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New cycle counting method for multiaxial fatigue

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ABSTRACT

Multiaxial fatigue is a very important physical phenomenon in several mechanical components. Fatigue life study under cyclic stresses is of utmost importance to avoid unexpected failure of equipments, vehicles or structures. Among several fatigue characterization tools, a correct definition of a loading cycle under multiaxial fatigue loading conditions shows to be crucial to estimate multiaxial fatigue life.

The aim of this work is to achieve a correct definition for a multiaxial fatigue loading cycle and accomplish a multiaxial fatigue model to estimate block's fatigue life under multiaxial loading conditions. To reach this goal, several loading paths were carried out using the 42CrMo4 low alloy steel under different loading conditions. Sequential, proportional, non-proportional and asynchronous loading effects were modulated through eleven loading blocks. Furthermore, two models were proposed: a cycle counting method and a fatigue life evaluation criterion. The results from the proposed models were correlated with the fatigue data and compared with two well known cycle counting models: the Bannantine and Socie and the Wang and Brown criteria. The proposed models were successfully validated by experimental data. Results show that the new proposals lead to an improved multiaxial fatigue characterization under complex loading conditions.

1. Introduction

In simple fatigue loading cases the cycle definition using an equivalent stress is very prompt and the inherent fatigue life correlations provides acceptable results. However, in complex loading histories, the fatigue life estimations under equivalent stress approaches, most of the times, are not in agreement with experimental data. Equivalent stress approaches are unsuitable to characterize directly the block's fatigue damage, because they yield non-conservative fatigue live estimations. In other words, the loading block's fatigue damage is greater than the one estimated by the greatest equivalent stress found in that same loading block.

Therefore, block's fatigue damage characterization must consider what happens during the entire block's loading history. Multiaxial cumulative damage is commonly calculated using the Miner's rule, or its different versions, as is used in uniaxial loading conditions.

In addition, Miner's rule considers a damage parameter in association with a cycle counting method [1]. Damage parameters must capture the physical fatigue behavior to allow considering the cumulative damage as a cycle damage summation [2–5]. Equivalent damage parameters, such as equivalent stress, keep the time relation between multiaxial load components, which is a plus, but they have some shortcomings. For instance, time histories of an equivalent stress are always positive and due to that, their time history is unsuitable to capture the whole physical damage process.

The load sign of multiaxial load components is essential information because it identifies a different damage behavior. For instance, compression and tension stress states have negative and positive sign and distinct fatigue damage behaviors. Compression stresses tend to slow down the fatigue damage and the tension ones tend to speed up the damage process. Moreover, SN damage curves are established based on a pair of positive and negative reversals i.e. a tension and compression load pair. Each uniaxial reversal contributes in a different way to the SN unitary damage composed by the compression/tension damage pair, in the case of an axial SN curve.

Therefore, a rainflow cycle counting over the time variation of an equivalent stress does not capture whole the fatigue damage behavior [6,7].

Nowadays, new approaches on cycle counting are very few [5–10]. Well-known cycle counting methods use the rainflow method or its variants. They have acceptable results under uniaxial loadings, but under multiaxial loading conditions the fatigue life estimations yields poor results. Some cycle counting criteria are

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critical plane based methods, they use the rainflow method applied to the stress/strain time variation, on each projection plane, to account loading reversals. For instance, Bannantine and Socie (BS) proposed a cycle counting criterion that accounts the number of loading reversals, in the critical plane, through a rainflow routine [11].

Subsequently, a damage parameter is determined, at each reversal, using a critical plane model according to the axial or shear based damage approaches. BS method has some shortcomings in damage characterization, because the contribution of the axial and shear loading components to the fatigue damage are disconnectedly computed. Therefore, the time relation between shear and axial load components is ignored, and the joint damage effect is not captured. Wang and Brown (WB) [2] proposed a new cycle counting method to overcome the sign lost shortcoming in their equivalent strain approach. WB cycle counting criterion is based in the von Mises relative strains and in the classic rainflow cycle counting method.

The loading cycles are extracted from the von Mises relative strain time variation and the WB damage parameter is computed for every extracted cycle. Then, an accumulated criterion must be used to calculate the loading block's total damage in order to estimate block's fatigue life. The WB criterion has one main shortcoming, which is the possibility to miss the greatest stress range during the loading time history [12,13].

Meggiolaro and de Castro, proposed one modification to the Wang and Brown criterion to overcome this shortcoming. The change was to expand the WB criterion to the five-dimensional Euclidean space to ensure that the highest relative strain amplitude is always accounted [6,7]. Wei and Dong proposed an equivalent stress cycle counting method using the time evolution of the equivalent stress in the von Mises stress space. The equivalent stress is mapped to extract loading cycles and overcome the missing loading path-dependency verified on the WB criterion [12–14].

