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Comparison of stress state on the fatigue crack tip from FEA solution with experimental measurement

Porovnání stavu napjatosti na čele únavové trhliny z numerického řešení MKP s experimentálním měřením

Radek Doubrava

Abstract

Modern computational technology has been become inseparable part of world-wide an aircraft structure development. It is used not only for design but for check and optimisation too. The most popular numerical technique is analyses by means of finite element technique. The submitted article summarises the results of crack growth modelling during random loading and comparison with experimental measurement. The experimental measurement on M(T) specimen and real aircraft component such as wing flange-plate was selected for comparison of impact of stress state in front of the crack tip on crack tip geometry and on fracture surface. The influence of range of plastic zone on shear lips formation is discussed. Furthermore the influence of stress peak during fatigue crack growth propagation is discussed. The technique for qualified assessment of fatigue crack growth rate in 3D body during randomise loading has been proposed. The PREDIKCE code developed by Strength Reliability Department has been used for crack growth rate propagation on the base of elastic stress intensity factor from FEA. The results of experimental measurements on specimens made from Al-alloy was used for verification of mathematical models.

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Keywords: fatigue, FEA, crack, J-integral

Nomenclature

a	[mm]	crack length
B	[mm]	thickness
da	[mm]	crack growth
dk	[%]	change of curve gradient
dK	[MPa.m$^{1/2}$]	stress intensity factor amplitude
dN	[1]	number of cycle
J	[MPa.mm]	Rice’s contour integral
$\mathbf{K_I}$	[MPa.m$^{1/2}$]	stress intensity factor
FEA		Finite Element Analysis
N	[1]	number of cycle
$\mathbf{r_p}$	[mm]	range of plastic zone
t	[s]	time
ε	[%]	strain
σ	[MPa]	stress

Ing. Radek Doubrava, Výzkumný a zkušební letecký ústav, a.s., Beranových 130, Praha, doubrava@vzlu.cz

Introduction

Increases of requirements on reliability, safety and life of aircraft structures are reflected in technique of aircraft structures certificate. Introduction of new design of aircraft structures philosophy such as fail-safe and damage tolerance relates with this requirements. Indivisible part of aircraft structure certificate under damage tolerance philosophy is crack growth rateassessment. We need to describe conditions near the crack tip for crack growth prediction. First mathematical simulation of crack growth in 3D body was published in last decade.

The technique where is the crack characterised by means of stress intensity factor was developed in the Aeronautical Research and Test Institute [1]. The stress intensity factor has been found using the FEA code. The PREDIKCE code [2] developed by Strength Reliability Department has been used for crack growth rate propagation on the base of elastic stress intensity factor from FEA. The results shown good agreement in the centre of part of structure from point of view growth rate, but deviation near the free surfaces from point of view crack tip geometry. This deviation flows from different stress state in front of the crack tip along thickness of part. The influence of material and loading on to change of stress state is evident from typical fracture surface (fig.1).

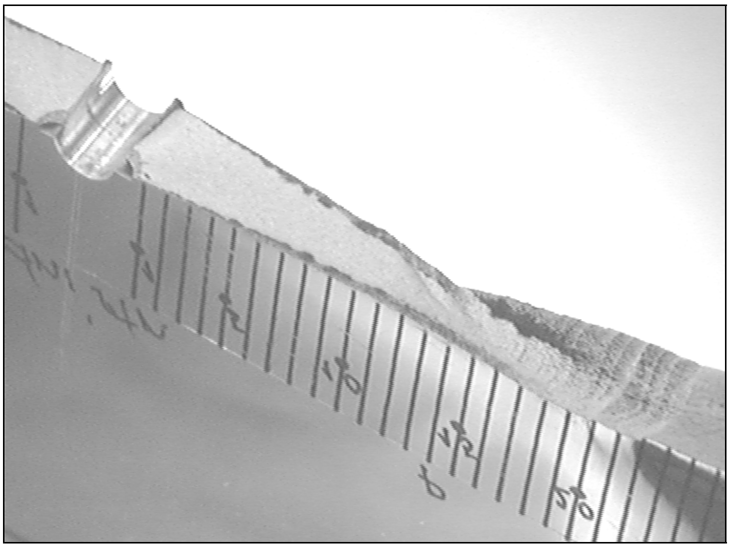

Fig.1 – Typical fracture surface on the M(T) specimen [3].

The results of experimental measurements on specimens made from Al-alloy was used for verification of mathematical models.

