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Fatigue life calculation for a specimen with an impact pit considering impact damage, residual stress relaxation and elastic-plastic fatigue damage

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ABSTRACT

In this study, a continuum damage mechanics based method is proposed to calculate the fatigue life of a specimen with an impact pit. The impact process is simulated by a quasi-static analysis. The residual stress and the impact damage are calculated. Then, the elastic-plastic fatigue damage of the material is considered as the specimen experiences cyclic loading. The residual stress relaxation is investigated via a coupled analysis of the residual stress and elastic-plastic damage evolution. The calculated results agree well with the experimental results. The effects of the impact depth and radius that the impact object has on the fatigue failure are also discussed.

1. Introduction

In the process of manufacturing, assembling or servicing engineering structures, defects, such as impact pits, tend to be generated on the surfaces of structures due to an accidental bump or a drop of a foreign object [1,2]. An impact pit has a non-negligible negative effect on the fatigue life of structures. However, if all structures containing impact damage are considered unfit for service, a great deal of waste will be generated, as some damaged structures are still able to sustain cyclic loading and even meet the fatigue life requirements [3]. A reasonable and effective method is necessary to quantitatively evaluate the influence caused by impact damage and to accurately predict the fatigue life of a structure containing an impact defect.

Fatigue life prediction of components is an important issue in engineering applications. Some methods have been proposed and practically used. The local stress strain method [4], based on the stress-strain course at the notch root in combination with the material fatigue characteristic curve, is convenient to use. However, this method is confined to some simple cases. The critical plane method [5] has been applied more widely due to its board applicability and good accuracy by presenting a semi-empirical formulation expressed with the maximum fatigue damage parameter over a number of different planes. However, the parameter lacks explicit physical significance. These several methods utilized for plain fatigue problems cannot be directly used for failure analyses of structures with impact damage due to the complex effects induced by the impact. The impact damage [6–8] can influence the subsequent fatigue life of components by three main factors: (i) impact-induced residual stresses, (ii) impact damage associated with local plastic deformation, and (iii) local stress concentrations around the impact pit. The continuum damage mechanics based method [9–11], which is a relatively new method developed in recent decades, also has the capability of analyzing fatigue failure in structures. This method describes the damage evolution process using damage variables and has been widely used to address a number of practical problems. Better yet, the continuum damage mechanics method can reasonably analyze the three effects induced by impact damage and present quantitative results and the process of damage evolution.

In the previous work [12], fatigue life calculations for defected structure were conducted, which considered the effects of the initial impact damage associated with the local plastic deformation and the local stress concentrations around the impact pit. However, the initial residual stress was assumed to remain unchanged and its effect was measured by simply superposing the cyclic stress due to the total stress on the specimen being less than the yield

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stress. Thus, the residual stress relaxation and plastic damage were not taken into account. In the material around the impact pit, it is easy to incur plastic deformation because of the effect of the stress concentration as cyclic loading increases. Therefore, on one hand, it is necessary to consider the elastic-plastic fatigue damage in the fatigue life calculation. Meanwhile, the residual stress field will vary when the specimen experiences inelastic deformation. Thus, the effect of residual stress relaxation also needs to be considered. The effect of residual stresses on the fatigue life of structures has been extensively studied for years and is reasonably well understood [13–15]. In particular, near surface tensile residual stresses tend to accelerate the initiation and growth phases of the fatigue process, whereas compressive residual stresses close to a surface may prolong the fatigue life. However, the residual stress state induced by the impact of a projectile onto a metallic surface can be significantly altered during subsequent fatigue loading. Studies [16–22] have shown that the relaxation of residual stress occurs during cyclic loading and the rate of residual stress relaxation can be significant in the early stages of cyclic loading. In some cases, residual stress can be entirely relaxed in the first few load cycles. Such mechanical cycle-dependent redistribution of residual stresses is often termed cyclic relaxation [23,24]. Therefore, it is difficult to accurately predict the residual stress relaxation effect. Through experiments, Mattson and Coleman [25] observed cyclic residual stress relaxation many years ago and found that their predicted fatigue lives were shorter than the experimental results if residual stress relaxation was not taken into consideration. A theoretical method to describe this phenomenon is still required.