In this paper is studied eleven loading blocks with several different loading effects using the Bannantine and Socie, Wang and Brown and a new proposed multiaxial cycle counting method. The new cycle counting method, the Stress Scale Factor (SSF) virtual cycle counting, is based on the SSF equivalent shear stress early proposed by the authors in [15].

Moreover, a new criterion to evaluate fatigue life under complex loadings is proposed, this method uses the new cycle counting method proposed here and is an update of the SSF equivalent shear stress to block loading conditions.

In order to validate the proposed methods it was performed a fatigue life correlation using fatigue data from eleven loading blocks. Moreover, the proposed models estimations were compared with two state-of-the-art models estimations in this field. Results show that the proposed cycle counting and fatigue life estimation approaches yields better results. In addition, the proposed models computational work is far less than the one necessary in BS and WB fatigue life evaluation.

2. Theoretical development

To estimate fatigue lives from loading blocks is necessary to consider a multidisciplinary approach in fatigue damage characterization. Multiaxial block loadings have much more intricate loading histories than the reference ones used to set up SN curves. To achieve block loading damage is necessary to enter with three main fatigue approaches: a cycle counting method, a damage criterion and a damage accumulation model. The damage criterion is the base stone to set up random fatigue. The damage parameter must capture the fatigue damage behavior to allow set up a cycle counting method and an accumulation model.

2.1. Multiaxial cycle counting

Uniaxial cycle counting is a well-understood matter. Hysteresis analysis to find a load cycle is a method that has proved to be reliable in uniaxial fatigue damage characterization. However, under multiaxial loading conditions such prompt method does not exist. Efforts has been done to adapt the uniaxial cycle counting method to the multiaxial loading histories [16–19]. BS and WB cycle counting methods are an example of that; they use the rainflow paradigm to extract the loading cycles within a multiaxial loading history.

2.2. Bannantine and Socie (BS)

Bannantine and Socie [2] proposed a multiaxial cumulative damage criterion based on a mix of critical plane damage parameter, rainflow cycle counting method and Miner's rule. The main concept behind BS criterion is based on the experimental evidence that some materials are more sensitive to axial strains than to shear strains and vice versa.

Therefore, authors concluded that the axial and shear strains have different damage scales in the same material. Bannantine and Socie considered that the block damage under multiaxial loading conditions could be estimated through axial strains or shear strains.

Thus, the criterion of choice is based on the material sensitivity to axial or shear damage. To evaluate complex loadings Bannantine and Socie proposed that the multiaxial axial and shear strains components could be treated as uniaxial loads in the critical plane search. Therefore, the multiaxial loading is projected into the candidate plane, and then the in-plane and normal strains are separately computed with a rainflow method.

After that the axial and shear accumulated damage is calculated for each plane. The plane with the highest accumulated damage is the critical plane. BS approach states that the rainflow cycle counting on each plane can be associated with the hysteresis loops in that same plane. The BS approach uses the original main paradigm behind the rainflow cycle counting methodology [11,20–22] to capture the critical plane damage. The damage accumulation at each plane is accounted through any cumulative damage model. The most used is the Miner's rule, where is performed by a linear summation of each loading cycle damage. Several accumulative damage approaches based on the Miner's rule can be found in literature [1,23]; they are mainly a non-linear versions of the Miner's original law. In the authors' opinion, the non-linearity in damage accumulation must be left to the damage parameter since SN curves are already non-linear. Therefore, in this study the linear Miner's rule is adopted. The BS damage parameter is determined based on a specific critical plane criterion. For instance, if the axial strains are cycle counted, then a critical plane model based on normal strains must be considered. Likewise, if the in-plane strains (shear strains) are cycle counted then a critical plane based in shear strains must be considered. For example, reversals damage can be accounted using Eq. (1) in shear strains and in axial strains can be used Eq. (2).

Fatemi–Socie (F–Socie) damage parameter:

$$\max_{\theta}\left\{\frac{\Delta\gamma_{\max}}{2}\cdot\left(1+k\cdot\frac{\sigma_{n,\max}}{\sigma_y}\right)\right\}=\frac{\tau'_f}{G}(2N_f)^{b\gamma}+\gamma'_f(2N_f)^{c\gamma} \quad (1)$$

where $\Delta\gamma_{\max}/2$ is the maximum shear strain amplitude on a θ plane, $\sigma_{n,\max}$ is the maximum normal stress on that plane, σ_y is the material monotonic yield strength and k is a material constant, $k = 1.0$ in this case. G is the Shear modulus, $2N_f$ is the fatigue life and τ'_f, b, γ'_f, γ and c are material's constants (cyclic properties).

SWT damage parameter: