

Fatigue Life Predictions under General Multiaxial Loading Based on Simple Material Properties

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ABSTRACT

A procedure for fatigue life estimation of components and structures under variable amplitude multiaxial loadings based on simple and commonly available material properties is presented. Different aspects of the analysis consisting of load cycle counting method, plasticity model, fatigue damage parameter, and cumulative damage rule are presented. The only needed material properties for the proposed procedure are hardness and monotonic and axial cyclic deformation properties (HB , K , n , K' and n'). Rainflow cycle counting method is used for identifying number of cycles. Non-proportional cyclic hardening is estimated from monotonic and axial cyclic deformation behaviors. A critical plane approach is used to quantify fatigue damage under variable amplitude multiaxial loading, where only material hardness is used to estimate the fatigue curve, and where the needed deformation response is estimated based on Tanaka's non-proportionality parameter. The commonly used linear damage rule is then used as a cumulative damage rule, to predict fatigue life. This procedure, when compared to experimental results, is shown to yield reasonably accurate predictions under some challenging axial-torsion loading conditions for a medium carbon steel with no non-proportional hardening, and a stainless steel with significant non-proportional hardening.

INTRODUCTION

The state of stress at critical location of most components and structures is multiaxial. Such components and structures are typically subjected to variable amplitude or random loading conditions. On the other hand, testing facilities for multiaxial loading are not as widely available as for uniaxial loading and generating multiaxial data is much more time and cost consuming. Therefore, having a comprehensive and simple procedure for fatigue analysis under variable amplitude multiaxial loading is a necessity in many applications.

Multiaxial fatigue models relating multiaxial fatigue life to uniaxial fatigue properties have been developed to predict fatigue life under multiaxial loading condition. Among all categories of multiaxial fatigue models, critical plane approaches which reflect damage mechanism on the specific critical plane(s) within the material have been known to be more accurate. Critical plane approaches can be categorized in three groups of stress-based, strain-based, and strain-stress-based models. Stress-based critical plane approaches including only stress terms may be appropriate in long life regime with mostly elastic deformation. Strain-based critical plane approaches consistent of only strain terms may be useful for both short and long life regimes. Nevertheless, such approaches do not reflect the constitutive behavior of material, such as non-proportional cyclic hardening.

Strain-stress-based models as the last group of multiaxial critical plane approaches can be also used for both short and long life fatigue regimes. These types of critical plane approaches include both a strain component as the driving parameter and a secondary stress component which reflects constitutive behavior of material such as non-proportional cyclic hardening. Fatemi-Socie (FS) [1] and Smith-Watson-Topper [2] damage parameters are two examples of strain-stress-based critical plane approaches for shear and tensile failure mode materials, respectively. Cyclic hardening due to non-proportionality of loading as well as mean and residual stresses are taken into consideration by the normal stress term in these models.

Although strain-stress-based critical plane approaches usually result in more accurate fatigue life predictions by reflecting the constitutive behavior of material, they require knowing the stress response under general multiaxial loading. On the other hand, even the uniaxial fatigue data may not be available in some applications. In order to predict multiaxial fatigue life in absence of any fatigue data, a multiaxial fatigue model [3] only based on hardness level of steels is used in this study. To find the stress response under variable amplitude multiaxial loading including the non-proportional effects, Tanaka's non-proportionality parameter [4] coupled with an Armstrong-Fredrick incremental plasticity model are used. This model is a simplified one [5] and only requires cyclic deformation properties including cyclic strength coefficient, K' , and cyclic hardening exponent, n' , as well as non-proportional cyclic hardening coefficient, α . Non-proportional cyclic hardening coefficient is also estimated from the recently proposed equation [6] based on the comparison of the monotonic and uniaxial cyclic deformation curves. Other material constants for this plasticity model are set to reasonable values for steels.

If a plasticity model is not available, the stress response under non-proportional loading can be estimated using a phenomenological approach, such as Kanazawa et al. method [7]. Although empirical methods are not as accurate as plasticity models [5], they are simple and widely used for fatigue life predictions under non-proportional loading conditions.

Bannantine-Socie cycle counting method [8], which is based on the critical plane approach, is used for identifying number of cycles in each shear strain level and the corresponding maximum normal stress to be used for the FS multiaxial damage parameter. The shear strain as the driving force in the main channel and the normal stress as the secondary parameter accelerating (if tensile) or retarding (if compressive) the fatigue damage in the auxiliary channel are considered for the rainflow cycle counting. The multi-channel rainflow cycle counting is performed on various planes within the material. Fatigue damage caused by each cycle is then evaluated by the aforementioned multiaxial fatigue

model only based on hardness of steel [3]. This model was developed based on the FS critical plane approach and Roessle-Fatemi hardness method [9]. Palmgren-Miner linear damage rule is then employed to calculate cumulative fatigue damage on various planes within the material. Plane with the greatest value of cumulative fatigue damage is considered as the critical plane.

The above-mentioned procedure only requires monotonic and axial cyclic deformation properties including strength coefficient, K , strain hardening exponent, n , cyclic strength coefficient, K' , cyclic strain hardening exponent, n' , and Brinell hardness, HB . The proposed procedure is applied to estimate fatigue life of 1050 steel in quenched and tempered (QT) condition with no non-proportional hardening and 304L stainless steel with significant non-proportional cyclic hardening, and under a variety of axial-torsion strain paths. Predictions are compared with experimental observations at each stage of the proposed fatigue life predictive technique.

