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Analysis of the coefficient of normal stress effect in chosen multiaxial fatigue criteria

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ABSTRACT

The paper undertakes a comparison of the experimental and calculated fatigue lives by using criteria formulated by Findley, Matake and Dang Van for S355J2WP, S355J2G3 and 30CrNiMo8 steels. The considered criteria include the coefficient *k* (the coefficient of material sensitivity to the normal or hydrostatic stresses) which originally is related to the fatigue limits. It is shown that the value of *k* coefficient depends on the number of cycles to failure and better results are obtained using the proposed idea of calculating the *k* value for number of cycles specified for analysed steels than using the original concept of the fatigue limits. Analysis of the criteria consisted in comparison of the experimental and calculated results obtained for different values of the *k* coefficient determined for different number of cycles. The results of calculations were compared with the experimental results for cyclic bending, torsion and proportional combination of bending with torsion.

1. Introduction

Fatigue of structural materials is a very complex phenomenon, and fatigue failure is dependent on various factors, such as the type and state of the material [1], geometry of the element [2,3], the kind of loading, history of loading [4–7], stress state [8,9], and residual stresses [10,11]. It is quite common [1,4,9] to use phenomenological models which reflect general macroscopic material response to fatigue loading instead of modelling of complex behaviour of material at the micro or mesoscopic scale. In such modelling the so-called reference fatigue curves which reflect general cyclic response to uniaxial fatigue loading are usually necessary for fatigue life calculation. These experimentally curves obtained, e.g. under cyclic tension–compression and torsion loadings have a form of functions between fatigue life N_f and amplitudes of applied stresses or strains [1].

In the case of the multiaxial stress state occurring usually in real structures or machine elements, it is necessary to reduce that state to an equivalent uniaxial state. Depending on the used fatigue hypothesis the equivalent state could be calculated for the whole loading history or only for amplitudes. Finally, the equivalent stress amplitude is used to calculated fatigue life via the mentioned reference curve. The present article is focused on the fatigue hypotheses that relate the reduction of multiaxial stress state with a plane in material with fixed orientation. This methodology has gather a lot of attention since its emerging in 1935 [13] due to its wide range of applicability and physical background [9,12,14–22]. It is known as the critical plane approach. There are numerous critical plane fatigue criteria based on various assumptions and parameters describing the fatigue processes. Some criteria are based on combination of the hydrostatic and the shear stresses [1,15,22–24], some others are linear or nonlinear functions of normal and shear stresses [15,25–27]. There are also criteria using strain energy density being a combination of energy density of normal and shear strains [1,4,15,28–30]. Participation of particular stress components occurring on the critical plane to fatigue damage in the criterion is determined by consideration of a certain number of material coefficients. The most common criteria reduce multiaxial state to equivalent shear stress state using linear relation between normal and shear stresses on the critical plane. The physical interpretation was given by Stanfield [13] as follows: the normal stress changes an internal friction forces between two surfaces in the critical plane which reduces or adds the shear fatigue endurance. Such influence of the normal stresses [1,15] depends on material type which is reflected by certain material coefficient *k*. This coefficient is usually derived (if possible) by application the formula for equivalent stress to the fatigue limits obtained under uniaxial cyclic torsion, bending and push–pull loadings (reference curves). It must be noticed that using the fatigue limits restrains the application of this equivalent stress formula to regime around fatigue limit. Unless the uniaxial

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Nomenclature

E	Young's modulus
k	coefficient of material sensitivity to the normal or hydrostatic stresses
m_σ	fatigue strength exponent for fully reversed cyclic bending
m_τ	fatigue strength exponent for fully reversed cyclic torsion
N_f	number of cycles to failure according to reference curve (fatigue characteristic)
$\sigma_{0.2}$	yield stress
$\sigma_{af,b}$	fatigue limit for fully reversed cyclic bending
σ_{UTS}	ultimate tensile strength
ν	Poisson ratio
τ_{af}	fatigue limit for fully reversed cyclic torsion

Table 1
Basic mechanical properties of the considered materials.

