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A micromechanical cyclic void growth model for ultra-low cycle fatigue

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ABSTRACT

The influence of stress triaxiality and Lode parameter on microvoid growth phase of ductile fracture under ultra-low cycle fatigue (ULCF) ($N_f < 100$, N_f = cycles to failure) loading is investigated using micromechanical analyses. A new micromechanical cyclic void growth model (MM-CVGM) to predict the ULCF life of ASTM A992 steels is presented. The MM-CVGM is calibrated and validated from the experiments conducted on axisymmetrically notched specimens. Number of cycles to failure (N_f) and the fracture initiation locations predicted by the model closely matched the experimental observations.

1. Introduction

Several field observations, full scale and conventional fracture tests in the labs conclusively show that ductile fracture is the fracture initiating mechanism in structural steels when subjected to ultra-low cycle fatigue (ULCF) [1–3]. During earthquakes the steel structures are typically subjected to ultra-low cycle fatigue loading. Ductile fractures in steel bridge piers and moment resisting frame connections were observed in the site investigations after 1994 Northridge and 1995 Hanshin-Awaji earthquakes (for instance see [4] and references therein). The ultra-low cycle fatigue is generally characterized by very few load reversals (typically less than 100, i.e. $N_f < 100$) that cause large local plastic strains leading to the ductile fracture initiation. Ductile fracture is a multistep process initiated by microvoid nucleation, followed by microvoid deformation (dilation or elongation), and finally resulting in fracture initiation due to unstable coalescence of microvoids [5]. In structural steels, the ductile fracture initiation is mainly dependent on the state of stress and the applied plastic strain field [6].

In general the state of stress is characterized by two dimensionless parameters: (a) stress triaxiality (T_σ) and (b) Lode parameter (L). While the stress triaxiality provides a measure of hydrostatic stress, the Lode parameter (L) indicates the relative orientation of the principal stresses. Recent experimental and computational studies have shown that the damage due to the ductile fracture under monotonic loading cases is sensitive to both triaxiality and Lode parameter [7–11]. These studies concluded that microvoids dilate rapidly but elongate slowly at higher stress triaxialities when compared to lower stress triaxialities. But at low stress triaxialities, microvoid elongation is found to be dominant when compared to dilation. Furthermore, the microvoid elongation at low stress triaxiality is found to be sensitive to the Lode parameter. However, comprehensive studies on the microvoid evolution under ULCF loading are currently lacking. Although, an attempt was made in the past in this direction [12], many questions still remain unanswered. Specifically, the influence of triaxiality and Lode parameter on the microvoid elongation and the corresponding damage quantification under ULCF are some of the important issues that are yet to be addressed in order to formulate robust damage models that can be used to predict the initiation of ductile fracture in steel structures subjected to seismic loading.

Many models were proposed in the past to predict the fracture initiation in metals subjected to fatigue. The Miner's cumulative damage model for high cycle fatigue ($10^4 < N_f < 10^7$) [13] and Manson and Coffin's law for low cycle fatigue ($1000 \leqslant N_f < 10^4$) [14] are among the popular fatigue models (Table 1). These empirical models were recently used to predict the ULCF life of steels and were found to be inadequate in such cases [15]. This inadequacy can be attributed to the difference in the primary damage causing mechanism that leads to failure in ultra-low cycle ($N_f < 100$) and low/high cycle fatigue ($N_f > 1000$). Unlike the low or high cycle fatigue, the ultra-low cycle fatigue causes large plastic strains leading to a ductile crack initiation instead of a fatigue crack. Neither Miner's rule nor Manson–Coffin's relationship accounts for the damage due to microvoid growth and coalescence, and hence cannot be applied for the ULCF loading. Other commonly used fatigue models like Manson–Coffin–Basquin model (Table 1) and energy based fatigue

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Table 1
Previously proposed fatigue models.

