Khalid Ahmed Eldwaib[1], Aleksandar Grbović[1], Gordana Kastratović[2], Dorin Radu[3], Simon Sedmak[4]

FATIGUE LIFE ESTIMATION OF CCT SPECIMEN USING XFEM

PROCENA ZAMORNOG VEKA CCT UZORKA PRIMENOM PMKE

Originalni naučni rad / Original scientific paper
UDK /UDC: 539.422:519.673
Rad primljen / Paper received: 12.10.2017

Adresa autora / Author's address:
[1)] University of Belgrade, Faculty of Mechanical Engineering, Serbia agrbovic@mas.bg.ac.rs
[2)] University of Belgrade, Faculty of Transport and Traffic Engineering, Serbia
[3)] University of Brasov, Faculty of Civil Engineering, Romania
[4)] University of Belgrade, Innov. Centre of Faculty of Mech. Engng., Belgrade, Serbia

Keywords
- stress intensity factor (SIF)
- fatigue life estimation
- XFEM

Ključne reči
- faktor intenziteta napona (FIN)
- ocena zamornog veka
- PMKE

Abstract

In this study a central crack tension (CCT) specimen is chosen for analysis to demonstrate the capability and reliability of the extended finite element method (XFEM) in predicting the crack propagation trajectory and evaluating stress intensity factors (SIFs). This specimen is frequently used in fatigue tests for studying various effects on fatigue crack propagation and for obtaining crack growth properties of a material. The XFEM obtained SIFs solutions are compared with several well-known solutions from literature. Evaluation of fatigue life of the CCT specimen is also carried out and compared with the obtained by NASGRO.

Izvod

U radu je prikazano predviđanje putanje širenja prsline i ocena faktora intenziteta napona (FIN) primenom proširene metode konačnih elemenata (PMKE). U tom cilju je izabrana epruveta sa centralnom prslinom za ispitivanje zatezanjem (CCT), kako bi se demonstrirale mogućnosti i pouzdanost ove metode. Ovakve epruvete se često koriste pri ispitivanju zamora i proučavanju različitih uticaja na širenje prsline, kao i za dobijanje osobine rasta prsline za dati materijal. Rešenja za FIN dobijena pomoću XFEM su upoređena sa nekoliko najpoznatijih rešenja iz literature. Takođe je izvršena procena zamornog veka CCT epruveta i upoređena sa rezultatima dobijenim metodom NASGRO.

INTRODUCTION

Fatigue life prediction of any damaged structure demands accurate calculation of stress intensity factors. Those factors can be calculated using stress and strain analysis or parameters that measure the energy released by crack growth. In recent years, with booming development of computer technologies, numerical analyses became a dominant tool for SIF calculations, as well as crack growth simulations and fatigue life estimations. Also, the importance of accuracy in stress intensity factor calculations generated the need to formulate numerical methods that can model fracture problems both accurately and efficiently.

Classical finite element method (FEM) and boundary element method (BEM) have been used for decades for calculating SIFs, but due to some restrictions (such as need for mesh update after each crack propagation step) they are nowadays replaced with extended finite element method (XFEM), /1, 2/. XFEM suppresses the need to mesh and re-mesh the crack surfaces and is used for modelling different discontinuities in 1D, 2D and 3D domains. Cenaero /3/ has developed a crack growth prediction add-in *Morfeo/Crack for Abaqus*© which relies on the implementation of the XFEM method available in *Abaqus* software. Problems involving static cracks in structures, evolving cracks, cracks emanating from voids etc., are numerically studied and the results are compared against analytical and experimental results to demonstrate the robustness of the XFEM and precision of *Morfeo/Crack for Abaqus*, /4, 5/.