Comparison between elastic and elasto-plastic solution

The experimental measurement on M(T) specimen was selected for comparison of stress states near the crack tips. The specimen was made from wing flange-plate semifinished product. The geometry of fatigue crack tips was obtain from fractographic analyses (fig.2).

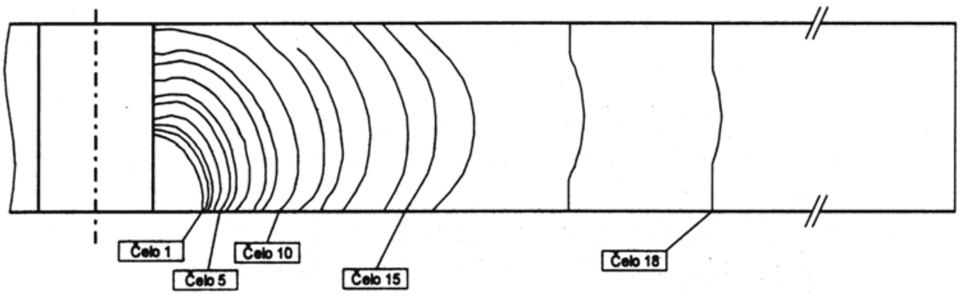

Fig.2 - The geometry of fatigue crack tips from fractographic analyses [4].

The three crack tips was selected from results of fractographic analyses. The crack tips was selected from point of view fracture surface and occurrence of shear lips. The crack tip no. 11, 13 and 16 was selected for this purpose (fig.2). The stress state near the selected crack tips was calculated by elastic and elasto-plastic FEA solution. The range of plastic zone was determined on the base vonMises yield criterion from elasto-plastic FEA solution.

Comparison of influence of crack tip geometry on range of plastic zone was realised for real crack tip from fractographic analyses and for straight crack tip with length corresponding internal length of real crack tip. The range of plastic zone calculation in front of the straight crack tip with length corresponding internal length of real crack tip was performed for comparison crack tip geometry influence on stress state. The range of plastic zone calculation was executed for maximal loading in real aircraft structure [1]. The size of load was determine from elasto-plastic solution and from the influence of stress peak during fatigue crack growth propagation.

The peak of stress highlights change of stress state along the crack tip in the case of fatigue crack growth in 3D body. Comparison between the real crack tip geometry and equivalent straight crack tip is shown in fig.3 [5].

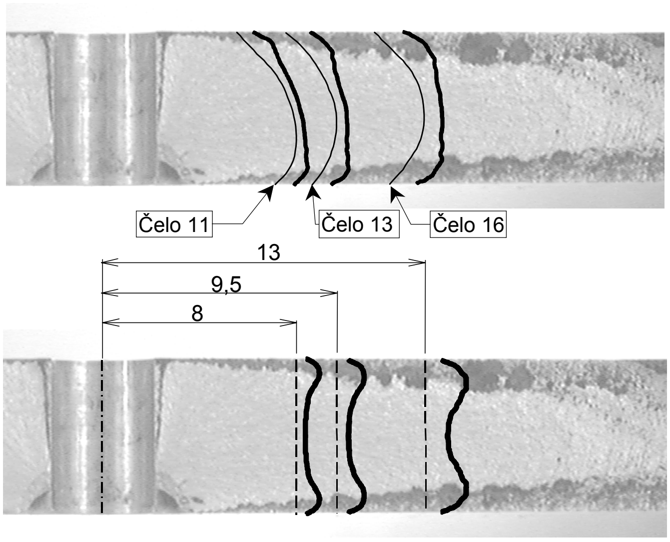

Fig.3 – The range of plastic zone (distance between thin line and thick line) in front of the real crack tip geometry (above) and straight crack tip (below).

It is evident, from comparison of geometry and range of plastic zone between real crack tip and equivalent straight crack tip (fig.3), that maximal range of plastic zone was obtain under free surfaces. Position of maximal range of plastic zone under free surfaces is corresponding with shear lips (dark colour in fig.3 – the influence of crack closure during crack growth [6]).

Comparison FEA solution between elastic stress intensity factor and range of plastic zone in front of the real crack tip are shown in fig.4.

