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A critical distance/plane method to estimate finite life of notched components under variable amplitude uniaxial/multiaxial fatigue loading

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ABSTRACT

The present paper summarises the main features of a design technique we have devised to specifically perform, by post-processing the linear-stress fields in the vicinity of the assumed crack initiation sites, the fatigue assessment of notched components subjected to in-service variable amplitude (VA) uniaxial/multiaxial fatigue loading. In more detail, fatigue damage is estimated through the Modified Wöhler Curve Method (MWCM) applied along with the Theory of Critical Distances (TCDs), the latter being used in the form of the Point Method (PM). According to the philosophy on which the linear-elastic TCD is based, the adopted critical distance is treated as a material property whose length increases as the number of cycles to failure decreases. To correctly apply the MWCM, the orientation of the critical plane is suggested here as being calculated through that direction experiencing the maximum variance of the resolved shear stress. Further, the above direction is used also to perform the cycle counting: since, by definition, the resolved shear stress is a monodimensional stress quantity, fatigue cycles are counted by taking full advantage of the classical three-point Rain Flow method. From a philosophical point of view, the real novelty contained in the present paper is that eventually all the different pieces of theoretical work we have done over the last 15 years by investigating different aspects of the uniaxial/multiaxial fatigue issue are consistently brought together by formalising a design methodology of general validity. The accuracy and reliability of the proposed fatigue assessment technique was checked by using 124 experimental results generated by testing notched cylindrical samples of carbon steel C40. The above tests were run under three different load spectra, by exploring uniaxial as well as in- and out-of-phase biaxial situations, in the latter case the axial and torsional load signals being not only characterised by non-zero mean values, but also by different frequencies. To conclude it can be said that such a systematic validation exercise allowed us to prove that the proposed approach is highly accurate, resulting in estimates falling within the constant amplitude (CA) fully-reversed uniaxial and torsional scatter bands used to calibrate the method itself (this holding true independently of both complexity of the applied VA loading path and sharpness of the tested notch).

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1. Introduction

Examination of the state of the art shows that if, on one hand, several approaches suitable for estimating fatigue lifetime of unnotched engineering materials subjected to VA multiaxial fatigue loading have been formalised and validated through appropriate experimental investigations, on the other hand, only a few attempts have been made so far to devise design methods specifically devoted to the fatigue assessment of notched components damaged by in-service VA multiaxial loading paths.

In more detail, with regard to the problem of estimating VA medium/high-cycle fatigue damage in unnotched materials, so far the scientific community has focussed its attention mainly on the formalisation of approaches taking full advantage of the critical plane concept, such a classical idea being applied in terms of either stress or energy quantities [1–5]. On the contrary, to estimate VA fatigue lifetime of unnotched components failing in the low/medium-cycle fatigue regime, a lot of work has been done by several researchers [6–12] to check the accuracy and reliability of both the SWT parameter [13,14], Kandil, Brown and Miller's criterion [15,16], and Fatemi and Socie's method [17,18].

As to the design strategies that have been explored so far, it is worth mentioning here also that the above criteria were attempted to be applied by post-processing the input load histories not only in the time, but also in the frequency domain [19–22].

Turning back to the problem of estimating fatigue lifetime of notched components damaged by in-service VA multiaxial loading paths, it can be highlighted here that the research work done so far has been mainly based on the idea of extending the use of the

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classical strain-based critical plane approaches mentioned above also to those VA situations involving stress/strain concentration phenomena [23,24]. As to the in-field usage of such a strategy, it has to be said that, unfortunately, correctly estimating root stresses and strains by simultaneously modelling the material elasto-plastic stabilised response under VA loading is never a simple task: this should make it evident that properly using the above approaches results in an inevitable increase of the time and costs of the design process.

In this complex scenario, the present paper attempts to formalise a novel design methodology based on the use of the MWCM [25] (applied in conjunction with the TCD [26]) suitable for estimating fatigue lifetime under VA uniaxial/multiaxial fatigue loading by directly post-processing the linear-elastic stress fields damaging the material in the vicinity of the stress raisers being assessed.

2. The MWCM applied along with the PM

The MWCM [25,27] is a bi-parametrical critical plane approach which postulates that lifetime under CA multiaxial fatigue loading can directly be estimated through the shear stress amplitude, the mean normal stress, $\sigma_{n,m}$, and the amplitude of the normal stress, $\sigma_{n,a}$, relative to that plane (i.e., the so-called critical plane) experiencing the maximum shear stress amplitude, τ_a [28,29]. In order to simultaneously take into account the above stress components, their combined effect is directly evaluated by means of the following stress ratio [30]:

$$\rho_{\text{eff}} = \frac{m \cdot \sigma_{n,m} + \sigma_{n,a}}{\tau_a}, \quad (1)$$

where mean stress sensitivity index m is a material property to be determined experimentally and varying in the range 0–1 [25,30]. Thanks to the way ρ_{eff} is defined, such a stress ratio is seen to be sensitive not only to the presence of superimposed static stresses, but also to the degree of multiaxiality and non-proportionality of the applied loading path [25]. As to the latter aspect, it is worth recalling here that in unnotched materials a fully-reversed uniaxial loading results in a ρ_{eff} ratio invariably equal to unity, whereas under fully-reversed torsional loading ρ_{eff} equals zero [25].

