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FATIGUE TESTS OF NOTCHED SPECIMENS - MODELS AND EXPERIMENT

ÚNAVOVÉ ZKOUŠKY TĚLES S VRUBY - MODELY A EXPERIMENT

Abstract

The paper present a model of synthetic fatigue stress curves of specimens with a bored fatigue crack. The model is verified by fatigue tests on the cracked specimens with and without a cold expanded hole on the end of a crack. A stress gradient and cold working effect on a fatigue strength are discussed. FEM calculation results and experimental stress analysis of specimens with composite repair of crack are compared.

Abstrakt

Příspěvek pojednává o modelu konstrukce syntetických únavových křivek těles se zavrtanými únavovými trhlinami. Ověřuje ho únavovými zkouškami těles se zavrtanou trhlinou s protaženým a neprotaženým otvorem. Diskutuje vliv gradientu napětí a efektivní vrubový účinek protažení otvoru na únavovou pevnost. Porovnává výsledky výpočtů napjatosti pomocí MKP a pomocí metod experimentální analýzy napětí na tělesech s kompozitovou opravou únavových trhlin.

1 INTRODUCTION

At present, the finite element method (FEM) is a standard method for assessing the states of structural deformation and stress. Nowadays new experimental stress analysis methods are going to bring real information about the strain field in the critical area of a part, for example 3D ESPI or correlation systems. Local non electric methods are also in using, for example strain sensors in optical fibres (Fiber Brag Gratings) [1]. The classical nominal stress approach (NSA) is based on the classification of stress states (tensile stress, bending stress, local stress, etc.) and on the calculation or measurement of stress amplitudes and mean stress values in the critical cross section. It assumes the knowledge of the fatigue stress curve (S-N curves) in nominal stresses or at least its qualified estimation. The main disadvantage of NSA is its complicated application in the FEM calculations, because it requires calculating stress concentration factor and calculation of the nominal stress. For this reason, the so-called local approaches are applied. In the region of a high-cycle fatigue, i.e. approximately ower a service life of $N=5\cdot10^4$ cycles, it is sufficient to use the local elastic stress approach (LESA). The advantage of this approach is that the local stresses and FEM calculations can be used. Some of the most important aspects of this method will be discussed in the following paragraphs, where the method will be compared with the nominal approach.

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2 ANALYTICAL MODELS OF THE NOTCH EFFECT

2.1 Stress concentration and effective notch effect on the fatigue strength

It is also known that the effect of the stress peaks on the notch fatigue strength is not as significant as it would correspond to the theoretical stress concentration factor K_t. Experiments define the effective notch effect on the fatigue limit by a notch factor K_f. Let us define the ratio of the shape and notch factor by the fatigue ratio n. The methods for expressing the n quantity can be split into two major groups. The first group is formed by relations that are determined in dependence on the notch root radius, ρ. The second group involves expressions depending on the magnitude of the relative stress gradient, G. In the Tab. 1 are a representative rules for the both groups of fatigue ratios n_ρ and n_G .

Tab. 1 The ratio n, of the shape and notch factor

Author	Fatigue ratio n	Note	Eq.
Neuber	$n_\rho = 1 + \frac{A}{\rho} \cdot \left(1 - \frac{1}{K_f}\right)$	where A=f(R_m) is the Neuber factor	(1)
FKM - Guideline[2]	$n_G = 1 + \sqrt[e]{G} \cdot 10^{-\left(a + \frac{R_e}{b}\right)}$	where R_e is the yield strength, a,b,e are regression parameters	(2)

2.2 Synthetic nominal and fictive notch fatigue curves

For the FEM applications, the expression by means of the stress gradient, G, especially with according of the equation (2), turns out to be more convenient. An application of this regression model needs the fatigue experiments on specimens with different stress concentration factors. The S-N fatigue stress curves of the used material e.g. the Al-alloy 2024 T3, according to MIL-HDBK catalogue [3] here, was found, and on the R_m=462 MPa tensile strength modified. The K_t factors of published specimens data were 1.0; 1.5, 2.0, 4.0, 5.0.

The best approximation model, according of minimum mean square error (MSE) was determined in the form of the equation (2). Analogously to the K_f factor introduced in the region of the permanent fatigue strength, it is possible to define the notch factor, $K_{f,N}$, in the region of the limited life.. The next rule was proposed to extend this fatigue ratio $n_{G,N}=f(N)$ in the limit fatigue life region:

$$n_{G,N}(N) = \frac{K_t}{K_{f,N}} = 1 + (G)^{\frac{1}{e}} \cdot 10^{-\left(a + \frac{R_m}{b}\right)} \cdot \frac{(\log N)^E}{B + (\log N)^E} , \tag{3}$$

with the parameters e=2, a=0.6, b=2700, E=4.0 and $B = \frac{-650}{(1+G)^{3.0}}$.