EXPERIMENTAL PROGRAM

Medium carbon 1050 QT steel and 304L stainless steel thin-walled tubular specimens were utilized in this study. Monotonic and cyclic stress-strain curves for these two materials are presented in Figure 1. As can be seen from this figure, 1050 QT steel is a cyclic softening material and 304L stainless steel is a cyclic hardening material. Monotonic and cyclic properties for these materials are also listed in Table 1. Material properties listed in this table are the only input required for multiaxial fatigue life predictions. Since uniaxial cyclic properties were not available, cyclic in-phase (IP) data were used in this study. Specimens were designed and fatigue tests were performed according to ASTM Standard E2207 [10].

Table 1. Monotonic and cyclic properties for 1050 QT steel and 304L stainless steel (SS).

	1050 QT Steel	304L SS
Monotonic Properties		
Brinell hardness, HB	360	120
Strength coefficient, K , MPa	1,461	680
Strain hardening exponent, n	0.060	0.214
Cyclic Properties (from IP Tests)		
Cyclic strength coefficient, K' , MPa	1,558	2,841
Cyclic strain hardening exponent,	0.123	0.371

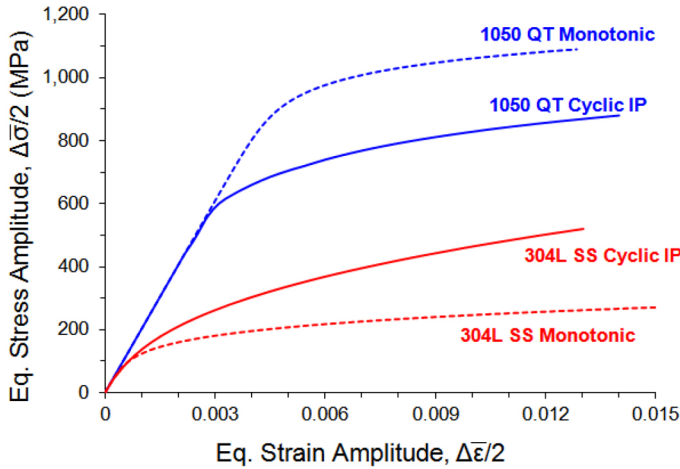


Figure 1. Comparison of cyclic and monotonic stress-strain curves for 1050 QT steel and 304L stainless steel.

A closed-loop servo-controlled hydraulic axial-torsion load frame in conjunction with a digital servo-controller was used to conduct the tests. Strain-controlled sinusoidal in-phase and 90° out-of-phase waveforms were applied to generate constant amplitude multiaxial fatigue data. In addition, some variable amplitude star shape strain paths [11], shown in Figure 2, were used for both materials in this study. FRI strain path in Figure 2 includes 360 proportional fully-reversed axial-torsion cycles with 1° increments starting from the pure axial cycle with circular boundary in $\gamma/\sqrt{3}$ - ε axes. FRR strain path also includes 360 proportional fully-reversed axial-torsion cycles, but in random sequences with circular boundary in $\gamma/\sqrt{3}$ - ε axes. This strain block is similar to FRI strain path, but rather than 1° increment, the sequence of straining is in random manner between 1° to 360°. FRI15 strain path consists of 24 proportional fully-reversed axial-torsion cycles with 15° increments starting from the pure axial cycle with circular boundary in $\gamma/\sqrt{3}$ - ε axes. Finally, PI strain path in Figure 2 includes 360 proportional pulsating axial-torsion cycles with 1° increments starting from the pure axial cycle with circular boundary in $\gamma/\sqrt{3}$ - ε axes. This strain path is similar to FRI strain path, but it is not fully-reversed. More details regarding these star shape strain paths and experimental results can be found in [5, 11]. Failure criterion was considered as 5% load or torque drop, whichever occurred first, compared with the stable value obtained at midlife. This load or torque drop corresponded to crack lengths of at least 10 mm on the specimen gage section surface.

PREDICTION OF NON-PROPORTIONAL CYCLIC HARDENING COEFFICIENT

The first step for a general multiaxial fatigue life prediction is to find the sensitivity of material under non-proportional loading. This sensitivity is usually determined by non-proportional cyclic hardening coefficient defined as:

$$\alpha = \frac{\bar{\sigma}_{OP}}{\bar{\sigma}_{IP}} - 1 \quad (1)$$

where $\bar{\sigma}_{OP}$ is 90° out-of-phase equivalent stress and $\bar{\sigma}_{IP}$ is in-phase equivalent stress at the same strain level. Equivalent stress and strain are defined based on von Mises criterion.

Non-proportional cyclic hardening coefficient, α , will be later used for estimation of stress response under general variable amplitude multiaxial loading. Shamsaei and Fatemi [6] observed that cyclic hardening materials mostly exhibit additional non-proportional hardening, whereas cyclic softening materials usually exhibit no additional cyclic hardening under non-proportional loading. They related both cyclic hardening coefficient and non-proportional hardening coefficient for steels to the stacking fault energy and proposed the following relation between non-proportional cyclic hardening and simple monotonic and cyclic coefficients as follows:

$$\alpha = 1.6 \left(\frac{K}{K'} \right)^2 \left(\frac{\Delta \varepsilon}{2} \right)^{2(n-n')} - 3.8 \left(\frac{K}{K'} \right) \left(\frac{\Delta \varepsilon}{2} \right)^{(n-n')} + 2.2 \quad (2)$$

where K , K' , n , and n' are strength coefficient, cyclic strength coefficient, strain hardening exponent, and cyclic strain hardening exponent, respectively. For the case of 90° out-of-phase loading resulting in the maximum possible strain hardening, the 90° out-of-phase stress amplitude, $\Delta \bar{\sigma}_{OP} / 2$, can be simply related to the axial cyclic stress amplitude or the equivalent in-phase stress amplitude, $\Delta \bar{\sigma}_{IP} / 2$, as follows:

$$\Delta \bar{\sigma}_{OP} / 2 = (1 + \alpha) \Delta \bar{\sigma}_{IP} / 2 \quad (3)$$