Material (EN)	E (GPa)	$\sigma_{0.2}$ (MPa)	σ_{UTS} (MPa)	ν (–)
S355J2WP	215	414	556	0.29
S355J2G3	213	394	611	0.31
30CrNiMo8	217	812	1014	0.30

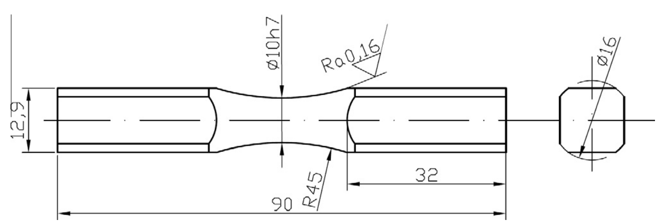

Fig. 1. Specimen geometry used for fatigue tests of two steels: S355J2WP and S355J2G3 [31].

fatigue reference curves have the same fatigue strength exponents (m_σ, m_τ). In other case, the k coefficient depends on a number of cycles to failure N_f. In spite of recent development of the critical plane approach this feature has not been noticed and studied.

The aim of the paper is to analyse the three commonly used fatigue criteria based on the critical plane concept formulated by Findley [25,26], Matake [27] and Dang Van [24] in respect to changes in k coefficient being m_σ different from m_τ (the slopes of fatigue characteristics). Although, the applied criteria belongs to high cyclic fatigue regime the changes in k value cannot be disregarded. The considered criteria include the k coefficient expressed originally through the fatigue limits. The test results for bending, torsion and proportional combination of bending with torsion are used in the analysis. The analysis of the criteria consisted in comparison of experimental and calculated fatigue lives for different values of the coefficient k. Values of the coefficient k were determined for six different numbers of cycles and compared with the value obtained for the fatigue limits.

2. Experimental data

The calculated results were compared with the experimental ones for three materials: alloy steels: S355J2WP (according to PN: 10HNAP) [31] and S355J2G3 (according to PN: 18G2A) [31,32] and a medium-alloy steel 30CrNiMo8 [33]. Basic

Table 2
Loading parameters and the experimental number of cycles to failure N_{exp} for S355J2WP steel [31].

σ_a (MPa)	τ_a (MPa)	N_{exp} ($\times 10^3$ cycles)		
379	0	158	237	130
360	0	317	226	–
352	0	501	465	–
319	0	1485	1360	–
0	200	101	231	–
0	192	303	242	–
0	178	550	401	–
0	130	2068	2323	–
175	175	120	160	–
162	162	250	286	–
154	154	328	474	–
145	145	1630	2052	–

Table 3
Loading parameters and the experimental number of cycles to failure N_{exp} for S355J2G3 [31,32].

σ_a (MPa)	τ_a (MPa)	N_{exp} ($\times 10^3$ cycles)		
400	0	153	127	166
365	0	403	335	378
275	0	1295	2938	3363
0	224	300	236	282
0	196	632	813	784
0	184	3150	4238	2310
200	200	190	225	168
183	183	739	626	610
167	167	2117	1409	1320
316	158	110	100	111
284	142	345	366	347
260	130	739	626	610
222	111	2117	1409	1320

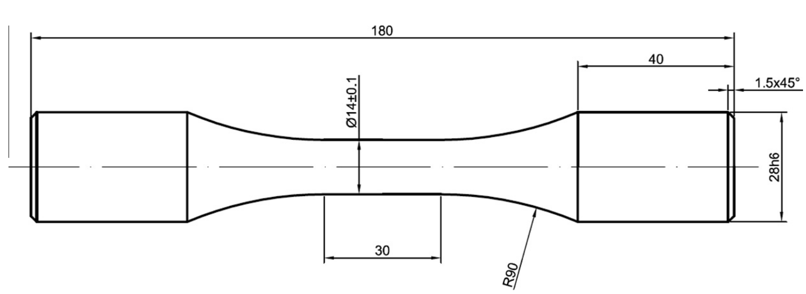

Fig. 2. Specimen geometry used for tests of the 30CrNiMo8 steel [33,34].