The verification of XFEM is conducted on a 'benchmark' model. It is referred to as a CCT specimen (Centre Cracked Tension). In ASTM Standard, /6/, it is labelled as M(T) specimen (Middle Cracked Tension). This specimen is frequently used in fatigue tests for studying various effects on fatigue crack propagation and for obtaining crack growth properties of a material. Dimensions of the specimen (shown in Fig. 1) used in XFEM simulations are: semi-height h = 40 mm, semi-width b = 20 mm, thickness t = 1 mm. Initial length of the crack is $2a_0$ = 4 mm and a uniform tensile stress of 25 MPa is used.

In general, there are three types of loading that a crack can experience: Mode I loading, where the principal load is applied normally to the crack plane; Mode II loading corresponds to in-plane shear loading; and Mode III refers to out-of-plane shear. A cracked body can be loaded in any one of these modes, or a combination of two or three modes. Each mode can be described by corresponding SIF. The stress intensity factor is usually given a subscript to denote the mode of loading, i.e. K_I, K_{II}, or K_{III}, /7/. In the literature, stress intensity factor solutions typically exist

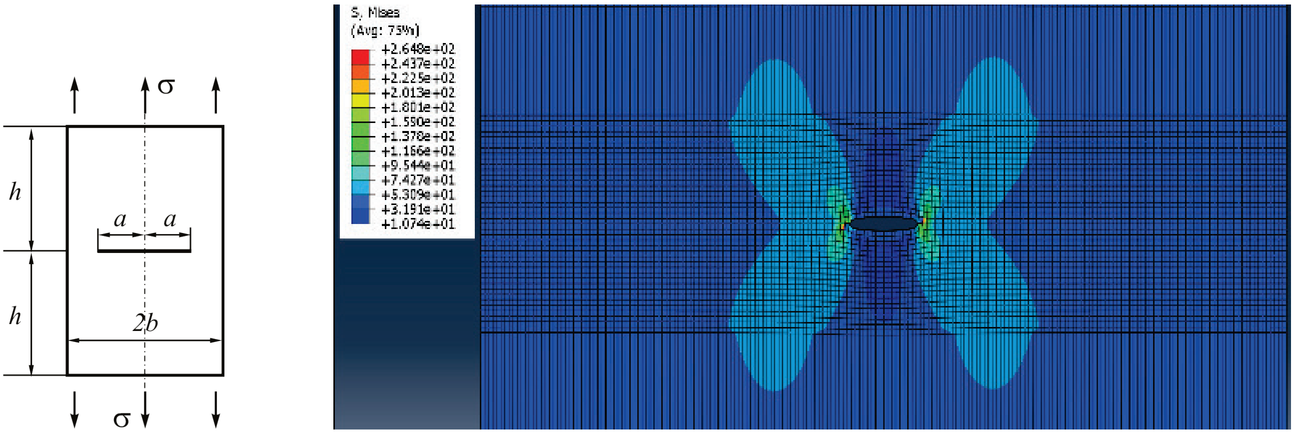

Figure 1. The CCT specimen subjected to uniform tension (left) and XFEM model (right).

only for simple geometries and loadings. Despite the extensive literature on K-values, in many practical cases K-solutions for cracks are not available. Sometimes the values can be approximated by available solutions for less complicated geometries. Therefore, for more complicated scenarios, alternate methods must be used, such as finite element analysis, /8/.

In case of CCT it is obvious that only Mode I exists and according to /9/ the stress intensity factor K can be calculated using formula

$$K = \sigma(\pi a) F\left(\frac{a}{b}\right) \tag{1}$$

where: σ is the remote loading stress; a –crack length; and $F(a/b)$ –dimensionless factor depending on the geometry of the specimen or structural component.

Empirical formulae for calculating geometry factor $F(a/b)$ of the centre-cracked specimen under uniform tension are developed by Irwin (1957), Brown (1966), Feddersen (1966) and Tada (1973). Brown has proposed the following equation based on least squares fitting to Isida results, /9/:

$$F\left(\frac{a}{b}\right) = 1 + 0.128\left(\frac{a}{b}\right) - 0.288\left(\frac{a}{b}\right)^2 + 1.525\left(\frac{a}{b}\right)^3 \tag{2}$$

For each step of crack propagation (i.e. crack length a) Eqs.(1) and (2) are combined to find the K_I values.

