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Review

On the material's sensitivity to non-proportionality of fatigue loading

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ABSTRACT

Many researches have shown that fatigue behaviour of a number of materials is significantly different in non-proportional loading conditions when compared to proportional ones. These differences concern stress–strain characteristics, fracture, the phenomena taking place in the material, and finally fatigue life. The aim of this study is to provide a survey on basic experimental results and methods of taking into account a material's sensitivity to non-proportionality of loading in multiaxial fatigue life estimation models for metals.

1. Introduction

It is well known that material fatigue is a common cause of failure of engineering structures. In real operating conditions many of these structures are very often subjected to multiaxial loadings. Despite a growing number of studies, a multiaxial fatigue assessment still remains a great challenge. This is due to the fact that the fatigue phenomenon is very complex and fatigue failure is affected by many factors. On the other hand, all methods of multiaxial fatigue life estimation present in the literature have some limitations and drawbacks, as a result of which none of them are fully accepted as suitable for a general case of multiaxial loading.

In most cases, material properties in relation to multiaxial fatigue criteria are taken into account by the inclusion of uniaxial fatigue limits for fully reversed tension-compression or bending and torsion. In some of them, other parameters of a material, such as ultimate tensile strength, pulsating fatigue limits or uniaxial *S-N* curves, are also used.

Recently, more attention has been paid to another material property, which is sensitivity to non-proportionality of loading. In new criteria proposals, Anes et al. [1], Noban et al. [2] and Li et al. [3] used material parameters expressing a material's sensitivity to non-proportionality of loading. It was observed that even the criteria which correctly distinguish proportional and non-proportional loadings by using a proper damage parameter sometimes do not give satisfactory results for some materials or load cases It is well known that the estimation of fatigue strength in torsion or proportional loadings by using fatigue strength in tension-compression or bending, as well as Huber-von Mises $(1/\sqrt{3})$ or Tresca (1/2) equivalence ratio, is inaccurate. Some researchers suggest that it is not enough to use only the fatigue limits or strengths in tension-compression or bending and in torsion to estimate the fatigue limit or strength in non-proportional loadings, since different materials are not equally sensitive to non-proportional loadings [1,3]. What is more, non-proportional loading can be characterized by different degrees of non-proportionality.

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Many factors have been proposed to define and describe the degree of non-proportionality. They are discussed in Section 3. In [4], non-proportional loading is defined as loading which results in the rotation of principal axes of stress or strain. From that point of view, the degree of non-proportionality is related to the range and duration of principal axes' rotation in a loading cycle. Non-proportionality of loading also causes the rotation of shear stress or strain vectors on most of the sectional planes crossing the analyzed point of the material and rotation of stress or strain vectors in normal-shear stress ($\sigma - \tau$) or strain ($\varepsilon - \gamma$) coordinates. This rotation results in the description of locus, which in the fatigue literature is most often referred to as the loading path.

The most examined feature of loading that affects the degree of non-proportionality is the phase shift between periodical time courses of strains or stresses. The degree of non-proportionality rises as the phase shift angle rises from 0° to 90°. Thus, in view of the phase shift, the most non-proportional loading is the one characterized by the phase shift angle δ equal to 90°. Fig. 1(a) presents paths for loadings with different phase shift angles which have the same range in Huber-von Mises' strain coordinates. The loading path for proportional loading is a straight line. The most non-proportional loading, for which $\delta = 90°$, the frequency ratio equals 1 and strain ratio $\lambda_a = 1/\sqrt{3}$ gives a circular loading path. The degree of non-proportionality is then related to the features of the loading path such as the described area, length or longest to shortest chord ratio. In [5–7], the term "degree of non-proportionality" was used regarding the loading paths.

However, the degree of non-proportionality also depends on shear to normal strains or stresses amplitudes ratio λ_a, loadings waveforms frequencies ratio and their shape. Even if the phase shift angle is equal to 90°, the degree of non-proportionality can be small if one of the strains or stresses dominates, that is the λ_a ratio tends to zero or infinity (Fig. 1). In [8], it was shown that for two different materials the same value of the phase shift angle and stress ratio can have a different influence on fatigue life. It can be interpreted as a different sensitivity to non-proportionality of loading.