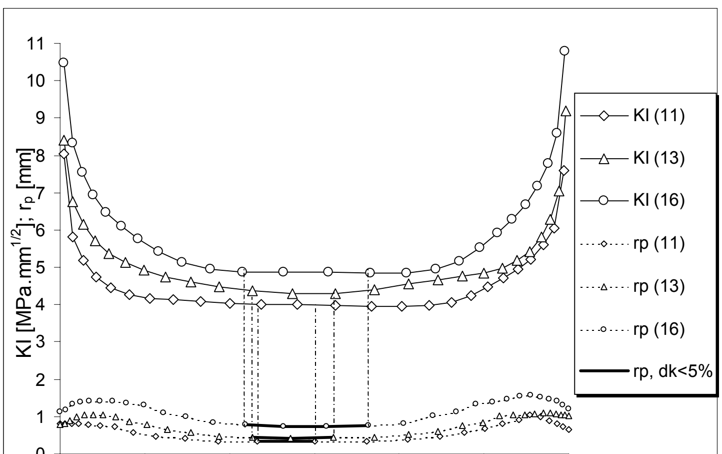

Fig.4 – Stress intensity factor and range of plastic zone in front of the real crack tips. Thick curves delimit area where is range of plastic zone increasing up to 5% of total range.

Validity of elastic stress intensity factor was determine on the base of range of plastic zone increasing (fig.4). The experiment results show, that crack extends more in the central area of the specimen thickness (mid-thickness) than at the surfaces.

Above mentioned results confirm condition for modelling of the crack tip perpendicular to free surfaces [1]. Condition of crack tip modelling results from discrete FEA model and elastic stress intensity factor behaviour.

Computation of J-integral along the straight crack tip has been performed on the base of above mentioned results.

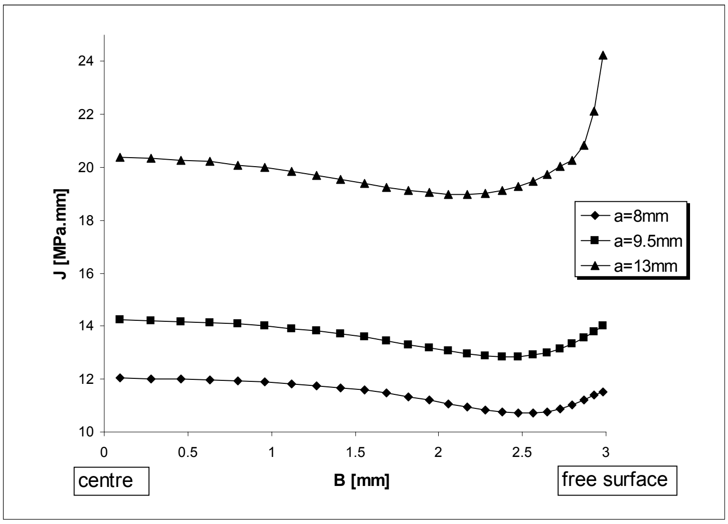

Fig.5 - J-integral value along straight crack tip for loading of maximal stress.

The value of change of J-integral from centre of specimen to the free surfaces has been used for emendation of crack tip geometry. This parameter has been used only up to maximal range of plastic zone. From fig.3 is evident that shear lips are forming in the area between maximal range of plastic zone and free surface. Linear extrapolation of emended crack tip geometry has been used in the area between maximal range of plastic zone and free surface.

Proposed technique of fatigue crack growth prediction is schematically show in fig.6.