Feddersen, /9/, has proposed the following equation as guess based on Isida results:

$$F\left(\frac{a}{b}\right) = \sqrt{\sec\frac{\pi a}{2b}} \tag{3}$$

Koiter, /9/, suggested asymptotic approximation:

$$F\left(\frac{a}{b}\right) = \frac{1 - 0.5\left(\frac{a}{b}\right) + 0.326\left(\frac{a}{b}\right)^2}{\sqrt{1 - \left(\frac{a}{b}\right)}} \tag{4}$$

while Tada proposed two equations which are a modification of the Koiter formula, /9/, and a modification of the Feddersen formula, respectively:

$$F\left(\frac{a}{b}\right) = \frac{1 - 0.5\left(\frac{a}{b}\right) + 0.370\left(\frac{a}{b}\right)^2 - 0.044\left(\frac{a}{b}\right)^3}{\sqrt{1 - \left(\frac{a}{b}\right)}} \tag{5}$$

$$F\left(\frac{a}{b}\right) = \left\{1 - 0.025\left(\frac{a}{b}\right)^2 + 0.06\left(\frac{a}{b}\right)^4\right\}\sqrt{\sec\frac{\pi a}{2b}} \tag{6}$$

The empirical formulae Eqs.(2), (3), (5) and (6) are used for verification of SIF values obtained by means of XFEM.

Fatigue life is usually defined as a number of loading cycles that will extend the crack to a critical length. When SIFs are known, the critical crack size for failure can be computed for a given fracture toughness. The fatigue crack growth rate in metals can usually be described by the empirical Paris relationship $da/dN = C(K)^n$, where da/dN is the crack growth per cycle, K is the stress intensity range during the fatigue cycle ($K = K_{max} - K_{min}$), and C and n are material constants. Damage tolerance allows subcritical cracks to remain in a component, but when they grow, an allowable flaw size must be defined, usually by dividing the critical size by a safety factor. The critical crack size is computed from the applied stress and fracture toughness, and the service life of the structure can then be obtained by calculating the time (number of cycles) required for crack to grow from its initial- to the allowable size, /7/.

It is important to emphasize that 2D simulations of crack propagation are still dominant in papers, /10/, and – to the best authors' knowledge – simulations presented here are one of the first attempts of XFEM use for 3D crack growth analysis. In 2D simulations, values for SIFs are calculated in one point only – at the tip of the crack propagating in plane, whereas, in 3D simulations, the values are calculated in several points/nodes along the crack front that propagates in space. This way, it is possible to determine the stress intensity factors for all three Modes (which is important for fatigue life estimation in the case of mixed loading), while 2D analysis determines K_I and K_{II} only.

Abaqus© defines initial crack as a separate entity with no element mesh and the first step in 3D analysis of crack propagation is crack 'opening' followed by stress calculations. *Morfeo/Crack for Abaqus* uses *Abaqus* solutions to calculate stress intensity factors in nodes of the crack front and generates a file with K_I, K_{II} and K_{III} results. Then, the equivalent stress intensity factor K_{eq}, /8/, which combines all three SIF modes, is calculated as well as the kink angle (crack propagation angle) that defines the direction in which crack will be propagated in a next step. At the same time, Morfeo*/Crack for Abaqus* calculates the number of loading cycles necessary to extend the crack by a given length.

Values for all three Modes and equivalent SIF are displayed for (x,y,z) coordinates of the nodes on the crack fronts after each step of crack propagation. Table 1 shows SIFs and coordinates of the nodes on one of the crack fronts after the 1st and 2nd step of crack growth in CCT specimen. It is evident that SIF values K_{II} and K_{III} are practically zero and that K_I is dominant. The equivalent stress intensity factor is practically equal to K_I due to the fact that the applied load is normal to the crack plane.

