NUMERICAL EVALUATION OF A CRACK GROWTH ALGORITHM UNDER 2D NON-PROPORTIONAL MIXED MODE

J. Ondráček, A. Materna

Abstract

A 2D elastic-plastic FEM simulation of a growing fatigue crack in the Al-alloy AA2017 CTS specimen under I and II mixed mode non-proportional loading is performed in this study. The simulation of elastic-plastic stress and strain fields in the vicinity of a crack tip allows the determination of the amount of the total plastic energy dissipation per cycle throughout the zone. Fatigue crack growth rates computed by the FEM model were compared to fatigue crack growth experiments from the literature. Numerical simulations are able to predict experimentally observed higher crack growth rates in the shear mode crack growth under non-proportional mixed mode loading.

Keywords: fatigue crack, non-proportional loading, mixed mode I + II, FEM

INTRODUCTION

The loading sequences of engineering components and structures tend to be uncorrelated in praxis. It means that at the fatigue crack tip the ratio between normal and shear stress changes during the loading process and thus non-proportional mixed mode situations occur. It was shown by many authors [1] that fatigue lives greatly differ under proportional and non-proportional loading conditions. Plank and Kuhn [2] experimentally studied behavior of compact tension shear (CTS) specimens made from various aluminum alloys subjected to non-proportional mixed mode cyclic loading. They induced the non-proportional loading by superposing cyclic mode II on static mode I. Two basic modes of crack growth were observed: tensile and shear mode growth. In case of the tensile mode growth the fatigue crack was the mode I controlled and changed the direction of propagation soon after it was subjected to mixed mode loading. On the other hand, in case of the shear mode growth the crack was mode II controlled and continued to spread in the direction of initial precrack cycled in pure mode I. The crack path was, however, strongly zigzag and the propagation rate was higher than for the tensile mode growth.

In this study the crack growth under tensile and shear mode was modelled using a finite element method (FEM). The total plastic energy dissipation per cycle ahead of a crack tip dW/dN was computed for a growing crack in order to compare dissipated plastic energies for the tensile and shear modes of growth. According to Klingbeil's theory [3] the fatigue crack growth rate is proportional to the dW/dN in ductile solids. It is therefore possible to compare computed tensile and shear mode fatigue crack growth rates (FCGRs) in terms of Klingbeil's theory with experimental data of FCGRs for tensile and shear growth modes presented in [2].

Jan Ondráček, Aleš Materna, Czech Technical University in Prague, Faculty of Nuclear Sciences and Physical Engineering, Dept. of Materials, Trojanova 13, 120 00 Prague 2, Czech Republic

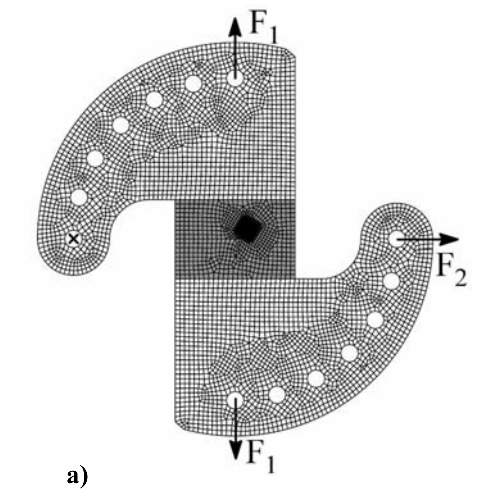
MIXED MODE SPECIMEN GEOMETRY

A CTS specimen suggested by [4] for mixed mode fatigue fracture experiments was used in order to study proportional and non-proportional loading. The width of the specimen used in this work is w = 100 mm and the thickness t = 10 mm, other dimensions of the specimen, which are proportional to its width, are specified in [4].

NUMERICAL PROCEDURES

Finite element mesh

A 2D FEM model of a CTS specimen with a loading device was built in order to calculate the dissipated plastic energy ahead of a crack tip per cycle dW/dN (Fig.1a). The region of the specimen material is grayed out on the picture, the rest of the mesh represents the loading device. Two different meshes were created in order to simulate tensile and shear mode growth. The finite element model (Fig.1a) uses a linear 4-noded quadrilateral plane full integration elements. The region of crack growth is meshed with square elements parallel to the crack propagation direction. The crack propagation direction was adjusted to correspond to the one experimentally observed. The refined region for tensile mode is kinked by 58° at a = 50 mm towards the upper edge of the specimen. The smallest element size in the refined region is 12 × 12 μm, sufficient to cover the plastic zone with at least 5 elements in width [3]. The rest of the specimen is meshed using an automatic mesh generator with an average element size of 3.7 mm.



