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Coupling damage and reliability model of low-cycle fatigue and high energy impact based on the local stress–strain approach

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Abstract Fatigue induced products generally bear fatigue loads accompanied by impact processes, which reduces their reliable life rapidly. This paper introduces a reliability assessment model based on a local stress–strain approach considering both low-cycle fatigue and high energy impact loads. Two coupling relationships between fatigue and impact are given with effects of an impact process on fatigue damage and effects of fatigue damage on impact performance. The analysis of the former modifies the fatigue parameters and the Manson–Coffin equation for fatigue life based on material theories. On the other hand, the latter proposes the coupling variables and the difference of fracture toughness caused by accumulative fatigue damage. To form an overall reliability model including both fatigue failure and impact failure, a competing risk model is developed. A case study of an actuator cylinder is given to validate this method.

1. Introduction

Products which have fatigue failure mechanism suffer not only complex fatigue loads, but also impact loads, which can be called a fatigue damage process.[1,2] Both the failure modes of fatigue and impact associated to dynamic loads can cause the initiation of cracks in products, which may propagate to a macroscopic fracture size eventually. However, the loading rate of the impact load is much higher than that of the fatigue loads, which may lead to some changes of material properties. Hence, impact damage and fatigue damage have similarities as well as distinctions.

Fatigue load may cause a certain amount of fatigue damage in each cycle, and when the total damage cumulates to a certain threshold, the failure caused by fatigue (fatigue failure for short) takes place. There are various kinds of fatigues, such as mechanical fatigue,[3] thermal–mechanical fatigue,[4,5] corrosion fatigue,[6] etc. Except for mechanical fatigue, the rest of them are the combinative effects of environment and specific mechanical stresses, which make them more complex than sole mechanical fatigue. To simplify our assumption, this paper focuses only on mechanical fatigue. As we know, fatigue damage and life related researches generally based on different

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definitions and assumptions. Among them, the traditional nominal stress method based on the stress and stress-life (*S-L*) curve is the earliest and most widely used. However, plastic deformation is not considered in the traditional nominal stress method, and it cannot be applied to the analysis of low-cycle fatigue. To overcome the disadvantages of the traditional nominal stress method, a local stress strain approach is developed. Furthermore, to analyze both high-cycle fatigue and low-cycle fatigue, a number of methods have been developed by combining the Basquin model and Manson–Coffin model.[7,8]

The analysis of impact damage is more difficult than that of fatigue, because of the complex properties of materials corresponding to dynamic stresses. There are two extreme conditions for impact damage. If the energy of impact is large enough, it may cause impact damage at once, such as one-impact fracture. If the impact energy is very low, the accumulated impact failure can be approximated to fatigue damage. The conditions between the two extremes are much more complex, and when fatigue damage exits at the same time, they may have a coupling relationship which leads to a more difficult issue.

Even though both fatigue and impact have been studied copiously in previous literature, the research of their relationship is rare. Refs.[9–12] studied the fatigue performance with post-impact damages, but most of them focused on composite materials. Ding et al.[9] performed the tensile and compressive residual-strength tests on carbon-epoxy composites to obtain the fatigue performance after drop-weight impact. The impact damage followed by tensile fatigue cycling reduced the fatigue performance of the material. The results showed that tensile fatigue strength had a linear relationship with the cycle number, and the cycle-impact sequence gave more damage than impact-cycle loading. Beheshty et al.[11] developed a fatigue life-prediction model for carbon-fibred laminates with impact damage. Tai et al.[12] noted the impact energy caused the decrease of strength, and the damage zone increased with the increase in impact energy. However, due to the characteristics of composite materials, they show more susceptibility to impact load than metal materials do. Furthermore, the failure modes of composites are different from those of metals. Therefore, the analysis method of composites with fatigue and impact cannot be applied to other materials directly.

Other researchers are interested in the studies on metal materials influenced by foreign object damage.[13–16] Martinez[13] investigated the strength of engine blades due to foreign object damage. The results in Thompson[14] indicated that residual stress relief improved the limit stress, and that dynamic impacts had less influence on the fatigue strengths than that predicted from conventional analysis. Nowell et al.[15] showed damage depth had a significant effect on fatigue strength, and the Kitagawa–Takahashi diagram was used to predict the variation of fatigue strength with crack arrest in small cracks. Most of these references gave only qualitative analysis.

Moreover, there is some research with respect to the qualitative relationship between fatigue and shock damage. The coupling effects of fatigue damage and impact damage were analyzed to define the damage as cumulative dissipated energy.[17] The analysis showed that fatigue damage and impact damage were coupled, and impact damage greatly influenced fatigue evolution. Zhao et al. performed a test to investigate single impact effects with high strain rate on the low cycle fatigue life of 1Cr18Ni9Ti.[18] The result showed that the effects were dependent on a coupling action of the residual welding stress and the plastic impact mechanism.

The above references illustrate fatigue damage and impact damage affect each other rather than being mutually independent, which means the coupling relationship of fatigue and impact cannot be ignored. Chen discussed the coupling relationship between high-cycle fatigue and low-energy shocks and the effects of shocks on the fatigue damages were expressed as the degradation of the ultimate stress of the material.[19] The traditional nominal stress method was used to analyze the fatigue process. An overall reliability and life prediction model with fatigue failure and shock failure was developed. However, he did not consider the plastic deformation caused by large local stress. Besides, when the load is larger than the yield limit of the material, it creates a plastic deformation zone, and the premise of the traditional nominal stress method is no longer satisfied. Hence, a local stress strain approach is adopted here, because this paper focuses on the low-cycle fatigue and high-energy impacts, and the local stress strain approach is a classical, practical and effective fatigue analysis method for low-cycle fatigue with a great number of applications. A coupling damage and reliability model of low-cycle fatigue and high energy impact based on the local stress–strain approach is developed in a following paper.

2. Fatigue and impact analysis

2.1. Fatigue analysis based on local stress–strain approach

The fundamental idea of the local stress–strain approach is to convert the nominal load or stress spectrum of a component to the local stresses and strains of critical locations via elastic–plastic analysis or other methods which combines with a cyclic stress–strain curve or hysteretic loop. There are two specific methods to complete this conversion: the modified Neuber equation method[20] and the plastic–elastic finite element analysis method. The modified Neuber equation is presented here.

Step 1. Analyze the fatigue load history, and utilize the rain-flow method to count the effective cycles.

Let e_i be the *i*th peak or valley strain value, if $|e_i - e_{i-1}| \geqslant |e_{i-1} - e_{i-2}|$, $i \geqslant 3$, then an effective closed loop is formed, and the range of strain of the closed loop is

$$\Delta e = |e_{i-1} - e_{i-2}| \tag{1}$$

Step 2. Convert the nominal stress and strain to the local stress and strain.

The range of nominal strain Δe corresponding to the range of nominal stress ΔS can be obtained from

$$\frac{\Delta e}{2} = \frac{\Delta S}{2E} + \left(\frac{\Delta S}{2K'}\right)^{1/n'} \tag{2}$$

where K' is the cyclic strength coefficient, and n' the cyclic strain hardening exponent, E the elasticity modulus.

In the plane stress condition, the range of local stress and strain can be solved through

$$\begin{cases} \Delta\varepsilon = \Delta\sigma/2E + (\Delta\sigma/2K')^{1/n'} \\ \Delta\varepsilon\Delta\sigma = K_{\mathrm{f}}^2 \Delta e \Delta S \end{cases} \tag{3}$$

where $\Delta\varepsilon$ is the local strain, $\Delta\sigma$ the local stress, and K_{f} the fatigue notch factor. When the nominal stress belongs to the