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Low-cycle fatigue analysis using the direct cyclic approach

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ABSTRACT

The traditional approach for determining the fatigue limit for a structure is to establish the $S-N$ curves (load versus number of cycles to failure) for the materials in the structure. Such an approach is still used as a design tool in many cases to predict fatigue resistance of engineering structures although it is generally conservative and no relationship between the crack length and the cycle number is available. One alternative approach is to predict the fatigue life by using a crack/damage evolution law based on the inelastic strain/energy when the structure response is stabilized after many cycles. Because the computational cost to simulate the slow progressive damage in a material over many load cycles is prohibitively expensive for all but the simplest models, numerical fatigue life studies usually involve modeling the response of the structure subjected to a small fraction of the actual loading history. This response is then extrapolated over many load cycles using empirical formulae such as the Coffin-Manson relationship to predict the likelihood of crack initiation and propagation. Such a simplified practice does not necessarily account for the evolution of the crack/damage while predicting the number of cycles to failure based on a constant crack/damage growth rate.

The direct cyclic analysis capability in Abaqus/Standard provides a computationally effective modeling technique to obtain the stabilized response of a structure subjected to

periodic loading and is ideally suited to perform low-cycle fatigue calculations on a large structure. The capability uses a combination of Fourier series and time integration of the nonlinear material behavior to obtain the stabilized response of the structure directly. This capability has been used successfully in the past to predict the stabilized response of an elastic-visco-plastic structure subjected to cyclic thermal-mechanical loading such as exhaust manifold and cylinder head in automotive industry and solder joints in electronic industry

The direct cyclic low-cycle fatigue capability is an extension of the direct cyclic capability that includes damage accumulation and damage extrapolation. It provides capabilities to model both damage growth in ductile bulk materials, such as in solder joints in an electronic chip packaging, and delamination/debonding growth at interfaces such as in laminated composites. In the bulk material the cyclic loading leads to stress reversals and the accumulation of plastic strains, which in turn cause the initiation and propagation of cracks. The damage initiation and evolution are characterized by the stabilized accumulated inelastic hysteresis strain energy per cycle. At interfaces of laminated composites the cyclic loading leads to interface strength degradation causing fatigue delamination growth. The onset and delamination growth are characterized by the relative fracture energy release rate at the crack tip based on the Paris law, with the fracture energy release rate being calculated using the Virtual Crack Closure Technique (VCCT). Both the progressive damage mechanism in the bulk material and the progressive delamination growth mechanism at interfaces can be considered simultaneously, with the failure occurring first at the weakest link in a model in the low-cycle fatigue analysis.

This capability developed in Abaqus/Standard has applications in Solder Joint Failure in Electronics, Powertrain Durability in Automotive, Composite Damage and Strength in Aerospace, and Bone Degradation in Medical applications. In this study, several numerical simulations have been performed and the results have been compared with experimental data and theoretical results. Significant performance gains with good accuracy of the direct cyclic low cycle fatigue capability are clearly demonstrated.