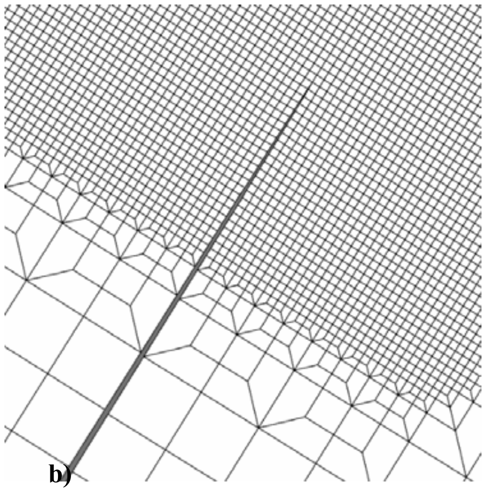


Fig.1. FEM mesh of the specimen (a) and a close-up view of the region of the FCG (b)

Boundary conditions and the crack advance algorithm

The loading of the specimen was realized by point loads placed according to Fig.1a. The F_1 loads are static. The F_2 load is used for cyclic loading. The displacements of the specimen-loading device are fixed on the leftmost hole, only vertical displacements are fixed at the point of F_2 load. The value of the static load F_1 was set to 1 800 N and the dynamic sinusoidal load F_{2max} was 6 700 N with the stress ratio R = 0.1. A reference computation using the same mesh in pure mode I was also carried out. The value of the cyclic F_{1max} load was set to 3 300 N with the stress ratio R = 0.1.

The crack tip advance was modeled by a sequential splitting of finite element mesh along element edges during the cyclic loading (Fig.1b). The loading process consisted of a sequence of alternating so called active and idle cycles. During an active cycle the crack moved along an element edge at the minimum of the cycle. The crack growth increment was therefore one element edge size per active cycle. Crack closing and opening during loading cycles was simulated by the MSC.Marc's node-to-segment contact algorithm. During an idle cycle the crack was fixed in length to achieve a numerically stabilized solution necessary for proper calculation of plastic energy increment per one loading cycle.

Numerical evaluation of stress intensity factors

The stress intensity factor ranges ΔK_I and ΔK_{II} were evaluated numerically using the virtual crack closure technique (VCCT) based on the energy release rate calculation on the FEM mesh presented in Fig.1.

Material input data

The material used for presenting simulations is aluminium alloy AA2017 (AlCuMg1 type). The mechanical properties of the alloy are taken from [2] and are listed in the following table.

Tab.1. Mechanical properties for alloy AA2017

Young modulus E	Poisson's ratio ν	Yield strength $R_p0.2$	Tensile strength R_m	Total enlongation at fracture A
74 800 MPa	0.34	307.7 MPa	441.2 MPa	19.8 %

The plastic response of the material is represented by a linear work hardening curve. The kinematic hardening rule is used.

RESULTS AND DISCUSSION

Dissipated plastic energies per cycle ahead of a crack tip *dW/dN* in a growing fatigue crack were computed for both tensile and shear mode crack growth under plane stress and strain conditions. Stress intensity factors ΔK_I and ΔK_{II} computed by the VCCT technique corresponding to individual fatigue crack lengths were transformed to an equivalent ΔK_{eq} proposed by [4] using the following empirical relation:

$$\Delta K_{eq} = \frac{\Delta K_1}{2} + 2\frac{1}{2}\sqrt{\Delta K_1{}^2 + 5.34\Delta K_{II}{}^2} \qquad (1)$$

(1) was used to compare *dW/dN* in tensile and shear crack growth mode. The results of tensile and shear mode growth *dW/dN* computations showed the same dependence on ΔK_{eq} under both plane stress and strain conditions. The amount of *dW/dN* in plane stress computations was approximately 5x bigger than in plane strain.

In order to compare fatigue crack growth rate *da/dN* (FCGR) with the experimental data [2], Klingbeil's relation (2) for transforming *dW/dN* to FCGR was used.

$$\frac{da}{dN} = \frac{1}{Gc}\frac{dW}{dN} \tag{2}$$

G_c is a critical energy release rate. G_c is related to the fracture toughness K_c as $G_c = K_c^2/\bar{E}$, $\bar{E} = E$ in plane stress and $\bar{E} = E/(1 - \nu^2)$ in plane strain. In order to compare simulation data with experimental results, the Paris relation with $C = 3.26 \times 10^{-12}$ m/cycle and $m = 4.71$ was used [2]. The value of plane strain fracture toughness $K_{Ic} = 48$ MPa.m$^{1/2}$ was taken from [2]. The specimen thickness of 10 mm was however not sufficient to fulfill linear fracture mechanics criteria for plane strain. Irwin's approximation formula given by (3) was used to reflect the influence of specimen thickness t on the fracture toughness K_{Ic} [5].

