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Time-based subcycle formulation for fatigue crack growth under arbitrary random variable loadings

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ABSTRACT

A time-based subcycle fatigue crack growth (FCG) formulation and validation are proposed to calculate the fatigue crack growth under general random variable amplitude loadings. The intrinsic difficulties of the classical cycle-based formulation for general random variable loadings are discussed first. Several typical spectrums that are not appropriate for cycle-based FCG are illustrated, such as the "Christmas tree" spectrums. A time-based subcycle formulation is then proposed to address this difficulty. The proposed model includes three major component: (1) a time-based crack growth kinetics function at the subcycle (time) scale; (2) an efficient crack tip opening displacement (CTOD) estimation method; (3) a crack tip plasticity zone tracking algorithms for crack opening level determination of a growing crack. Detailed derivation and calculation procedures are given. Following this, several numerical examples are illustrated for the proposed model under different loading spectrums for the crack growth and CTOD calculation. Randomly generated loading spectrums are used to illustrate the capability of the proposed method under arbitrary loadings. Next, in-house testing for "Christmas tree spectrum" and literature data on several representative variable loading spectrums are used for model validation. Finally, some conclusions and future work are drawn based on the proposed study.

1. Introduction

Fatigue crack growth analysis (FCG) of engineering materials and structures is critical for the damage tolerance design and structural integrity assessment. Both constant amplitude and variable amplitude loadings of FCG have been investigated extensively in the past, in which majority of the studies are on the constant amplitude loadings. Most existing studies on the variable amplitude loadings used periodic overload (or underload) spectrums, variable block loading spectrums, and random peak/valley spectrums [1,2]. In realistic operational conditions, the loading spectrum is much more complex and sometimes cannot even be described as cyclic [3]. The most classical cycle-based formulation will be difficult to be applied under these conditions. In order to illustrate this, several typical loading spectrums are shown in Fig. 1. Fig. 1(a) is for a periodic overload and underload spectrums and Fig. 1(b) is a variable block loading spectrum. Both types of loading spectrums are suitable for cycle-based formulation as the peak-valley is well defined and there is no ambiguity for the characterization of "cycle." Fig. 1 (c) is a "Christmas tree" spectrum where a high cyclic loading is embedded with many small cycles. Fig. 1(d) is a random spectrum where the loading includes numerous large and small cycles embedded together. Both types of loading are difficult

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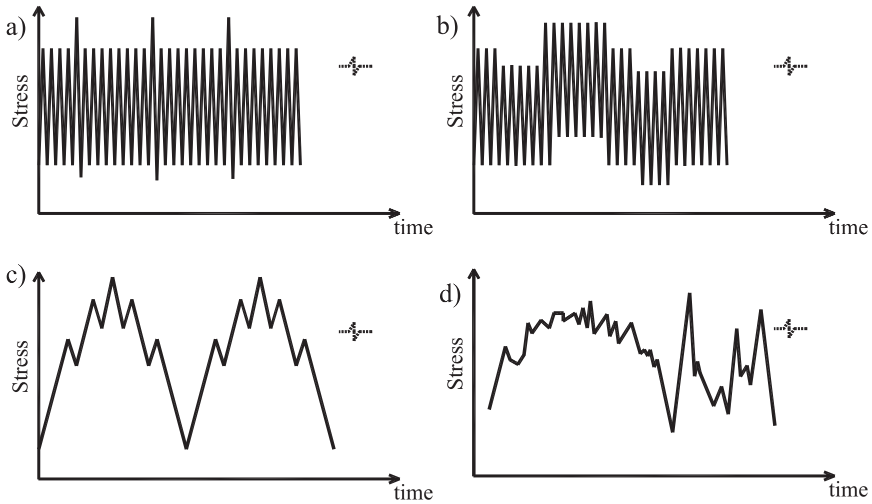

Fig. 1. Schematic illustration of random variable loadings (a) periodic overload/underload spectrum; (b) variable amplitude block load spectrum; (c) "Christmas tree" spectrum; (d) random spectrum.

for the cycle-based formulation since (1) the calculation of crack growth per cycle is ambiguous as the short cycle is embedded within the high cycle. The sequence of the summation in a cycle-by-cycle calculation (e.g., large-small or small-large) will cause difference in the final crack length as the crack growth law is nonlinear; (2) the representation of results as *a-N* curve is problematic as the corresponding "*N*" cycle is not clearly defined due to the embedded nature of the spectrum. A time-based *a-t* curve will be more appropriate for the presentation of the calculation data. In reality, the randomness of the structural loading will make the situation more complicated and will make the application of cycle-based FCG analysis more problematic. Thus, one of the major motivation for the proposed study develops a time-based formulation, which will be more suitable for general variable random loading.

A time-based FCG formulation has been proposed by Lu and Liu [4]. The key concept in [4] is to define a subcycle crack growth kinetics function by correlating the instantaneous crack growth with the crack tip opening displacement (CTOD) and utilize the crack closure concept to determine the portion for the time-domain integration for the crack length calculation. [4] introduces the new concept for FCG analysis, but it has several limitations mainly due to its hypothesis in developing the model. For example, the linear relationship between the crack growth and the CTOD variation is used, which may not be true based on the in situ scanning electron microscope (SEM) fatigue testing [5,6]. Also, the CTOD calculation in [4] does not consider the random loading effect and cannot be applied to arbitrary loading spectrums. An analytical formulation for the CTOD estimation under random loading has been proposed in [7] for stationary crack without crack surface contact. The major benefit is due to the linearization by the Dugdale model, and swift CTOD calculation can be achieved under arbitrary random loadings. Very accurate results were obtained compared to the finite element-based calculation with only a small fraction of the computational time. Extension of this algorithm [7] for a growing fatigue crack (e.g., the inclusion of plasticity-induced crack closure) will greatly facilitate the FCG analysis under arbitrary loadings. Thus, one major component of the proposed study is to combine the main concepts in the time-based formulation [4], in situ SEM observation for subcycle crack growth kinetics [5,6], and efficient CTOD estimation algorithm [7] to develop a new model for the FCG analysis under arbitrary loadings.

One of the challenges in this development is the determination of the crack opening stress level for an arbitrary loading spectrums. Detailed crack closure analysis involves time-consuming numerical simulations. For example, De Matos and Nowell [8] studied fatigue crack closure model using dislocation-based simulations. Newman [9–11] analyzed the crack closure problems by developing a strip yield model, which employs spring-type of the element for crack closure tracking. The application of these type of crack closure analysis is difficult under arbitrary loadings. A typical practice is to use an averaged crack closure level together with a "cycle-jumping" technique to achieve the better computational efficiency [11]. Zhang and Liu [6] developed a simplified model by using a virtual crack to replace detailed crack surface contact analysis and validated the crack opening stress levels under constant amplitude loadings with in situ SEM testing results. The key idea is to use the crack tip plasticity zones (both monotonic and reversed) sizes to indicate the crack closure or opening. This model provides a simple way to track the crack closure/opening in arbitrary loading by monitoring the crack tip plastic zone boundaries. It should be noted that the largest plastic zone boundary may not be produced by the adjacent previous cycle under arbitrary variable amplitude loadings and may be generated by a loading in the history. This is known as the load history effect in FCG (e.g., overload retardation and under load acceleration). The tracking of the plastic zone boundaries has been proposed in Wheeler model and Willenborg model [12,13]. The major difference in this proposed study is that the tracking was used to indicate the crack closure/opening level, rather than the modification of the remote applied loading [12,13]. Thus, the