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Analysis of the Effectiveness of the Fatigue Criteria for Biaxial Loading of Notched Specimen

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Abstract. This article deals with biaxial fatigue strength of notched cylindrical specimen made of Cr-Al-Mo steel and tested under combined tension and torsion loading. Fatigue life is one of the important factors in design since majority of engineering components are subjected to variable loading. Most of mechanical components in engineering practice are subjected to combined loading, which can lead to sudden fatigue failure. Experiments were focused on the high-cycle fatigue region (over 10^5 cycles to final failure). The most relevant goal of this paper is to verify the efficiency of modified fatigue criteria.

Introduction

Metal fatigue can result in an unexpected and catastrophic failure [1,2]. Therefore, developing a fatigue-safe structural component is probably one of the critical problem in theindustry. Throughout last thirty years, a permanent effort is applied to the fatigue damage prediction. Many bi-axial fatigue criteria have been represented in the literature [1-3].

Many machine parts containing various notches and fatigue cracks mostly initiate at notch. The assessment of the notch weakening effect on the fatigue strength and life is essential in fatigue designs. These criteria are often based on the critical plane approach formulated by Fatemi [4]. Also modified classical criteria can be used for life prediction of notched specimen. Modification of fatigue criteria for notched was proposed by authors R. Nemeš and J. Pokluda [5].

The motivation of this work is: (a) to verify the efficiency of classical and advanced multiaxial criteria on using smooth specimens made of low-alloy high strength steels, (b) to apply those criteria to notched specimens.

Theory

Multiaxial Loading. In the continuum mechanics is the state of deformation and stress described by tensors. The most commonly used type of loading in engineering practice is the sinusoidal harmonic loading. Generally, the sinusoidal loading can be expressed as:

$$\sigma_{ij}(t) = \sigma_{ijm} + \sigma_{ija} \sin\left(\omega_{ij}\, t + \varphi_{ij}\right). \qquad (1)$$

Fatigue Criteria. In this paper fifteen classical and advanced multiaxial criteria were applied to predict thefatigue life of specimens made of high-strength steel. The multiaxial criteria

divide the stressspace to the safe and the unsafe parts. The points bellow the boundary line lie in the safe region whereas the points above the line are in the unsafe region.
The most general form of fatigue criteria can be written as an inequality [2,3]:

$$a.f\left(\tau_a\right)+b.g\left(\tau_a\right)\leq f_{-1}. \tag{7}$$

The accuracy of the fatigue life prediction by means of multiaxial criteria can be expressed by the so-called error index I:

$$I = (LHS - RHS).100\% \frac{\square}{RHS}. \tag{2}$$

where RHS is the right-hand side of the inequality. The error index expresses a percentage of deviation from the real fatigue life. The ideal prediction leads to $LHS = RHS$, i.e. $I = 0$. The positive value of the error index means, that the criterion yields conservative results, that the real fatigue life is higher than that calculated.

Scope of this article does not allow a deeper analysis of all the compared criteria, and for this reason are discussed only some selected criteria:

McDiarmid criterion. The McDiarmid criterion is often used in practice, because this criteria is used in commercial fatigue software. McDiarmid identifies the plane of maximum shear stress range. Damage is computed on this plane by combining the shear stress and normal stress [6]. The McDiarmid criterion can be written according to convention used here generally:

$$\frac{f_{-1}}{t_{PI}}\tau_{a,\max}+\frac{f_{-1}}{2R_m}\leq A_{MD}.f_{-1} \tag{3}$$

In this equation, R_m represents the ultimate strength of material. The subscripts a and max denotes amplitude and maximum value of stress. The parameter A_{MD} ($0 < A_{MD} \leq 1$) is obtained from Wöhler curves.
Matake criterion. This criterion [1,7] can be expressed as:

$$C_M\, a_M\, \tau_{a,MSSR}+D_M\, b_M\, \sigma_{\max,MSSR}\leq A_M\, f_{-1} \tag{12}$$

Subscript $MSSR$ by normal and shear stress means critical plane set criteria according to Maximum Shear Stress (or Strain) Range. Parameters a_M and b_M in Matake criterion are defined as $a_M = \kappa$ and $b_M = 2-\kappa$. Variable κ is fatigue limits ratio $\kappa = f_{-1}/t_{-1}$. Parameters A_M, C_M and D_M are equal to 1 for smooth specimens.
Keunmegna criteria. This criteria based on integral approach is one example of advanced stress based multiaxial criteria [8]. The Keunmegna (integral approach) criterion can be written as:

$$\sqrt{\int_{\varphi\_0}^{2\pi}\int_{\psi-0}^{\pi}\frac{\phi\left(\tau_{a,}\sigma_a\sigma_m\right)}{4\pi}\sin\psi\cdot d\psi\cdot d\varphi}\leq Q_N\, f_{-1}. \tag{15}$$