Two crack fronts move simultaneously in opposite directions; they start from the sides of initial notch and then propagate in –X axis direction (crack front 1) and +X axis direction (crack front 2). After 22 steps of propagation, the simulation is interrupted (length of crack 1 is 12 mm). Values of SIFs Mode I for crack front 1 obtained in the numerical simulation using XFEM and by empirical formulae are presented in Table 2, as well as the percentage differences between results (since each node has its own K_I value, the maximum value along the front is taken as representative K_I). Differences in K_I values range between 4 and 9%; in most cases they are less than 7%. Among the used empirical formulae, Eq.(3) (Feddersen formula, /9/) gives the best fit to the numerical results.

Before evaluating fatigue life of CCT specimen, another check of calculated SIFs values is made. NASA's software NASGRO, /11/, is used for SIFs calculation for crack lengths from 2 to 12 mm (and later for fatigue life estimation). Comparison between XFEM results and NASGRO results is presented in Table 3. Again, good agreement between values is obtained. (It is important to mention that NASGRO calculates SIFs at the tip of the 2D crack, while Morfeo/Crack for Abaqus calculates SIFs at the nodes of 3D crack front; in Table 3 maximum values of SIFs along crack fronts are presented).

It can be concluded that, in general, XFEM gives somewhat greater SIF values which can be explained by the fact that the thickness of the analysed 3D model is relatively insignificant compared to other model dimensions. Number of elements in the thickness direction is significantly lesser than in the other directions, which it affects values obtained in the FE analysis. This was analysed in detail in /5/.

Table 1. SIFs in nodes on the crack front of CCT after 1st and 2nd step of XFEM simulation.

step	Crack front coordinates (mm)			Stress intensity factors (MPa√mm)			
	X	Y	Z	K_{eqv}	K_I	K_{II}	K_{III}
1	-1.99998	2.00E-05	0.916675	66.8281	66.8076	-0.09214	-0.01755
	-1.99998	2.00E-05	0.833342	66.8538	66.8325	-0.09058	-0.02179
	-1.99998	2.00E-05	0.750008	66.9632	66.9389	-0.08392	-0.03992
	-1.99998	2.00E-05	0.666675	66.9927	66.9674	-0.0816	-0.04049
	-1.99998	2.00E-05	0.583342	67.0087	66.9817	-0.07827	-0.0214
	-1.99998	2.00E-05	0.500008	67.0086	66.9796	-0.07766	-0.01064
	-1.99998	2.00E-05	0.499992	67.0086	66.9796	-0.07766	-0.01064
	-1.99998	2.00E-05	0.416658	66.9934	66.9623	-0.07632	-0.0038
	-1.99998	2.00E-05	0.333325	66.9328	66.8984	-0.0692	-0.00471
	-1.99998	2.00E-05	0.249992	66.8882	66.8531	-0.06796	0.001756
	-1.99998	2.00E-05	0.166658	66.755	66.7197	-0.06958	0.033029
	-1.99998	2.00E-05	0.083325	66.7238	66.6884	-0.06996	0.04035
2	-2.49628	2.00E-05	0.959695	73.814	73.761	-0.03894	1.20713
	-2.49721	2.00E-05	0.876362	73.8497	73.7974	-0.0097	1.0755
	-2.49821	2.00E-05	0.792193	74.0083	73.9587	0.120137	0.490966
	-2.49927	2.00E-05	0.70886	74.0539	74.0056	0.142891	0.310725
	-2.49984	2.00E-05	0.625054	74.0971	74.052	0.114583	0.098536
	-2.4999	2.00E-05	0.541721	74.1066	74.062	0.109764	-0.02283
	-2.49963	2.00E-05	0.458058	74.105	74.0589	0.116981	-0.33835
	-2.49905	2.00E-05	0.374724	74.0821	74.0342	0.12069	-0.50942
	-2.49787	2.00E-05	0.290413	73.9816	73.9269	0.12983	-0.94896
	-2.49616	2.00E-05	0.20708	73.9173	73.86	0.101647	-1.0251
	-2.49472	2.00E-05	0.122542	73.7281	73.6659	-0.03495	-0.92492
	-2.49356	2.00E-05	0.039209	73.6863	73.623	-0.06518	-0.90275

Table 2. Comparison of SIFs (*Morfeo/Crack for Abaqus vs.* empirical) for CCT, crack front 1 (-X-axis). All SIF values are in MPa√mm.

