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THE EXTENDED FINITE ELEMENT METHOD IN FATIGUE LIFE PREDICTIONS OF OIL WELL WELDED PIPES MADE OF API J55 STEEL

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Abstract: *This paper presents an application of the extended finite element method (XFEM) in the modeling and analysis of simultaneous cracks propagations in a seam casing pipe made of API J55 steel by high-frequency (HF) contact welding. The geometry used in simulations is pipe with axial crack subjected toconstant amplitude cyclic loads. Short theoretical background information is provided on the XFEM, as well as the demonstration of the method used for verification of computed stress intensity factors (SIFs). The obtained numerical results prove the efficiency of XFEM in the simulation of the axial cracks propagations in tube geometry. Some guidelines for improving the XFEM use in fatigue life predictions are also given.*

Keywords: *XFEM, seam casing pipes, axial surface crack, fatigue crack growth, fatigue life prediction*

INTRODUCTION

Pipelines are the most economical and safest way for oil and gas transport. However, majority of failures of welded steel pipelines occur due to insufficient resistance to crack initiation and growth, poor quality of welded joints and reduced capacity due to corrosion damage. Low-alloy steels are nowadays widely used for pipelines due to optimal combination of mechanical properties and weld ability, but their application for oil and gas pipelines is still related to failures.

The reliability of the oil rigs system is very important for the continued exploitation and for environmental protection as well. Therefore, the standards and recommendations for assessing the effects of cracks on the integrity of welded pipes were developed. However, welded casing pipes can also have an axial surface crack on the inner and/or outer surface, and be subjected to different loads, including external and internal pressure and axial loads (e.g. due to structure weight).

In order to keep pipeline safe and reliable in operation, its fatigue life is of utmost importance. The essential part in fatigue life prediction is to estimate precisely the maximum allowed pressure, as well as to evaluate fracture mechanics parameters, like stress intensity factor and J integral. So far, there are no detailed 3D finite element analyses of wide spectrum of outer surface cracks.

This paper presents an application of the extended finite element method (XFEM) in the modeling and analysis of simultaneous cracks propagations in a seam casing pipe made of API J55 steel by high-frequency (HF) contact welding.

The geometry used in simulations is pipe with axial crack subjected toconstant amplitude cyclic load.

Crack growth under cyclic loading

Crack growth under cyclic loading of machine parts and construction has a crucial influence on their lifetime. Therefore, of practical importance is to determine the relationship between the present stress state at the crack tip, which is at variable load determined by the stress intensity factor range ΔK, and the crack growth rate da/dN. The crack growth to its critical size primarily depends on external loads and crack growth rate. Paris equation for metals and alloys, establishes the relationship between fatigue crack growth da/dN and stress intensity factor range ΔK, using the coefficient C_p and the exponent m_p:

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C_p\left(\Delta K\right)^{m_p} = C_p\left(1{,}12\cdot\Delta\sigma\cdot\sqrt{\pi\cdot a}\right)^{m_p}$$

Resistance to crack growth of API J55

Pressured welded pipes can be very sensitive to cracks and their stable or unstable growth. Therefore, it is important to identify reliable criteria for assessing the remaining lifetime of pressured pipes with cracks in base material and weld. In order to understand better the crack initiation and crack growth in casing pipes exposed to high pressures, high temperatures and chemically aggressive work environment in oil rigs, the material behavior control parameters at the crack tip and the fracture resistance should be expressed quantitatively.

Tests of the modified CT specimens were carried out at room temperature on a machine SCHENCK-TREBEL RM 100. Modified CT specimen thickness is $d = 6.98$ mm (equal to the pipe wall thickness) [12]. Indirectly, through the critical J values J_{Ic}, the critical values of *stress intensity factor K_{Ic}, are determined, i.e., calculated using the expression (1) and are given in Table 1:*

$$K_{Ic} = \sqrt{\frac{J_{Ic} \cdot E}{1-\nu^2}} \qquad (1)$$

Using the expression:

$$K_{Ic} = 1{,}12 \cdot \sigma_c \cdot \sqrt{\pi \cdot a_c} \qquad (2)$$

and taking into account the values of stress, $\sigma = \sigma_c$, (where σ_c is fracture stress) approximate values of critical crack length (a_c) for base material (BM), heat affected zone (HAZ) and weld metal (WM) were calculated.