This study examines the issues of elastic-plastic fatigue damage and the corresponding effect that it has on residual stress relaxation. Specimens fabricated from TC4 are investigated in this work. The calculated results based on the proposed model are validated by the experimental results obtained by Peters [8]. First, to address the impact damage, impact-induced residual stress, and interactions between inelastic fatigue damage and residual stress relation, a quasi-static numerical simulation of the impact process is conducted. From this, the initial residual stress field and plastic strain field around the impact pit is obtained. Then, the initial impact damage can be calculated according to Lemaitre's ductile damage model. Second, the damage coupled elastic-plastic constitutive equations are adopted as the material model, and the inelastic damage evolution equations are used to evaluate the extent of the damage of material after a certain number of loading cycles. By virtue of the FE implementation used in ABAQUS, the effects of impact damage and residual stress are considered, and the interactions between inelastic damage evolution and residual stress relaxation are presented as well. The calculated fatigue life and residual stress relaxation effect are found to be in accordance with the experimental results. Additionally, some factors influencing elastic-plastic damage and fatigue life are also discussed.

2. Theoretical models

2.1. Impact stress analysis and initial impact damage analysis model

2.1.1. Initial stress analysis

In this study, a quasi-static numerical method is applied to simulate the foreign object impact process. This is based on two aspects. On one hand, the dynamic simulation of the impact process is time-consuming and the computational results are sometimes instable. On the other hand, it is easier to continually implement subsequent fatigue damage analysis using a quasi-static simulation than follow a dynamic simulation. To obtain equivalent results between the quasi-static simulations and dynamic simulations, the energy equivalence method [26] and experimental measurements of dynamic impact [27] need to be adopted, which guarantee that the static indentation and initial residual stress state of the quasi-static analysis are equivalent to the dynamic impact damage [23].

In the quasi-static simulation, considering the stiffness of the foreign object is much higher than that of the structure material, it is reasonable to regard the foreign object as a rigid body and the structure as an elastoplastic body. The elastic-plastic constitutive model proposed by Lemaitre and Chaboche [28] is used to describe the constitutive relationship of the structure material. During impact, large strains first form at the contact surface, and then, the strain diffuses in the vicinity of the contact surface. Once the impact process is completed, residual stresses and plastic strains exist in the zone around the impact pit.

2.1.2. Initial impact damage analysis model

Deterioration of material induced by an impact can be represented by the damage variable in the framework of continuum damage mechanics. Lemaitre and Chaboche [29] have presented the fundamental concepts of continuum damage mechanics. For the case of isotropic damage of isotropic materials, the damage variable D can be represented by the deterioration ratio of the stiffness of RVE (Representative Volume Element), which is expressed by:

$$D = \frac{E - E_D}{E}, \tag{1}$$

where E is the Young's Modulus of the material and E_D is the effective Young's Modulus of the RVE with damage. The value of E_D ranges from E to 0, and the value of D varies between 0 and 1.

After completion of the residual stress analysis, the initial damage induced by plastic deformation can be calculated according to Lemaitre's ductile damage model [30]:

$$\dot{D} = \left(\frac{\sigma_{eq}^2 R_v}{2ES(1-D)^2}\right)^s \dot{p}, \tag{2}$$

where σ_{eq} is the equivalent stress, $\dot{p}$ is the rate of accumulated plastic strain, S and s are material parameters, R_v is the triaxiality function: $R_v = \frac{2}{3}(1+\mu) + 3(1-2\mu)\left(\frac{\sigma_H}{\sigma_{eq}}\right)^2$, and σ_H is the hydrostatic stress.

This formula can be integrated over time to calculate the initial damage induced by the impact as follows:

$$D_0 = \left(\frac{\sigma_{eq\max}^2 R_v}{2ES}\right)^s \Delta p, \tag{3}$$

where Δp is the accumulated plastic strain over this period.

2.2. Fatigue damage analysis model

2.2.1. Damage-coupled elastic-plastic constitutive model

In the framework of a small deformation, the total strain ε_{ij} can be decomposed into:

$$\varepsilon_{ij} = \varepsilon_{ij}^e + \varepsilon_{ij}^p, \tag{4}$$

where ε_{ij}^e and ε_{ij}^p are the elastic and plastic strains, respectively. In the damage-coupled constitutive model, the damage is coupled with elasticity or plasticity using the effective stress instead of the stress in the elasticity law and the von Mises yield criterion. Based on the hypothesis of strain equivalence, the elastic strain takes the form of:

$$\varepsilon_{ij}^e = \frac{1+\upsilon}{E}\left(\frac{\sigma_{ij}}{1-D}\right) - \frac{\upsilon}{E}\left(\frac{\sigma_{kk}\delta_{ij}}{1-D}\right), \tag{5}$$