Step	a (mm)	a/b	K_I Morfeo	K_I Brown	ΔB (%)	K_I Fedd.	ΔF (%)	K_I Tada 1	ΔT_1 (%)	K_I Tada 2	ΔT_2 (%)
1	2.00	0.100	66.88	63.38	5.52	63.05	6.07	62.99	6.18	63.04	6.10
2	2.50	0.125	73.90	71.04	4.02	70.71	4.51	70.61	4.66	70.68	4.55
3	3.00	0.150	81.59	78.06	4.52	77.77	4.91	77.62	5.11	77.73	4.97
4	3.48	0.174	88.42	84.48	4.67	84.27	4.92	84.07	5.18	84.21	5.00
5	3.98	0.199	95.04	90.71	4.77	90.63	4.86	90.37	5.17	90.55	4.96
6	4.48	0.224	102.41	96.68	5.92	96.75	5.85	96.42	6.21	96.65	5.96
7	4.95	0.247	110.91	102.20	8.52	102.43	8.28	102.03	8.70	102.30	8.42
8	5.42	0.271	115.65	107.71	7.37	108.12	6.96	107.65	7.43	107.96	7.12
9	5.91	0.296	120.52	113.34	6.34	113.93	5.78	113.39	6.29	113.73	5.97
10	6.40	0.320	127.40	119.04	7.02	119.81	6.34	119.20	6.88	119.58	6.54
11	6.90	0.345	131.26	124.87	5.12	125.79	4.35	125.12	4.91	125.52	4.57
12	7.36	0.368	138.76	130.29	6.50	131.33	5.66	130.61	6.24	131.03	5.90
13	7.79	0.390	143.27	135.64	5.62	136.75	4.76	135.99	5.35	136.42	5.02
14	8.26	0.413	152.12	141.46	7.54	142.61	6.67	141.82	7.27	142.25	6.94
15	8.74	0.437	160.12	147.76	8.36	148.92	7.52	148.10	8.11	148.53	7.80
16	9.22	0.461	164.17	154.38	6.34	155.49	5.58	154.67	6.14	155.08	5.86
17	9.68	0.484	170.70	160.93	6.07	161.94	5.41	161.14	5.93	161.53	5.68
18	10.12	0.506	181.36	167.58	8.22	168.46	7.66	167.70	8.14	168.05	7.92
19	10.61	0.531	187.93	175.31	7.20	176.03	6.76	175.33	7.18	175.62	7.00
20	11.06	0.553	198.86	182.79	8.79	183.34	8.47	182.74	8.82	182.96	8.69
21	11.55	0.578	204.30	191.55	6.66	191.93	6.45	191.47	6.70	191.61	6.62
22	12.00	0.600	211.41	199.96	5.72	200.24	5.58	199.94	5.74	199.99	5.71

ΔB: percentage difference between XFEM and Brown formula; ΔF: percentage difference between XFEM and Feddersen formula ΔT_1: percentage difference between XFEM and Tada modification of Koiter formula; ΔT_2: percentage difference between XFEM and Tada modification of Feddersen formula

Table 3. Comparison of SIFs (*Morfeo/Crack for Abaqus* vs. NASGRO) for CCT, crack front 1 (+X axis). All SIF values are in MPa√mm.