S.N.	Study	Amplitude	Model	Parameters
1	Manson (1962) [14]	Constant amplitude model	$\varepsilon N_f^k = C$	ε – strain amplitude N_f – number of cycles for crack initiation C – material constant k – material constant
2	Miner (1945) [13]	Can be modified to accommodate variable amplitude loading	$\sum_{i=1} \frac{n_i}{N_i} = 1$	n_i, N_i – number of cycles at ith strain level and fatigue life at the ith strain level respectively
3	Manson–Coffin–Basquin curve [36]	Constant amplitude model	$\varepsilon = \frac{a}{E}(N_f)^b + d(N_f)^c$	a –fatigue strength coefficient d – fatigue ductility coefficient c, d – material constants
3	Du et al. (1992) [26]	Constant amplitude model	$\frac{\Delta\varepsilon_d}{1 - \frac{\varepsilon_{\max}^p}{\varepsilon^f}}\left(\frac{T_\sigma}{T_{\sigma 0}}\right) = CN_f^m$	$\Delta\varepsilon_d$ – diametrical strain range ε_d^T and ε_d^C – maximum strain in tension, compression cycles
			$\Delta\varepsilon_d = (\varepsilon_d^T - \varepsilon_d^C)$	T_σ – initial stress triaxiality ε_{max}^p – maximum tensile strain *Note:* see Table 2 for definition of ε_d
4	Kuroda (2002) [17]	Constant amplitude model	$\frac{\varepsilon_{\max}^p}{\varepsilon^f} + 4n\left(\frac{\Delta\varepsilon^p}{2\varepsilon^f}\right)^a + \frac{\Delta\varepsilon^p n^b}{C'} = 1$	n – number of cycles a, b, C' – material parameters $\Delta\varepsilon^p$ – plastic strain range
5	Tateishi et al. (2007) [15]	Variable amplitude model	$D = \begin{cases} \frac{\Delta\varepsilon^p - \varepsilon_{pd}}{\varepsilon^f - \varepsilon_{pd}} + \sum_{i=1} \frac{n_i}{N_i} & \text{if } \Delta\varepsilon^p > \varepsilon_{pd} \\ \sum_{i=1} \frac{n_i}{N_i} & \text{if } \Delta\varepsilon^p \leqslant \varepsilon_{pd} \end{cases}$	ε_{pd} – threshold plastic strain for the ductile fracture damage to initiate D – cumulative damage
6	Kanvinde and Deierlein [19]	Can be used for variable amplitudes	$VGI^{cr} = \sum_{\text{tension cycles}} \int_{\varepsilon_1}^{\varepsilon_2} \exp(\lvert 1.5T_\sigma \rvert) d\varepsilon_{\text{eff}}^p$	VGI^{cr} – critical void growth index
			$- \sum_{\text{comp. cycles}} \int_{\varepsilon_1}^{\varepsilon_2} \exp(\lvert 1.5T_\sigma \rvert) d\varepsilon_{\text{eff}}^p$	

models (see [16] and references therein) also cannot be used for the prediction of ultra-low cycle fatigue life for the reasons already provided. In fact none of the models that are applicable for the fatigue crack initiation can be used for the prediction of ULCF life.

Very few models exist in the literature that can be used to predict the ULCF life of metals. In general, most of these models account for both the damage due to cyclic loading and the static loading (followed by the cyclic loading) (Fig. 1). Du et al. [3] proposed an empirical model for predicting the ULCF life based on the experiments conducted on axisymmetrically notched tensile specimens (Table 1). In this model, the damage due to static loading is assumed to be proportional to the plastic strain due to the monotonic loading and the damage due to cyclic loading in this model is obtained by extending the Manson–Coffin's relationship [14] to incorporate the effect of stress triaxiality (T_σ) (Table 1). Although this model was validated on the notched specimens, the incorporation of the effect of stress triaxiality (T_σ) lacks a micromechanical basis. Another model was proposed by Kuroda [17] for the ULCF life prediction (Table 1). This model also accounts for the damage due to cyclic loading, static loading and fatigue crack growth. The damage due to cyclic loading in this model is obtained by extension of the Manson–Coffin's relationship [14] and the damage due to fatigue crack growth is derived from the small crack growth law proposed by Murakami et al. [18]. The effect of damage due to uniaxial elongation in this model is adopted from the work of Du et al. [3]. However, this semi empirical model does not consider the effect of stress state in the quantification of damage in both static and cyclic loading cases. Later, Tateishi et al. [15] proposed a new model to predict ULCF life (Table 1). The damage due to cyclic loading in this model is accounted through the Miner's rule [13] and the damage due to static loading is accounted in a way similar to the model proposed by Du et al [3]. Similar to the previous models, this model proposed by Tateishi et al. [15] lacks micromechanical basis and does not account for stress state dependence. A damage model that accounts for the stress state and its influence on the evolution of the microstructure is preferable when compared to empirical and semi-empirical models.

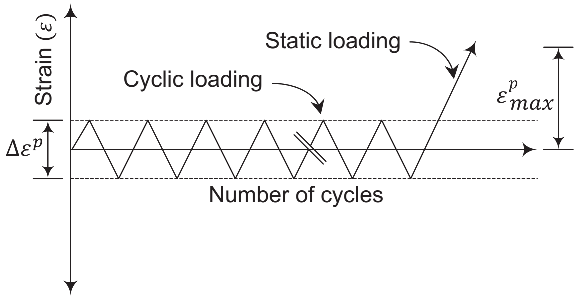

Fig. 1. General loading pattern in ultra-low cycle fatigue.

In a recent study, Kanvinde and Deierlein [19] proposed a cyclic void growth model that accounts for the influence of the state of stress on microstructure. In this study, Kanvinde and Deierlein [19] extended the existing Rice and Tracey void growth model [20] to the ULCF loading (Table 1). This model is based on a premise that the microvoids dilate and shrink under positive and negative stress triaxialities respectively. With this presumption, Kanvinde and Deierlein [19] postulated that the cyclic damage escalates in the tension part of the loading cycle due to micro void dilation