For crack growth from initial crack length until final length of 209.42 mm, 10548 cycles are necessary. Obviously, the most of them occur until the seventh step, in which the crack becomes through-wall crack (8606 cycles), while the further cracks growth requires a very small number of cycles.

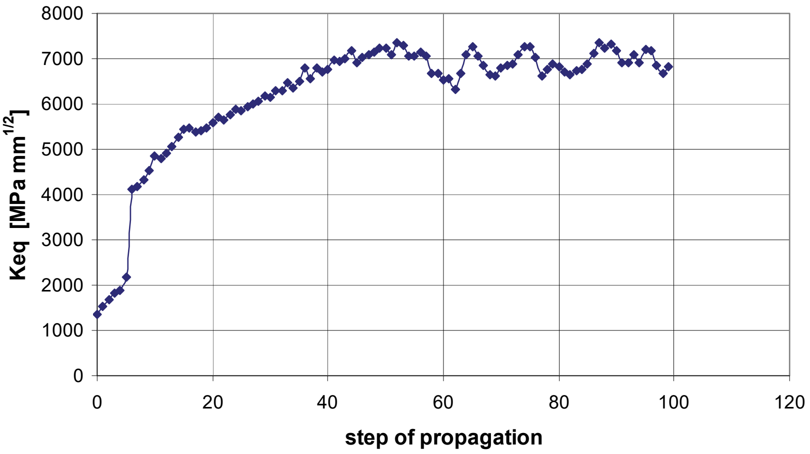

Figure 11: Relationship between equivalent stress intensity factor K_{eq} and propagation step.

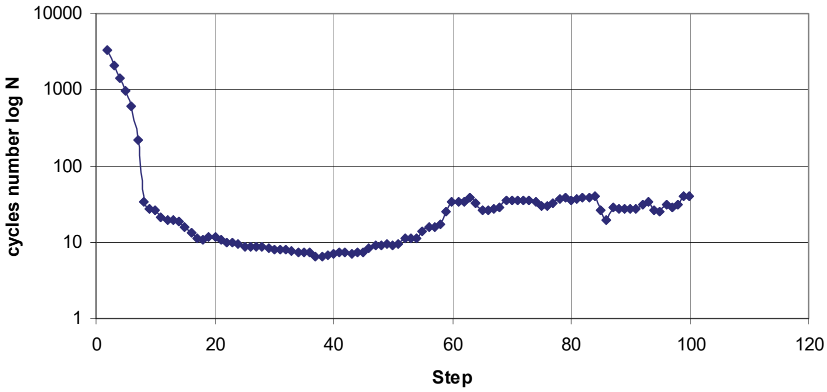

Figure 12: Obtained relationship between steps and number of cycles.

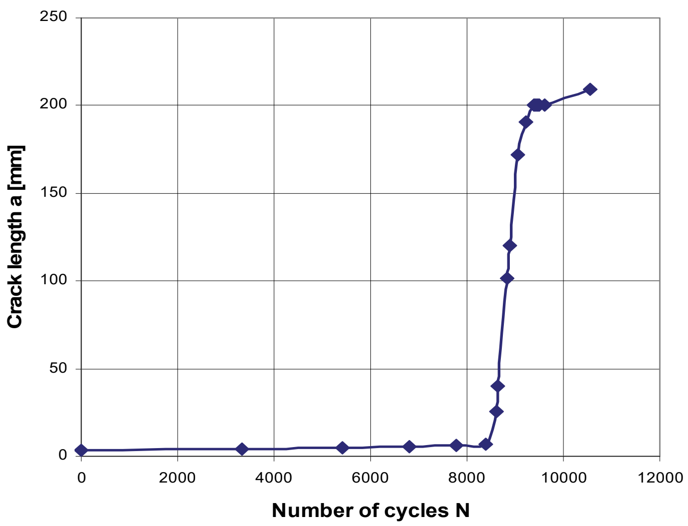

Figure 13: Relationship between crack length a and number of cycles N using 3D simulation.

Conclusion

Based on the presented results, one can conclude that experimental and numerical results agree well, with some differences which require further investigation. Therefore, the obtained stress intensity factor histories can be used to predict fatigue crack growth rates.

Based on the obtained values for K_{Ic} for the BM, HAZ and WM, one can conclude that the BM has the lowest resistance to crack initiation and propagation. The fatigue crack simulation for a surface crack in BM, with depth approximately half of the thickness (3.5 vs. 6.98 mm), and initial length 200 mm, indicated 8606 cycles needed for crack to grow through the whole thickness, and 10548 cycles to grow up to the final length of 209.42 mm, i.e. relatively fast growth once it became through-wall crack.

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