Fatigue life assessment under multiaxial complex loading

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Abstract

This paper aims at comparing two different modeling to assess the fatigue life of steel under complex multiaxial fatigue spectrum. The first model is based on a multiaxial fatigue criterion able to describe out of phase loading plus non-linear damage rule. The second one is based on an incremental mesoscale plasticity/damage modeling applied directly on the spectrum studied. Experimental results on 1045 steel are obtained under tension/torsion loading for out of phase variable loading spectrum representative of automotive chassis loading type. It is shown that the criterion with a non-linear damage rule is able to describe the experimental result for full spectrum (with overload) but the identification of the non-linearity is a function of spectrum type. The incremental approach gives better results for simplified spectrum (without overload) without any identification of the non-linearity of the damage.

1. Introduction

A reliable and tractable fatigue design methodology is a challenge for automotive industry designers because it allows detecting the critical points from the upstream phase, avoiding oversizing or undersizing and reducing the number of physical prototypes.

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This paper compares two different methodologies to estimate fatigue life in steel structures under an automobile spectrum loading. The first one associates a multiaxial fatigue criterion [1] and a classical cumulative damage rule. Two formulations are tested: Miner’s rule [4] is compared to a non-linear rule, “Damage Curve Approach” proposed by Manson et al. [2]. The second methodology is based on an incremental mesoscale plasticity/damage modeling [3], which uses the studied multiaxial fatigue criterion as yield surface to take into account multiaxial loading. The study is performed on 1045 steel, a material that benefits form a large experimental database [1, 3].

All technical details related to samples, fatigue results under constant amplitude loading, materials details are presented in ref [1, 3] from authors.

2. Automobile Spectrum

The behavior of 1045 steel is identified from tests performed on cylindrical specimens [1,3].

The loading spectrum (figure 1) used in tension-torsion tests is designed to represent a part of the real fatigue loadings undergone by in-service automotive structures. It is based on the loading spectrum used in automobile industry for rear-axles validation tests, and built using on-road measurements. Figure 1 presents the 3 blocks used in the spectrum, they are organized as follow: sequence = (50 (5(BP) + 12(T)) + 2(S)) with BP = Bad Pavements / T = Turns / S = Shocks. Load ratio: R(BP) = -0.8 / R(T)tension = -4.7 / R(T)torsion = -0.2 / R(S) = -0.7. Maximum load divided by the maximum load ratio for Shock (max load): max load (BP) = 0.46 (4 cycles) + 0.59 (4 cycles) / max load (T) = 0.48 / max load (S) = 1.

The spectrum reference parameter is the maximal von Mises stress in the “shocks” block (also called overload); the amplitude of other blocks is defined by a ratio with respect to this stress level.
Figure 2 presents experimental results for “FULL” spectrum as presented in figure 1 and “NO SHOCKS” spectrum, where “shock” cycles were suppressed. The results are presented in a graphic giving maximal Von Mises stress in “shocks” blocks vs. the number of tension cycles.

“Shock” represent only 0,1% of total spectrum, however a non-negligible impact of “shocks” cycles is observed on the fatigue life of specimens (figure 2).

3. Fatigue Life Prediction

This section compares two different methodologies to estimate specimen’s fatigue life presented in figure 2. The modeling is developed based on a multiaxial fatigue criterion [1]. In order to predict finite lifetimes, a simple damage rule (Damage curve approach - DCA [2]) is compared to an incremental mesoscale plasticity/damage modeling [3].

3.1. Multiaxial Fatigue Criterion

The fatigue criterion proposed by VU [1] is built from the invariants of the macroscopic stress tensor. The pertinence of the criterion under periodic loadings has been demonstrated in previous studies [1][5]; in this study, the criterion assessment is extended to variable amplitude spectra. The spectrum presented in section 2 serves as an example. Figure 3 shows the role of the principal terms of the criterion. The parameters of the criterion can be identified from two fatigue limits (such as fully reversed torsion and tension) and the ultimate strength “Rm”.

\[ \psi_0 = \max_t \left\{ J_2(t)^2 + \frac{J_2^{2,\text{moy}}}{J_2^{2,\text{moy}}(I_{1,m}, I_{1,m})} \right\} \]

Material Parameters

- Second invariant of stress deviator
- Phase shift effect (mean value of \( J_2 ^2 \))
- Hydrostatic stress effect (amplitude and mean value of hydrostatic stress)

Fig. 3. Multiaxial Fatigue Criterion
3.1.1. Damage curve approach

In this section Miner’s rule [4] is compared with a simple non-linear cumulative damage rule proposed by [2], the Damage Curve Approach - DCA. Standard Basquin formulation, identified on fully reversed torsion, is used as reference S-N curve [6].

The damage evolution in DCA is described by equation 1. The non-linearity is carried out by the parameter $\alpha$ experimentally identified. A value of $\alpha=0.6$ is identified for this application using uniaxial tension - torsion block loadings [6].

$$D = \left( \frac{n}{N_f} \right)^{\alpha}$$

(1)

Figure 4 compares numerical and experimental results for “FULL” spectrum and “NO SHOCKS” spectrum (section 2). It is observed that the linear damage accumulation predicted by Miner’s rule is not sufficient to accurately represent fatigue life for both “FULL” and “NO SHOCKS” spectrum. DCA ($\alpha=0.6$) can improve results for “FULL” spectrum but the progress is insufficient for “NO SHOCKS” spectrum. Thus $\alpha$ seems to be a function of spectrum and dependent of identification domain, the value of $\alpha=0.6$ is valid only for the “FULL” spectrum and can’t be transposed for “NO SHOCKS” spectrum.

Fig. 4. Confrontation of cumulative damage rules: Linear vs. non-linear

3.1.2. Incremental approach

The proposed model is based on Flacelière – Morel – Dragon model [7], which explicitly couples plasticity and damage at the grain scale and combines isotropic and linear kinematic hardening laws. This model has been improved by Vu et al. [3] to account for non-proportional and block loadings. The description of damage represents correctly the sequence effects well known in HCF (i.e non-linear damage accumulation). The incremental character of this model allows its use for variable amplitude loadings. All eleven parameters can be identified from two S-N curves (such as fully reversed torsion and tension) and an evolution crack length curve in tension [1, 3]. The proposed model was successfully tested on a number of non-proportional tests, such as sinusoidal out-of-phase tension-torsion tests with different values of amplitude ratio and mean stress [3] [5].

The actual version of this model is not adapted to compute cycles in the plastic domain, so the simulation was performed only for “NO SHOCKS” spectrum.
In figure 5, one can observe that the incremental model can provide better fatigue life estimations from “NO SHOCKS” spectrum than damage rule based methodologies. The good prediction can be associated with a stronger non-linearity in damage accumulation predicted by the incremental model that seems coherent for the studied spectrum. Despite an important CPU time, this model present good prospects. The integration of “shocks” is under development.

4. Conclusion

This analysis clearly identified the need for a robust tool to predict complex loading paths. Although the fatigue criteria associated with linear accumulation rule offer the advantage of being more computationally tractable, it may fail predicting correct lifetimes. DCA show good results for “FULL” spectrum. However the identified value for $\alpha$ seems to be a function of the spectrum, so this methodology can’t be transposed for “NO SHOCKS” spectrum without a new identification.

The incremental damage model appears as an alternative to improve predictions quality for “NO SHOCKS”. This model is identified only on uniaxial data and is able to take into account sequence effects and the non-linear damage accumulation. The actual version is not able to compute “shocks” cycles. The evolution of the model to integrate generalized plasticity is under progress.

References