$$K_c = K_{IC}\sqrt{1 + \frac{1.4}{t^2}\left(\frac{K_{IC}}{R_{p0.2}}\right)^4} \tag{3}$$

The resulting K_c used for computing critical release rate G_c for transforming *dW/dN* to *da/dN* (3) is equal to 146 MPa.m$^{1/2}$. The computed FCGRs for tensile, shear and mode I compared to experimental data are depicted in Fig.2. The computed FCGRs using (2) give substantially lower crack velocity predictions than experimentally observed. Shear mode FCGR does not lie in the experimental range. However, the dissipated plastic energy *dW/dN* can be transformed directly to *da/dN* by correlating experimental mode I FCGR and mode I *dW/dN* computation using a linear relation *da/dN = A dW/dN*. The regression coefficient A was used to directly compute $K_c = 32$ MPa.m$^{1/2}$ by comparing the previous relation to (2). The adjusted results of tensile and shear mode FCGRs are also shown in Fig.2.

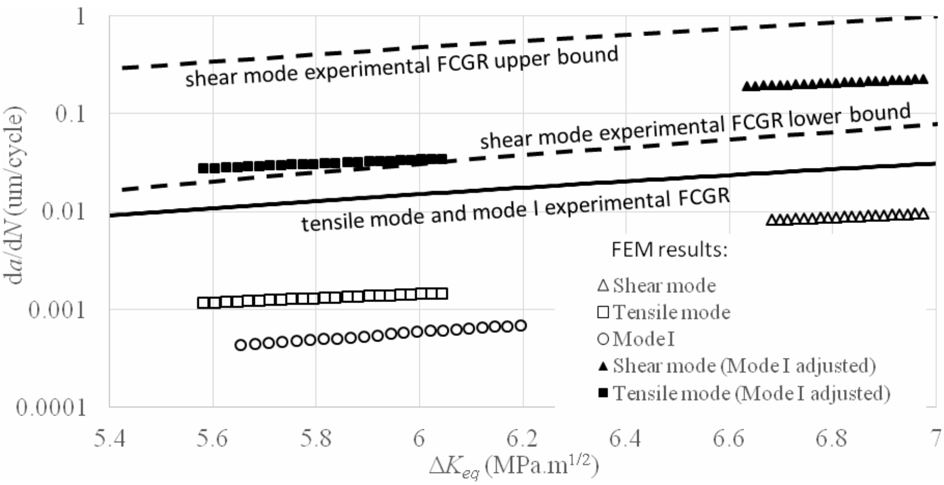


Fig.2. Plane strain FCGRs for tensile, shear and mode I growth modes compared to experimental data.

Lower FCGR predictions can be explained due to the fact that the portion of plane stress is still high in the specimen with a thickness of 10 mm. Plane strain computations give therefore lower crack velocity estimates. The predicted FCGRs are also strongly dependent on the fracture toughness parameter used. A thickness correction formula (3) does not have to provide satisfactory results of the fracture toughness parameter K_c for the studied material. Higher experimentally observed velocities of shear mode crack growth compared to tensile mode are however confirmed by modelling of the dissipated plastic energy ahead of a crack tip for a growing crack under non-proportional loading condition.

CONCLUSIONS

The comparison of the experimentally measured fatigue cracks growth rates in the alloy AA2017 under non-proportional mixed mode I and II loading condition with subsequent finite element simulations of the same growing crack led to the following conclusions.

FEM fatigue crack growth rate computations in shear mode growth at the same ΔK_{eq} give higher FCGRs than in tensile mode growth, which is in agreement with experimental data.

FCGRs computed using Klingbeil's formula (2) and 2D plane strain dissipated plastic energy ahead of a crack tip are sensitive to the value of K_c. K_{Ic} corrected for the actual specimen thickness does not lead to a satisfactory agreement with experimental data. Further experiments are desirable in order to obtain K_c of the specimen with a given thickness.

Using the mode I plastic energy computation for correlating the amount of dissipated plastic energy ahead of a crack tip to experimental data can give good predictions of tensile and shear FCGRs. The shear mode FCGR prediction lies within the experimental scatter.

Acknowledgements

The authors would like to acknowledge funding from SGS13/223/OHK4/3T/14.

REFERENCES

[1] Zerres, P., Vormwald, M.: Int J Fatigue, vol. 58, 2014, p. 75
[2] Plank, R., Kuhn, G.: Eng Fract Mech, vol. 62, 1999, p. 203
[3] Klingbeil, NW.: Int J Fatigue, vol. 25, 2003, no. 2, p. 117
[4] Richard, HA. In: VDI Forschungsheft, 631. Düsseldorf: VDI-Verlag, 1985
[5] Irwin, GR.: J Fluids Eng, vol. 82, 1960, no. 2, p. 417