Step	a (mm)	a/b	K_I Morfeo	K_I NASGRO	Δ (%)
1	2.000	0.100	66.88	63.05	6.07
2	2.498	0.125	73.90	70.71	4.51
3	2.995	0.150	81.59	77.77	4.91
4	3.482	0.174	88.42	84.27	4.92
5	3.981	0.199	95.04	90.63	4.86
6	4.476	0.224	102.41	96.75	5.85
7	4.946	0.247	110.91	102.43	8.28
8	5.422	0.271	115.65	108.12	6.96
9	5.911	0.296	120.52	113.93	5.78
10	6.405	0.320	127.40	119.81	6.34
11	6.903	0.345	131.26	125.79	4.35
12	7.357	0.368	138.76	131.33	5.66
13	7.795	0.390	143.27	136.75	4.76
14	8.256	0.413	152.12	142.61	6.67
15	8.738	0.437	160.12	148.92	7.52
16	9.222	0.461	164.17	155.49	5.58
17	9.679	0.484	170.70	161.94	5.41
18	10.122	0.506	181.36	168.46	7.66
19	10.611	0.531	187.93	176.03	6.76
20	11.058	0.553	198.86	183.34	8.47
21	11.553	0.578	204.30	191.93	6.45
22	12.001	0.600	211.41	200.24	5.58

EFFECT OF MESH SIZE ON ACCURACY OF STRESS INTENSITY FACTOR VALUES

In finite element analysis (FEA) the mesh size (or mesh density) is crucial. It closely relates to the efforts required for meshing finite element models, computing time and accuracy of results and determines the complexity level. It is well known that FE models with fine mesh (small element size) yield highly accurate results, but may take longer computing time, while FE models with coarse mesh (large element size) may lead to less accurate results, but also lesser computing time. Due to its importance in generating FEA models, the goal is to choose appropriate element type and size so that the created models will yield good FEA results while saving as much computing time as possible, /7, 12, 13/.

This is why the study of mesh size effect on the accuracy of SIF results is also conducted in this research. For the purpose of analysing effects of mesh size, two 3D FE models of a CCT specimen are generated using element sizes 0.2 mm and 0.4 mm in the regions where cracks are expected to propagate (to reduce computing time; in other regions a coarse mesh is generated, see Fig. 1). K_I values are calculated for different crack lengths using XFEM and Brown, Feddersen and Tada formulae, /9/. After that, XFEM results are compared to empirical values. As can be seen in Table 4, differences in K_I values for two FE models are obtained. Columns labelled ΔB, ΔF and ΔT show the percentage differences between XFEM results and analytical values. It is clear that results obtained for the model with mesh size 0.2 mm are closer to analytical values than results obtained for the model with mesh size 0.4 mm, as expected (calculated SIF values for element size 0.2 mm are given later in this paper).

Since analysis of the element size effect on SIF values shows that mesh with 0.2 mm quadrilateral elements generates more accurate (and acceptable) results, it is decided to use the FE model with finer mesh for fatigue life estimation of the CCT specimen defined above.

Table 4. Percentage difference between K_I values for CCT specimen, calculated using XFEM (*Morfeo/Crack for Abaqus*), and K_I values obtained analytically for different element sizes.

Mesh element size = 0.2 mm					Mesh element size = 0.4 mm			
Step	a (mm)	ΔB %	ΔF %	ΔT %	a (mm)	ΔB %	ΔF %	ΔT %
1	4.0	5.70	5.79	5.89	4.0	7.07	7.16	7.26
2	5.0	4.97	4.72	4.85	5.0	5.50	5.24	5.38
3	6.0	6.02	5.46	5.64	6.0	7.90	7.32	7.51
4	6.5	8.56	7.86	8.07	6.5	9.88	9.16	9.37
5	7.4	6.98	6.14	6.38	7.4	12.39	11.49	11.75
6	8.8	7.19	6.37	6.65	8.8	9.71	8.89	9.17
7	9.3	6.03	5.29	5.57	9.3	8.70	7.97	8.25
8	9.8	6.16	5.53	5.80	9.8	6.98	6.37	6.64
9	10.3	5.12	4.61	4.86	10.3	6.95	6.46	6.71
10	10.7	9.31	8.90	9.15	10.7	9.92	9.55	9.79
11	11.7	5.57	5.39	5.55	11.7	9.39	9.23	9.37
12	12.6	6.82	6.66	6.71	12.6	7.15	6.95	6.97
13	13.1	5.84	5.57	5.53	13.1	9.02	8.65	8.57
14	13.5	7.33	6.81	6.69	13.5	7.77	7.06	6.88
15	14.0	8.57	7.63	7.39	14.0	11.45	10.19	9.89
16	14.5	7.34	5.74	5.37	14.5	11.50	9.41	8.97
17	15.0	8.29	5.72	5.20	15.0	13.93	10.82	10.24