To obtain the fatigue curve of virtual stress values at the notch root in the region of the limited fatigue life it could be written by analogy

$$\sigma_{FEM} = \frac{K_t}{K_{f,N}} \cdot \sigma_C = n_{G,N} \cdot \sigma_C , \tag{4}$$

Such local S-N curve must lie above the smooth specimen

3 FATIGUE EXPERIMENTAL INVESTIGATIONS

Different experiments were done during a research of composite aircraft structure repairs. The fatigue curves and its synthetic models for Al- alloy specimens with the bored edge crack are demonstrated here. Both types of flat specimens with drilling edge crack were used, with and without a cold expanded hole on the end of a crack. The S-N curves were examined at the ČVUT in Prague on the high frequency test machine AMSLER HFP 100 kN. On the Fig. 1 the experimental results and synthetic fatigue curves which have been calculated according above described analytical models are depicted. Values of stress concentration factors, K_t and relative stress gradient, G of the Mises stress in the notch root were calculated on the FEM models.

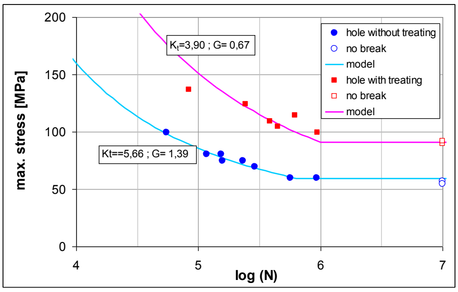


Fig. 1 Fatigue curves of Al alloy edge cracked specimens with and without treating of drilled hole in the crack tip.

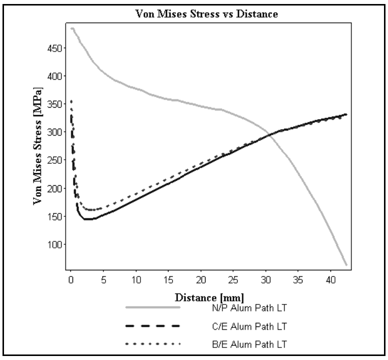
4 NUMERICAL AND EXPERIMENTAL STRAIN ANALYSIS OF COMPOSITE PATCH

The FE model examines and compares two specific patch fibre and adhesive system combinations, namely, carbon fibre/adhesive SW 9323 and boron fibre/adhesive FM 73. The crack, longitudinally centrally located on a single side of the 2 mm thick so-called dog bone specimen, is 0.1 mm wide and 4.375 mm long with a 3.25 mm diameter hole, drilled at the crack tip. The thickness of the adhesive layer was set to 0.2 mm. The patches were bonded onto the specimen employing an adhesive layer composed of cohesive elements. The results of the both analysis indicate that the examined patch materials are extremely effective at reducing the stress intensity factor and gradient of strain. The comparison of FEM results of Mises stress distribution along the transverse and longitudinal paths are depicted in Fig. 2 and Fig.3. However, it should be noted that the relatively higher stiffness of the boron fibers induces a compliance discontinuity in the model leading to peak stresses occurring in distal regions.

Quasistatic loading tests of specimen with a tri-layer carbon composite repair on the bored edge cracks were performed at the ČVUT in Prague. The special adhesive FM 73 for gluing of the patch was applied in Aero Vodochody. To compare strains distribution on the patch/in the patch with FEM calculation results, an experimental strains investigation were done. Both strain gauge measurement and fibre optic methods with Bragg Gratings Sensors (FBG) were used. The measurement systems HBM Spider 8 and the optic integrator SpectralEye SE400 were used for both strain gauge and optic fibre measurement. The comparison of measured values of the FBG sensor, strain gauges and values of FEM calculation is showed on the Fig. 4. Three local points in the cross section of the specimens were included in comparison. The first point is laying on the top of the patch and two others are far from the cracked edge on the aluminium plate. All data were linear with loading. Values of the relative deviations between numerical and experimental results were under 11 percent.

5 CONCLUSIONS

A performed analysis of an effective fatigue notch effect has showed that the synthetic fatigue curve model can give practical usable prediction of the notch effect or the S-N curves of arbitrary stress concentration factor and relative stress gradient in the notch root. FEM analysis on the model with composite repair simulation showed that both carbon as well as boron composite patches are effective to reduce cracks stress peaks and reinforce a damaged area. Fibre optic Bragg gratings sensors for local strain measurement were at the ČVUT Prague first time used.



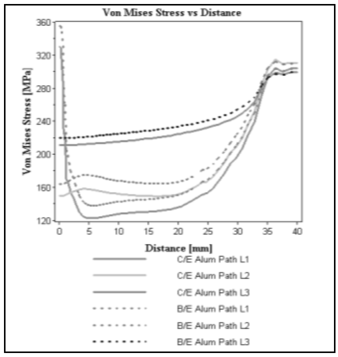


Fig. 2 and 3 Comparison of the Mises stress-distance profiles in aluminium parts for the carbon/SW9323 and boron/FM 73 system for various nodal paths.
(LT =transversely – on the left, L = longitudinally – on the right, N/P= without the patch)

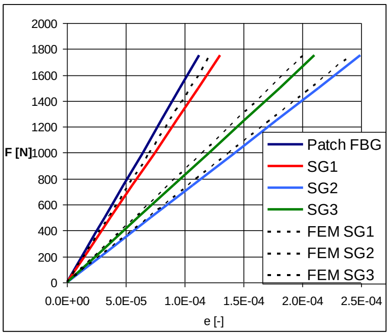


Fig. 4 Comparison of the FEM strain calculation with experimental investigation

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