Table 1. *The values of K_{Ic} - pipe from service*

Specimen	Temperature [°C]	J_{Ic} [kN/m]	K_{Ic} [MPa m$^{1/2}$]	a_c [mm]
BM-NR-E	20	35.8	91.4	14.4
HAZ-NW-E		48.5	106.4	19.6
WM-NW-E		45.7	103.3	18.5

Based on the obtained values of K_{Ic} for the base metal, HAZ and weld, the basic material (BM) has the lowest resistance to crack initiation and propagation.

XFEM in fatigue life prediction

The extended finite element method was developed to ease difficulties in solving problems with localized features that are not efficiently resolved by mesh refinement. One of the initial applications was the modeling of fractures in a material. A key advantage of XFEM is that in such problems the finite element mesh does not need to be updated to track the crack path. Morfeo/Crack for Abaqus relies on the implementation of the extended finite element (XFEM) method available in Abaqus. Morfeo/Crack for Abaqus is capable of performing crack propagation simulations in complex geometries. It calls Abaqus at each propagation step and between each step, then reads the Abaqus solution, recovers a richer, improved XFEM solution in a small area surrounding the crack and computes the SIFs. SIF values at crack tip determine the appropriate crack growth increment for crack. This procedure was performed 100 times in order to simulate incremental crack growth.

Fatigue life predictions of pipes with axial surface crack

The main technical characteristics of the oil rigs from where the observed pipe is are as follows:

- *Layerpressure (Kp-31): maximum=10.01 [MPa],*
  minimum=7.89 [MPa].
- *layertemperature: 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), Figure 1. 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 initial crack length used in the analysis was 200 mm, and it was 3, 5 mm deep. The growing crack was incremented at steps of 0.2 mm. Figure 2 shows crack at beginning (1st step- crack opening), figure 3, after 7th step of propagation when the crack grows through the wall, while Figure 4 shows the crack at the end of XFEM simulation (step number 100). The final crack length at the end of simulation was 219.8 mm.

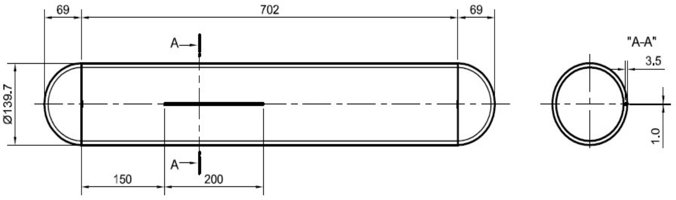

Figure 1. *Pipe (pressured vessel) with an axial surface crack on the outer surface*