The φ, ψ are Euler angles between a global coordinate system and an examined plane. Subscript m denotes mean value of stress σ. The function Φ can be expressed as:

$$\phi\left(\tau_{a,}\sigma_a\sigma_n\right) = A_{ELS,\tau} a_K \tau_a + B_{ELS,\sigma} b_K \sigma_a + D_{ELS,\Sigma} d_K \sigma_m \quad . \tag{16}$$

The a_K, b_K and d_K are material parameters and parameters with subscription *ELS* represent correlation of elevation of local stresses caused by cross-sectional reduction. The parameter Q_N is equal to 1 for smooth specimens.

Table 1. A Average I_{avr} and absolute average $I_{ABS,avr}$ values of error indexies. Abbreviations: EQ- Ellipse Quadrant, EA-ellipse arc, Critical Plane approach, IP - Integral approach.

Criterion	$I_{ABS,avr}$ [%]		I_{avr} [%]		*Var(I)* [-]	
Specimen	Smooth	Notched	Smooth	Notched	Smooth	Notched
Gough-Pollard	7,4	9.8	-3,4	-10.8	1.8	4.8
Gough-Pollard	7,3	19.8	-5,4	-21,8	2.3	9.0
Dang Van	7,4	13.7	-3	-14.8	1.7	6.2
Crossland	7,3	9.9	-5,4	-11,8	1.8	4.2
Sines	11,9	15.8	-11,2	-19.2	1.7	7.3
McDiarmin	7,1	8.7	-3	-9.8	1.5	4.2
Findley	7,1	14.6	-3,4	-15.8	1.8	6.5
Matake	7,1	13.5	-3,1	-12.5	1.2	5.1
Kenmeugne CP	11,2	28.7	4,7	16.9	2.9	7.1
Kenmeugne IP	8,8	13.7	3,2	12.5	3.7	5.2
Spagnoli	10,5	11.6	4,3	9.9	2.8	5.2
Papadopoulos IP	7,5	19.8	-3,3	-14.5	2.6	6.7
Papadopoulos CP	11,1	17.6	-6,3	-18.9	2.1	7.7
Zenner-Liu	8,5	17.1	4,2	15.5	2.2	6.5
Goncalves at all	7,6	6.7	-3,4	-7.8	1.6	2.9

Goncalves et alii. Criterion proposed by Goncalves, Araujo and Mamiya [9] was modified using parameters A_G and B_G. It is based on a construction of minimum circumscribed ellipsoid over the load path in five-dimensional deviatoric Ilyushin space. The Gonçalves criterion is expressed as

$$A_G . a_{GAM} \sqrt{\sum_{i=1}^{5} d_i^2} + B_G . b_{GAM} \sigma_{1,\max} \leq f_{-1} , \tag{18}$$

where parameters d_i can be determined from minimum and maximum values of the transformed deviatoric stress tensor

Experimental Procedure

The specimens were made of the high-strength low-alloy Cr-Al-Mo steel. The experiments were used smooth specimens and notched specimens. Both types of specimens were subjected to pure bending and pure torsion loading and its synchronous combination to final rupture. The V-notches present are deep 1 mm, and a notch opening angle is 90°. In both geometries for notched and smooth specimens is the diameter 8 mm in traverse area. The experimental work was realized at the Brno University of Technology. The fatigue experiments were made by means of the multiaxial-test machines MZGS-100. Specimens were loaded at the room temperature up to final rupture. The applied loading of frequency 29Hz comprised symmetric (R = -1) sinusoidal bending and torsion and their synchronous in-phase combination**.**

Summary

The calculated error indexes are shown in Table 1. For all criteria were calculated average I_{avr} and absolute average $I_{ABS,avr}$ values of error indexies and variance Var(I). The comparison of multiaxial criteria data relevealed that the Matake criterion was the most successful in the fatigue life prediction of smooth specimen. In the case of notched samples, the modified Goncalves is the best. The $\mathrm{I}_{\mathrm{AVR}^{\cdot\cdot},\mathrm{avr}}$ = 6.7 and $\mathrm{I}_{\mathrm{avr}}$ = -7.8. Also, the variance of Goncalves criteria ($Var(I)$ = 2.9) is favorable in comparison with other criteria. The Table 1 shows that the I_{avr} of fatigue criteria is mostly negative.

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