ΔB - percentage difference between XFEM result and Brown formula; ΔF - percentage difference between XFEM result and Feddersen formula; ΔT - percentage difference between XFEM result and Tada's modification of Feddersen formula

FATIGUE LIFE EVALUATION

Once SIF values are evaluated it is possible to estimate fatigue life, i.e. the number of loading cycles that would propagate a crack on CCT specimen to complete failure.

The fatigue crack growth model incorporated in *Morfeo/Crack for Abaqus* is a modified Paris law based on effective stress intensity rate:

$$da/dN = C(K_{eff})^n$$

The K_{eff} considers stress ratio $R = \sigma_{min}/\sigma_{max}$ through:

$$K_{eff} = K_{max}\left[1-(0.25+0.5R+0.25R^2)\right]$$

The stress ratio R and values for material coefficients C and n must be entered manually. Aluminium alloy 2024-T3 with mechanical and fatigue properties given in Table 5 is selected, while the value for stress ratio is $R = -1$. Simulation is run again and failure of CCT specimen occurs after 38 propagation steps.

Values obtained by Morfeo/Crack for Abaqus (Fig. 2) show that crack front 1 will move by 2 mm (from initial crack length $a_0 = 2$ to 4 mm) after approximately 700 000 cycles of applied load, while it will move the next 2 mm (to total crack length $a = 6$ mm) after approximately 250 000 cycles (due to the symmetry, crack front 2 will behave in the same manner). After that, front 1 will start to move rapidly and the crack length will be doubled ($a = 12$ mm) after another 250 000 cycles. It will take additional 40 000 cycles to grow the crack to a final length $a = 19$ mm just before complete failure.

Comparing XFEM results with the number of cycles obtained by NASGRO (Fig. 2), it is evident that NASGRO predicts longer fatigue life. This difference can be explained by the fact that *Morfeo/Crack for Abaqus* uses the Paris law for the number of cycle's calculations, while NASGRO uses a more sophisticated and empirically improved equation (known as the *NASGRO equation,* /11/). But, from an engineering point of view, results obtained by XFEM are absolutely acceptable, since the estimated life is less than NASGRO's.

Table 5. Mechanical and fatigue properties of aluminium alloy 2024-T3 used in fatigue life estimation.

Property	Symbol	Value
Yield stress (MPa)	Q_y	365.4
Ultimate tensile strength (MPa)	Q_u	455.1
Plane strain fracture toughness (MPa√mm)	K_{IC}	1042
Part through fracture toughness (MPa√mm)	K_{IE}	1459
Paris exponent	n	3.20
Paris coefficient	C	2.382×10^{-12}
Modulus of elasticity (GPa)	E	71.75
Fatigue strength coefficient (MPa)	f	130

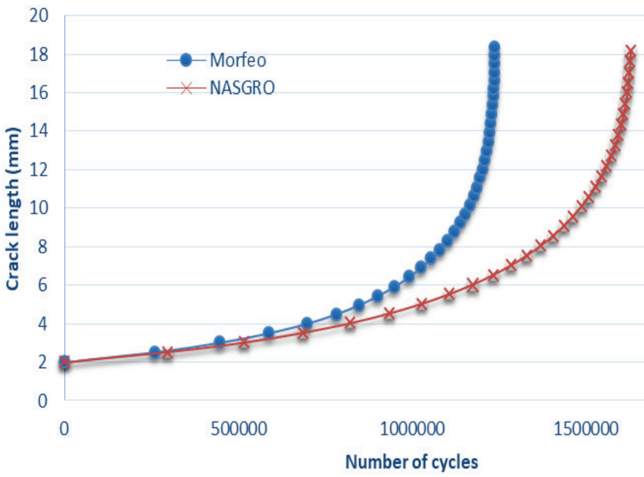

Figure 2. Estimated number of cycles vs. crack length for CCT.

