On the Effectiveness of a Multiaxial Fatigue-Life Predictive Method Based on a Virtual Strain-Energy Concept

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Fatigue criteria based on uniaxial cyclic fatigue data, often expressed in a two-term power-law equation, are still actively used in the structural design community, despite the fact that most structures are operating under complex loading. Although many multiaxial fatigue life predictive methods have been proposed in recent years, structural designers, as well as their code body, remain reluctant to adopt any of the proposed methods. The root causes of the pessimism are not entirely groundless, however. A few legitimate concerns can be cited: (1) lack of an effective means for general applications in situations such as non-proportional loading and out-of-phase multiaxial loading, (2) lack of rational and physical grounds in the fatigue damage parameters used to account for multiaxiality in some of the criteria, (3) lack of experimental multiaxial database to verify the effectiveness of each method, (4) conservatism, and, (5) generally, more complex in the multiaxial fatigue criteria. The complexity, however, should not be a major hindrance to the development of an effective method in view of today’s powerful computational capability.

Simplicity and the wealth of supporting fatigue data, although limited to the uniaxial mode in most cases, are the reasons that the classical method has been widely accepted for use in practical design applications. Accounting for multiaxiality that is ignored in the classical method is accomplished by substituting the uniaxial strain with an equivalent strain inferred from the von Mises equivalent strain formulation. This elementary idea is based on the observation that the von Mises equivalent strain reduces to the uniaxial strain under uniaxial loading. However, this approach often fails to summarize multiaxial fatigue data into a single fatigue curve. Other deficiencies are that the predictions can be overly conservative in some situations, and severely under-conservative in other situations.

Many methods for multiaxial fatigue-life prediction have been proposed to date. Some are based on philosophical approaches such as that discussed above, while others are based on physical approaches which have shown some success. However, no single approach has demonstrated to be superior to the others when applied to general situations, because each method was developed based on its own data that were generated under some special situations. In general, fatigue-life predictive methods are based on stress, strain, or energy as a correlation parameter, with little or no reference to physical fatigue failure modes. An excellent survey study on multiaxial fatigue have been conducted and results are reported in the open literature [1], in which the method to be discussed herein has been evaluated as the most promising approach.

A multiaxial fatigue-life predictive method has been developed at Oak Ridge National Laboratory [2]. The method introduced two parameters expressed in terms of virtual strain-energy (VSE) as a measure of fatigue damage on critical planes of crack nucleation, which precedes the initial stage of fracture. Mode-I fracture occurring on a critical plane is driven by the maximum principal stress and strain, and Mode-II fracture occurring on a different critical plane is driven by the maximum shear stress and strain. The VSE parameter of the first kind, ΔW_I, represents the maximum strain energy on the Mode-I fracture plane, and that of the second kind, ΔW_{II}, represents the maximum shear strain energy on the Mode-II fracture plane. The mode of crack initiation and propagation depends on inherent fatigue resistance characteristics of material, temperature, strain range, and stress/strain histories. Therefore, fatigue fracture does not always occur on the critical plane, which exhibits the greater of two competing VSE parameters under the loading. SAE 1045 steel at ambient temperature exhibits less resistance to shear fatigue compared to tensile fatigue; hence Mode-II fracture prevails. Test results show that ΔW_{II} correlates well with the cyclic fatigue life of SAE 1045 steel tested under both in-phase and out-of-phase biaxial cyclic loading conditions. Type 304 stainless steel (304s/s) shows less resistance to tensile fatigue compared to shear fatigue at low temperatures, but the situations are reversed as the temperature exceeds approximately 540°C. Using their own data for 304s/s subjected to a variety of complex out-of-phase biaxial loading paths, Ito, et al. [3] showed that their method and the VSE method were both superior compared to other methods. However, their method requires non-proportional loading factors in order to bring the data into a scatter band with a factor of 1.2. The VSE method does not require these factors.

Some deficiencies in existing theories for multiaxial fatigue lack a means to rationally account for the effects of complex non-proportional multiaxial loading path and cyclic mean stress on fatigue life. Other shortcomings are the inability to predict physical characteristics of cracks, such as fracture mode, crack orientation, growth behavior, and the absence of provisions to index fatigue damage accumulation under non-repeating cyclic loading with stress, strain and temperature histories. Some advance has been made recently, showing that crack nucleation, orientation, and growth can be predicted based on the concept of the VSE parameter. The effects of mean stress on cyclic fatigue life will also be presented.

References

1. B-R You and S-B Lee, Int. J. Fatigue, Vol. 18, No. 4, May 1996, pp. 235-244.
2. K. C. Liu, ASTM STP 1191, 1993, pp. 67-84.
3. T. Itoh, et al., J. Eng. Mat. & Tech., Vol. 117, July 1995, pp. 285-292.

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