2. Experimental results

Multiaxial strain-controlled fatigue tests have shown that for a number of materials cyclic hardening is higher in the case of non-proportional loadings than in the case of proportional loadings [4]. In [9], Kanazawa et al. assumed that from the microstructural point of view this additional non-proportional hardening is explained by the rotation of strain principal axes, which occurs in the case of non-proportional loadings and causes that more energy is needed to form stable dislocation structures. Consequently, the stress level is higher for a specified strain level, so the measured forces are also higher [10].

An example showing additional non-proportional hardening are experimental results presented by Shamsaei, Fatemi and Socie in [11,12] for 304L steel fatigue tests were conducted using in-phase and 90° out-of-phase loadings with strain control. Cyclic strain–stress behaviour for 304L steel is shown in Fig. 2, against monotonic uniaxial and cyclic proportional Ramberg-Osgood curves. Maximum equivalent von Mises stresses were calculated using the following formula:

$$\sigma_{eq}(\mathrm{MPa}) = \max_{\omega t}\left(\sqrt{[\sigma_a \sin(\omega t)]^2 + 3[\tau_a \sin(\omega t - \delta)]^2}\right), \quad (1)$$

where σ_a and τ_a are amplitudes of normal and shear stress, respectively, and δ is a phase shift angle. Maximum equivalent von Mises strains were calculated analogically:

$$\varepsilon_{eq}(\mathrm{mm/mm}) = \max_{\omega t}\left(\sqrt{[\varepsilon_a \sin(\omega t)]^2 + \frac{1}{3}[\gamma_a \sin(\omega t - \delta)]^2}\right), \quad (2)$$

where ε_a and γ_a are amplitudes of normal and shear strain respectively. The 304L steel showed cyclic hardening as well as additional non-proportional hardening, since points representing non-proportional loading lay above points representing proportional loading. To emphasize the effect of hardening, dashed lines corresponding to Ramberg-Osgood curve raised and lowered by 150 MPa were added. In the same papers, the authors also presented experimental results for 1050 quenched and tempered steel. The cyclic strain–stress behaviour for this material is presented in Fig. 3. A contrary behaviour can be observed there. When comparing cyclic and monotonic strain–stress curves, cyclic softening is visible. In the case of non-proportional loading, no additional hardening occurred.

Another example of a material showing no additional non-proportional hardening can be found in [2,13]. Noban et al. investigated the multiaxial fatigue behaviour of 30CrNiMo8HH

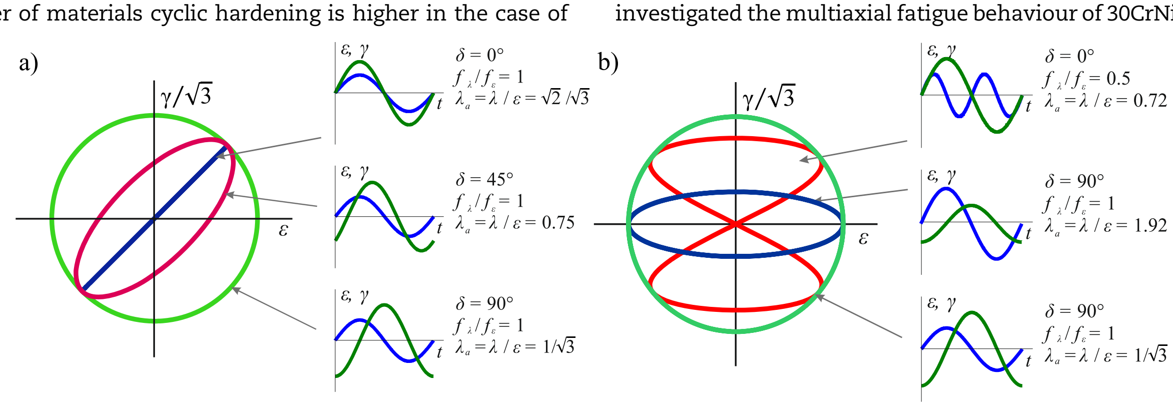

Fig. 1 – Loading paths with different degree of non-proportionality driven by phase shift angle δ (a) and by other features (frequency ratio f_γ/f_ε and amplitudes ratio λ_a) (b).