CONCLUSION

The verification of XFEM is conducted on a 'bench-mark' model: a CCT specimen, analysed as 3D model. Simulations presented here, to the best authors' knowledge, are one of the first attempts of XFEM use for 3D crack growth analysis. So, SIF values are calculated for different crack lengths using XFEM and Brown, Feddersen and Tada et al. formulae, /9/, and also using NASGRO software.

In general, XFEM gives somewhat greater SIF values. As already said, this can be explained by the fact that the thickness of the analysed 3D model is relatively small compared to other model dimensions.

Once SIF values are evaluated, the number of loading cycles, which would propagate a crack on CCT specimen to a complete failure is estimated, as well. This is also done by *Morfeo/Crack for Abaqus*, and by using NASGRO software. The longer fatigue life calculated by NASGRO can be explained by the fact that it uses an empirically improved equation for fatigue life estimation. The conducted analysis shows once again that XFEM is a very efficient tool for simulating crack propagation and predicting the crack propagation trajectory and for evaluating stress intensity factors.

REFERENCES

1. Hedayati, E., Vahedi, M. (2013), *Comparison extended finite element method with finite element method and theoretical method for computation of the stress intensity factor, crack growth simulation and predicting fatigue crack growth in a slant-cracked plate of 6061-t651 aluminum*. World Appl. Sci. J, 28(1): 20-26.
2. Moghaddam, H.N., Keyhanib, A., Aghayan, I. (2016), *Modeling of crack propagation in layered structures using extended finite element method*. Civil Engng. J, 2(5):180-188.
3. Cenaero Morfeo, available at http://www.cenaero.be (last accessed on 4th September 2016).
4. R. Branco (Ed.), Recent Trends in Fatigue Design, Nova Science Publishers, Inc. New York. Chapter 2, Grbović, A., Rašuo, B., *Use of modern numerical methods for fatigue life predictions*, 2014, pp.31-74.
5. Grbović, A., Investigation of fatigue life in super-alloys structural components, PhD Thesis (in Serbian), University of Belgrade, Faculty of Mechanical Engineering, Serbia, 2012.
6. Standard Test Method for Measurement of Fatigue Crack Growth Rates. ASTM Standard E647-91a, 1991.
7. Liu, W., Geni, M., Yu, L. (2011), *Effect of mesh size of finite element analysis in modal analysis for periodic symmetric struts support*. Key Engng. Mater., 462-463: 1008-1012.
8. Schijve, J., Fatigue of Structures and Materials, Springer Netherlands, 2009.
9. Tada, H., Paris, P.C., Irwin, G.R., The Stress Analysis of Cracks Handbook, 3rd Ed., ASME Press, New York, NY and ASM Int., Materials Park OH, 2000.
10. Singh, I.V., Mishra, B.K., Bhattacharya, S., Patil, R.U. (2012), *The numerical simulation of fatigue crack growth using extended finite element method*. Int. J Fatigue, 36(1):109-119.
11. NASGRO, http://www.swri.org/4org/d18/mateng/matint/nasgro/ (last accessed on 4th August 2017).
12. More, S.T., Bindu, R.S. (2015), *Effect of mesh size on finite element analysis of plate structure*. Int. J Engng. Sci. & Innov. Tech. (IJESIT), 4(3):181-185.
13. Dutt, A. (2015), *Effect of mesh size on finite element analysis of beam*. SSRG Int. J Mech. Engng. (SSRG-IJME), 2(12):8-10.