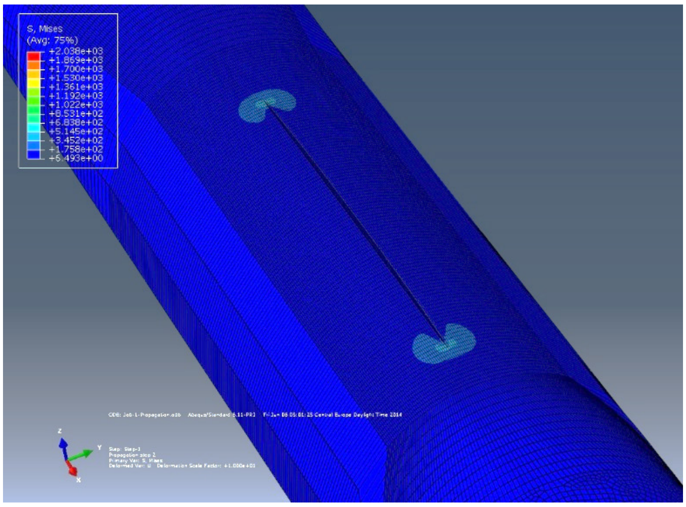

Figure 2. *Step 1 - crack opening andVon Mises stresses at crack tips*

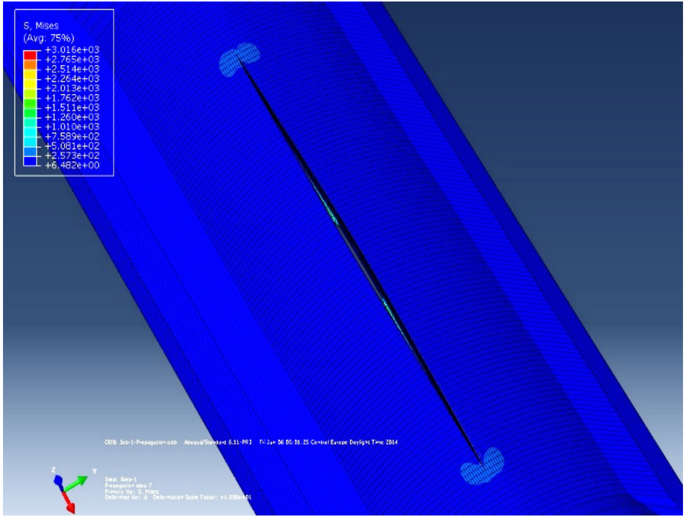

Figure 3. *Von Mises stresses at 7th step – crack became through-wall*

A finite element model of the pipe was created using the Abaqus software. Mesh was refined around the initial crack, and a uniform template of elements was used.

The prediction of crack growth rate and residual strength of pipe demands accurate calculation of stress intensity factors (SIFs). Morfeo/Crack for Abaqus calls Abaqus at each propagation step and between each step, then reads the Abaqus solution, recovers a richer, improved XFEM solution in a small area surrounding the crack and computes the SIFs.

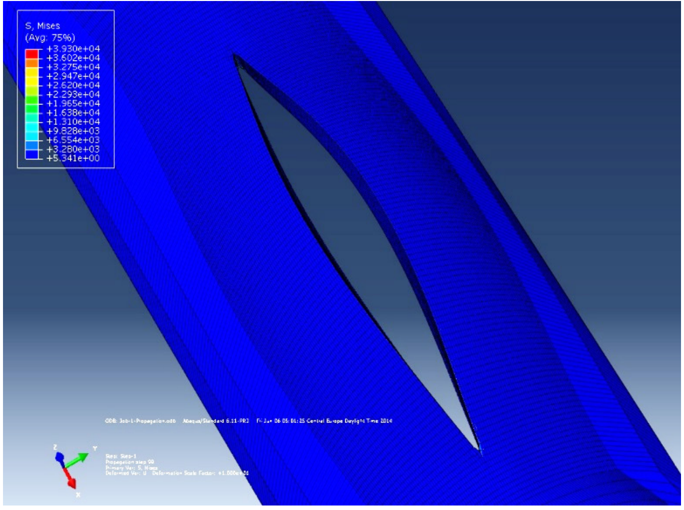

Figure 4. *Final crack length at 100th step (219, 8 mm) and Von Mises stresses*

SIF values at the crack tip determine the appropriate crack growth increment for the crack. This procedure was performed 100 times in order to simulate incremental crack growth. Some of the values obtained in Abaqus for every crack growth step are shown in Table 1. SIF values at the crack tip are shown in the last four columns. Those are equivalent SIF – Keq, and respectively SIFs for modes I, II and III, K_I, K_{II}, and K_{III}. Obviously, value K_I is more influential in crack growth then K_{II}, and K_{III}. Thus, it will be reasonable for further consideration to use stress intensity factor K_I, or even better Keq, in fatigue crack growth prediction rates.

Table 2. *Some of the values obtained in Abaqus for every crack growth step [x (front point coordinate): 50.7745]*

Curvilinear abscissa along the crack front	*y*	*z*	K_{eq}	K_I	K_{II}	K_{III}
0	*8.77E-05*	*69.4784*	*860.175*	*837.413*	*1.55444*	*1.65058*
0.349	*8.72E-05*	*69.1294*	*859.6*	*837.004*	*1.468*	*1.74059*
0.698	*8.68E-05*	*68.7804*	*859.072*	*836.648*	*1.38001*	*1.83133*
1.047	*8.64E-05*	*68.4314*	*858.595*	*836.348*	*1.29048*	*1.92288*
1.396	*8.59E-05*	*68.0824*	*858.175*	*836.113*	*1.19942*	*2.01528*
1.745	*8.55E-05*	*67.7334*	*857.82*	*835.95*	*1.10692*	*2.1085*
2.094	*8.51E-05*	*67.3844*	*857.54*	*835.868*	*1.01306*	*2.20247*

The obtained relationship between equivalent stress intensity factor K_{ekv} and crack length a, Figure 5, shows tendency of increasing K_{ekv} with increased crack length a, while the crack was reached up to 210 mm. The largest increase in value K_{ekv} , as expected, was before the seventh step, when crack penetrates the pipe wall. In working conditions leaking starts here and the pipe is already failed. However, the pipe is still in use for simulation.