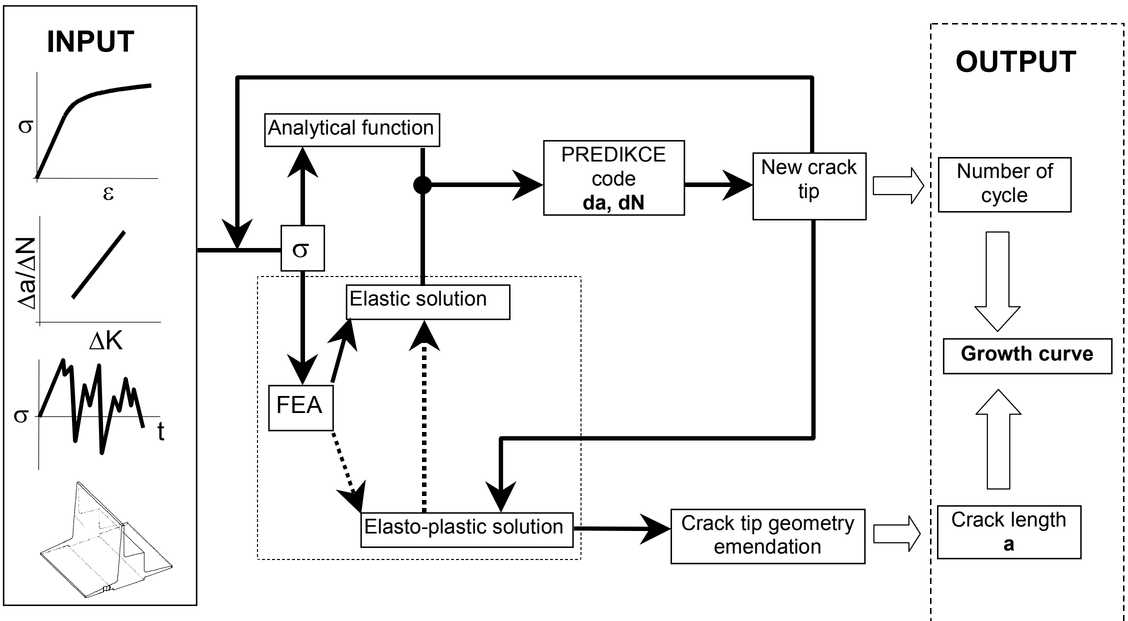

Fig.6 – Schematic technique of fatigue crack growth prediction in 3D body.

Application

Experimental measurement on M(T) specimen and real part of aircraft structure has been selected for application above mentioned technique. Booth parts has been made from same Al-alloy and loaded same random load sequences of real aircraft structure.

Comparison between calculation crack tip and real crack tip on the M(T) specimen are in fig.6.

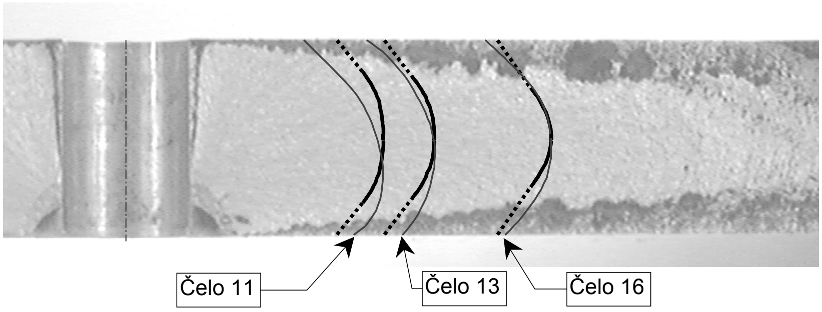

Fig.6 – Comparison between emendation straight crack tip geometry (thick curve) and real crack tip geometry (thin curve). Doted line marked linear extrapolation of crack tip emendation towards free surface.

Furthermore the results of fatigue crack growth prediction on the wing flange plate [1] was used for verification of proposed technique. The final crack tip geometry from experimental measurements has been chosen for verification stated above technique. Fig.8 shows comparison between experimental measurement and calculated crack tip.

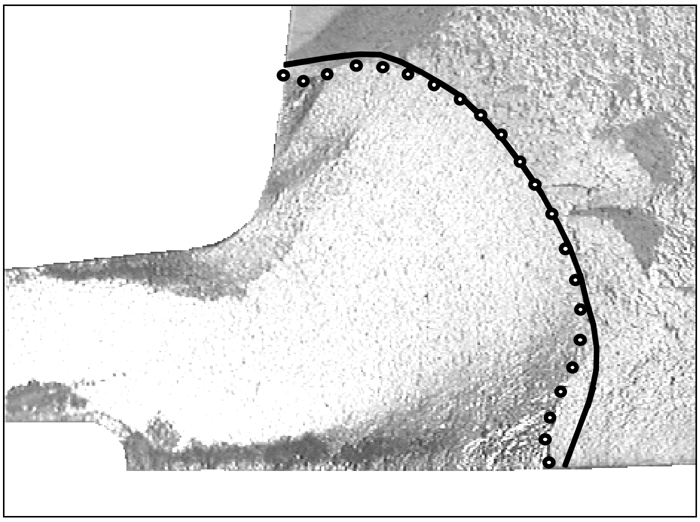

Fig.8 – Comparison between final calculation crack tip geometry (thick curve) and final crack tip geometry from experimental measurements (points).

Conclusion

The submitted article presents proposed technique for qualified assessment of fatigue crack growth rate in 3D body during random loading. The technique was verified on the real part of aircraft structure. The technique has been based on fatigue crack length calculation from elastic FEA solution with geometry boundary condition and emendation of crack tip geometry on the base of elasto-plastic FEA solution. The presented technique has arisen from aircraft producer requirements for certification and operation of structures designed under damage tolerance philosophy.

This work was execute under financial support of state funds through the mediation of the Ministry of Industry and Trade of the Czech Republic.

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