The way the MWCM works in practise is schematically shown by the modified Wöhler diagram [27] reported in Fig. 1a, such a log–log chart plotting the shear stress amplitude relative to the critical plane, τ_a, against the number of cycles to failure, N_f. According to the experimental evidence, it is seen that [25,31,32], given the material, different fatigue curves are obtained as ratio ρ_{eff} varies (Fig. 1a). If the classical schematisation used to summarise fatigue results is adopted also when they are plotted in Modified Wöhler diagrams, any Modified Wöhler curve can unambiguously be defined through the following linear relationships [25,31,32]:

$$k_\tau(\rho_{\text{eff}}) = (k - k_0) \cdot \rho_{\text{eff}} + k_0 \quad \text{for } \rho_{\text{eff}} \le \rho_{\text{lim}} \quad (2)$$

$$k_\tau(\rho_{\text{eff}}) = k_\tau(\rho_{\text{lim}}) = (k - k_0) \cdot \rho_{\text{lim}} + k_0 \quad \text{for } \rho_{\text{eff}} > \rho_{\text{lim}} \quad (3)$$

$$\tau_{A,\text{Ref}}(\rho_{\text{eff}}) = \left(\frac{\sigma_A}{2} - \tau_A\right) \cdot \rho_{\text{eff}} + \tau_A \quad \text{for } \rho_{\text{eff}} \le \rho_{\text{lim}} \quad (4)$$

$$\tau_{A,\text{Ref}}(\rho_{\text{eff}}) = \tau_{A,\text{Ref}}(\rho_{\text{lim}}) = \left(\frac{\sigma_A}{2} - \tau_A\right) \cdot \rho_{\text{lim}} + \tau_A, \quad \text{for } \rho_{\text{eff}} \le \rho_{\text{lim}} \quad (5)$$

where

$$\rho_{\text{lim}} = \frac{\tau_A}{2\tau_A - \sigma_A}. \quad (6)$$

In more detail, given a modified Wöhler curve characterised by a certain value of ρ_{eff}, $k_\tau(\rho_{\text{eff}})$ is its negative inverse slope and $\tau_{\text{Ref}}(\rho_{\text{eff}})$ is its reference shear stress amplitude extrapolated at N_A cycles to failure (Fig. 1a). Further, as explained in Fig. 1a, k is the negative inverse slope and σ_A the endurance limit at N_A cycles to failure characterising the fully-reversed uniaxial fatigue curve ($\rho_{\text{eff}} = 1$), whereas k_0 and τ_A are the corresponding quantities describing the fully-reversed torsional fatigue curve ($\rho_{\text{eff}} = 0$).

It is worth observing here also that both the negative inverse slope and the reference shear stress amplitude defining the fatigue curves to be used to estimate fatigue damage under a ρ_{eff} ratio larger than limit value ρ_{lim}, Eq. (6), are assumed to be constant and equal to $k_\tau(\rho_{\text{lim}})$ and to $\tau_{\text{Ref}}(\rho_{\text{lim}})$, respectively – see Eqs. (3) and (5) [25,30,33]. This correction, which plays a role of primary importance in the overall accuracy of the MWCM, was introduced in light of the experimental evidence that, given the shear stress amplitude relative to the propagation plane, when micro/meso cracks are fully open, an increase of the normal mean stress does not result in any further increase of fatigue damage [34].

To conclude it can be observed that, according to the schematic modified Wöhler diagram sketched in Fig. 1a, given the ρ_{eff} ratio as well as the shear stress amplitude, τ_a, relative to the critical plane, the corresponding number of cycles to failure can directly be predicted according to the following trivial relationship [25]:

$$N_{f,e} = N_A \cdot \left[\frac{\tau_{A,\text{ref}}(\rho_{\text{eff}})}{\tau_a}\right]^{k_\tau(\rho_{\text{eff}})}, \quad (7)$$

the appropriate modified Wöhler curve being obviously defined through Eqs. (2)–(6).

Thanks to its specific features, the MWCM can be used to predict fatigue damage not only in unnotched materials [31,32], but also in notched components, where in the latter case it can be applied in terms of both nominal [25,27] and local stresses [35–39]. In more detail, our multiaxial fatigue criterion can be used in conjunction with the TCD, formalised in the form of the PM, to estimate finite lifetime of notched components subjected to CA uniaxial/multiaxial fatigue loading [39], the correct way of employing our criterion for such a purpose being explained in Fig. 1b and c. As to the PM's *modus operandi*, it is worth recalling here that it was first proposed by Peterson [40], who argued that high-cycle fatigue strength of notched components could accurately be estimated by directly post-processing the stress state at a given distance from the assumed crack initiation point, such a distance being treated as a material properly.

Before briefly reviewing the in-field usage of such a method, it is worth recalling here that the critical distance to be used to estimate finite life of notched components is suggested as being defined as follows [25,38,39]:

$$L_M(N_f) = A \cdot N_f^B, \quad (8)$$

where A and B are material fatigue constants to be estimated from the fully-reversed unnotched fatigue curve as well as from a fully-reversed notch fatigue curve generated by testing samples containing a known geometrical feature [38,41]. With regard to the critical distance value to be used to estimate finite lifetime, it is worth observing here that, according to definition (8), as the number of cycles to failure decreases, length L_M increases. This assumption takes as a starting point the experimental evidence that the size of the plastic zone at the notch tip varies as the magnitude of the applied cyclic force changes: accordingly, since the PM as employed in the present study is applied by forcing engineering materials to obey a linear-elastic constitutive law, the cyclic plastic behaviour of ductile metals is accommodated into a linear-elastic model by simply making the size of the process zone (which is assumed to be related to L_M [25,26]) increase as the amplitude of the applied cyclic stress increases. The above considerations should make it evident that such an idea is, by nature, suitable for designing engineering mate-

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