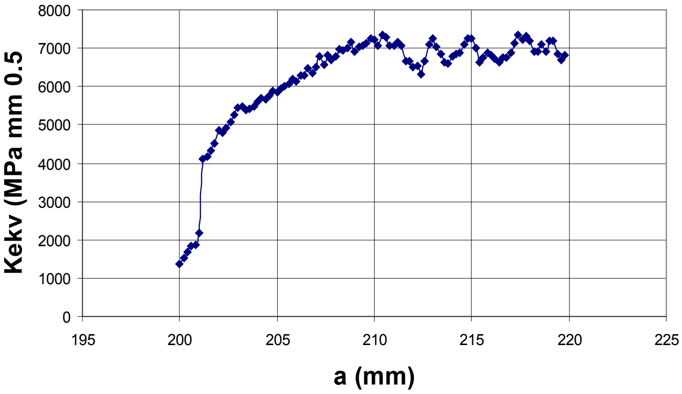

Figure 5. *Obtained relationship between equivalent stress intensity factor K_{ekv} and crack length a*

The chart in Figure 6 shows the obtained relationship between steps and cycles number logN.

After the seventh 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, when the crack length is 219.8 mm.

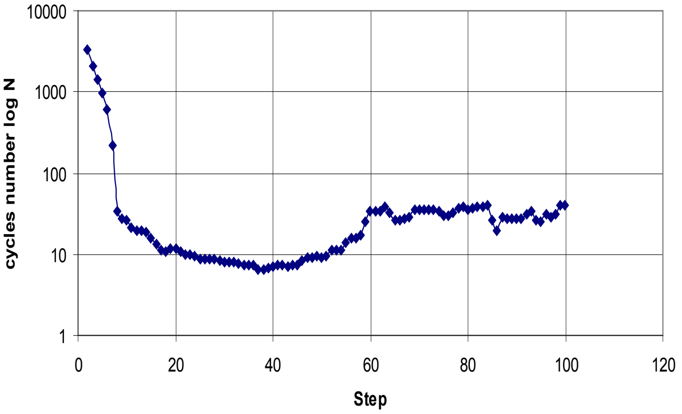

Figure 6. *Obtained relationship between steps and cycles number logN*

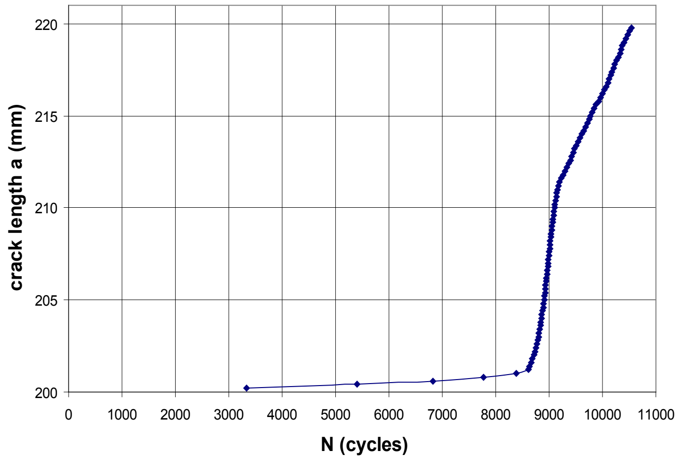

Figure 7. *Obtained relationship between crack length a and number of cycles N*

The chart in the Figure 7 shows the obtained relationship between the crack length a [mm] and the number of cycles N. Obviously, after the seventh step, in which the crack becomes through-wall crack, while the further cracks growth requires a very small number of cycles.

The obtained stress intensity factor histories can be used to predict fatigue crack growth rates by using them as input data for AFGROW of NASGRO software.

CONCLUSION

Fatigue life predictions of welded seam casing pipes with axial surface crack on the outer surface of pipes, made of API J55 steel, was performed in this paper using XFEM.

Based on the critical value of stress intensity factor K_{Ic} for the base metal, HAZ and weld metal, the critical crack lengths were calculated. The results indicate that the basic material has the lowest resistance to crack initiation and propagation, and according to that, the analysis of crack propagation in basic material was performed.

The obtained numerical results prove the efficiency of XFEM in the simulation of the axial cracks propagations in tube geometry.

Majority of failures of welded steel pipelines occurs due to insufficient resistance to crack initiation and growth. However, during its life cycle, welded casing pipes are exposed to corrosion effects, augmented with high pressure and high temperature environment. Having in mind the predicted severe exploitation conditions, significantly lower remaining fatigue life of welded casing pipes is expected.

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