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An approach to structural reliability evaluation under fatigue degradation and shocks

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ABSTRACT

Fatigue is one of the most typical failure mechanisms, which can be regarded as a degradation process. The non-linearity in fatigue damage due to shocks cannot be disregarded. The mechanical shock is a transient physical excitation, in which the structure is nonequilibrium caused by a sudden applied load with high stress level or an abrupt change in the direction or magnitude of velocity. After the shock, the rate of fatigue damage accumulated decreases for a long time. When shock exists, the degradation could be generally retarded. The retardation phenomenon has been proven by the experimental observation. Therefore, a new approach is proposed to evaluate the structural reliability, in which the fatigue strength degradation process considering the retardation effect is explained by a crack-closure based fatigue model. The lifetime will be extended due to the applied shock loads. This fatigue crack growth model is validated by the experimental data of aluminum alloy D16. In addition, considering the material parameter and the shock loads are indeterminate, the reliability assessment under the fatigue loading with shocks is performed. A case study is given and two shock scenarios are discussed. In the first scenario, shocks occur in a fixed time period; while in the second scenario, shock occurs with varying time periods. The results indicate that the proposed approach can account for the retardation and evaluated the fatigue damage more appropriately.

1. Introduction

Fatigue is one of the most common failure reasons in many structures and systems, which can be described as a continuous degradation process of fatigue strength in terms of time. In addition, the structure inevitably suffers from the shock loads which are simultaneous with the fatigue degradation process. The shocks severely impact the fatigue damage evolution, which makes the structural reliability analysis difficult.

The extensive researches have been devoted to evaluate the reliability of systems experiencing the degradation and shocks. Wang et al. derived the overall reliability equation considering the catastrophic failure, degradation and failure due to shocks [1]. In this model, the shock will cause either the failure rate increasing or the random increment in degradation. Zongwen An and Daoming Sun developed a reliability model for system experiencing the degradation processes with shock loads. The system will fail when the total degradation exceeds the threshold or the magnitude of the shock loads exceeds the threshold [2]. Rafiee et al. proposed the reliability models for a device subjected to dependent competing failure processes of degradation and shocks [3]. Chen et al. analyzed the reliability of a product involving the degradation of the

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Nomenclature

σ	stress level
σ_{op}	crack closure level
Y	geometry coefficient
a	crack length
a_0	initial crack length
a_c	critical crack length
da/dN	crack growth rate
da	crack increment
K	stress intensity factor
ΔK_{eff}	effective stress intensity factor range
K_{max}	stress intensity factor of the peak load
K_{op}	stress intensity factor of crack closure level
C, m	material calibration parameters
D_{eq}	equivalent plastic zone size
d	current plastic zone size
N	fatigue life
ΔN	delay cycles
F_1	static failure mode
F_2	failure due to fatigue degradation
F_3	failure due to shocks
D_f	damage threshold value
N_f	fatigue life when the crack firstly grows to the critical level
t	time
A	damage caused by shocks
$[0, A_s]$	small damage level
$[A_s, A_l]$	moderate damage level
$[A_l, +\infty]$	large damage level
P_s	probability that the damage falls into the region $[0, A_s]$
$P_{s,l}$	probability that the damage falls into the region $[A_s, A_l]$
P_l	probability that the damage falls into the region $[A_l, +\infty]$
T	fixed period
R(t)	time-dependent reliability

ultimate strength and the shock damage [4]. In their work, the effect of shock is supposed to accelerate the degradation. However, for the structural reliability evaluation under fatigue and shock damage, most of the existing degradation-shock-approaches are inadequate. The reason is that the shock will lead to fatigue damage retardation instead of acceleration [5–8], which is quite different from the other degradation processes. A few studies consider the retardation influence in the reliability analyzing. Tanaka proposed a reliability model, in which the retardation effect is expressed by the probability distribution of the total delay time [9]. Wujun Si et al. developed a physical-statistical model which quantitatively describe the retardation effect considering random errors [10]. Although these methods take the retardation into account, they are essentially mathematical statistic approaches. Actually, right after the shock load, the rate of fatigue damage accumulation will decrease in a certain spatial and temporal range. The retardation effect can lead to a nonnegligible fatigue life extension, which significantly affects the structural reliability. In this paper, a new approach is proposed to evaluate the structural reliability, in which the fatigue strength degradation process considering the retardation effect is explained by a crack-closure based fatigue model. It has been recognized that the crack closure, which denotes the premature contact of the crack surfaces, seriously affects the fatigue crack behavior [11,12]. Zhang and Liu performed an in-situ scanning electron microscope (SEM) experiment and directly observed the crack closure phenomenon [13,14]. The virtual crack annealing model is developed which is inspired from this experiment. The modified virtual crack annealing model is reviewed in this paper to simulate the degradation path with the shock effect, which is a physical-based formulation and can account for the retardation phenomenon well. During the process of structural reliability modeling, three failure modes are assumed to lead to degradation: static failure mode, fatigue and shocks. The static failure mode is independent of the fatigue and shock. The fatigue strength degradation process is estimated by using the aforementioned crack-closure based model, considering the material parameter and the shock load level are indeterminate. Finkelstein and Zarudnij proposed the shock damage models which are also employed [15]. In their work, the shock damage is assumed to follow Gaussian distributions. The proposed structural reliability approach can depict the fatigue life extension in consequence of shock loads based on the mechanism analysis, which is in agreement with the experimental observation. This model can calculate the structural reliability under the fatigue loading with shocks.

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