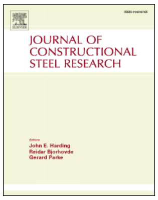
Journal of Constructional Steel Research 148 (2018) 542–550

Contents lists available at ScienceDirect

Journal of Constructional Steel Research



Fatigue life prediction of welded joints with artificial corrosion pits based on continuum damage mechanics

Zhiyu Jie [a,*], Yadong Li [b], Xing Wei [b], Ping Zhuge [a]

[a] *Faculty of Architectural, Civil Engineering and Environment, Ningbo University, Ningbo 315211, China*
[b] *School of Civil Engineering, Southwest Jiaotong University, Chengdu 610031, China*

ARTICLE INFO

Article history:
Received 21 March 2018
Received in revised form 29 May 2018
Accepted 7 June 2018
Available online xxxx

Keywords:
Fatigue life
Welded joint
Artificial corrosion pit
Damage variable
Damage evolution equation

ABSTRACT

An approach based on continuum damage mechanics (CDM) is applied to predict the fatigue life of welded joints with artificial corrosion pits. Full penetration load-carrying fillet cruciform welded joints with a 45° inclined angle were constructed, and artificial corrosion tests and fatigue tests of the welded joints were carried out. A new damage variable based on the crack size was defined to assess the stiffness degradation. Material parameters in the damage evolution equations were obtained from the fatigue experimental data. The CDM model combined with numerical simulations was used to describe the fatigue damage evolution process. A comparison between the fatigue life predicted results and the test results was made. The results show that fatigue life decreases with the increase of pit depth, decreasing by approximately 50% from $d = 0$ mm to 2 mm at the same stress range. The fatigue damage curves can be divided into three stages: the crack initial growth stage ($D < 0.3$), the crack slow growth stage ($0.3 \le D \le 0.8$), and the crack rapid fracture stage ($D > 0.8$). The fatigue damage curves for different stress ranges are nearly the same under the same pit depth. In addition to the material and loading conditions, the corrosive environment also has an effect on the material parameters in the fatigue damage evolution process. The fatigue life predicted results agree well with the test results, and the maximum relative error is 10.6%. The crack size can be used to describe the fatigue damage evolution of welded joints with artificial corrosion pits.

1. Introduction

Continuum damage mechanics (CDM) as a branch of solid mechanics was introduced by Kachanov [1] in the 1950s and was then developed rapidly by Lemaitre and Chaboche [2]. The advantages of continuum damage mechanics lie in the presence of micro defects (voids, discontinuities and cracks) that cause the damage that can be observed and measured by macro parameters (elastic modulus and area). CDM offers a new method to predict the total fatigue life, including crack initiation and propagation. Fatigue damage increases with the increase in the number of applied loading cycles in a cumulative manner, and the materials finally fail once the damage reaches a critical value.

In the present investigation, the CDM approach has been used to analyze the fatigue damage of welded joints. To quantify the damage, a damage variable is defined to describe the fatigue damage evolution process of materials subjected to cyclic loading. The elasticity modulus, cross-sectional area, hardness, stiffness, and potential can be used as damage variables. Cheng et al. [3] defined a fatigue damage variable based on the material ductility property. Dorgeuille et al. [4] proposed that the damage variable could be quantitatively measured by using the natural frequency. Aid et al. [5] used stress as the damage variable. However, it is difficult and inconvenient to measure these damage variables during the fatigue damage process. In addition, it is also difficult to ensure one basic definition of damage due to the different mechanisms involved in the damage process for different materials [6].

The fatigue damage analysis based on the CDM approach has been carried out by many researchers. The key points are to build a damage evolution equation to describe the process of fatigue damage and obtain the material parameters for the equation. Many fatigue damage models have been proposed. A classical fatigue damage model was established by Chaboche based on fatigue damage curves [7]. Another damage mechanics model was proposed by Lemaitre and Plumtree [8]. The CDM model considered the effect of mean stress, fatigue limit, and loading frequency [9–11]. Dattoma et al. [12] and Batsoulas [13] proposed a nonlinear CDM model under variable loading conditions. Qi et al. [14], Tong et al. [15], and Shen et al. [16] investigated the fatigue damage evolution of welded joints based on CDM. The CDM model can describe the initiation, growth and coalescence of microcracks through the material damage state. Once the fatigue damage model is determined, it can be used to predict the fatigue life. Other literatures [17–20] developed a

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[*] Corresponding author.
E-mail address: jiezhiyu_8@163.com (Z. Jie).

https://doi.org/10.1016/j.jcsr.2018.06.013
0143-974X/

damage mechanics-finite element method to calculate the fatigue life and simulate the fatigue process. Lee et al. [21] and Do et al. [22] assessed the total fatigue life of weld joints which included fatigue crack initiation and propagation by a nonlinear damage cumulative model. However, few studies focus on the application of the CDM model to the fatigue life prediction of welded joints. Furthermore, the CDM requires multiple material parameters in the damage evolution equations for welded joints. The accuracy of fatigue life prediction requires further verification for high cycle fatigue.

The fatigue life of metal materials is influenced by the corrosive environment [23, 24]. Welded joints widely used in steel bridges may generate corrosion pits in a marine atmospheric environment due to the presence of chloride ions. Fatigue failures may result due to the initiation and propagation of cracks at the corrosion pits. The reduction of the fatigue life is attributed to (a) the loss in the cross-sectional area, (b) the stress concentration effect of the corrosion pit, and (c) the increase of the crack growth rate [25]. Bastos et al. [26] proposed an evolution law that depended on the corrosive environment. Hu et al. [27] and Amiri et al. [28] predicted the corrosion fatigue crack initiation life based on CDM. Hu et al. [29] proposed a CDM approach coupled with an improved pit evolution model to predict the corrosion fatigue life of an aluminium alloy. Han et al. [30] proposed a nonlinear cumulative evolution model for corrosion fatigue damage and established the corrosion fatigue life evaluation model based on the damage evolution law. Consequently, the corrosive environment has an important effect on the CDM model. An in-depth study on the effect of corrosion on the fatigue performance of welded joints in steel bridges is needed.

According to the above statement, there are few studies on the effect of corrosion on the damage of welded joints for high cycle fatigue. Full penetration load-carrying fillet cruciform welded joints with a 45° inclined angle were constructed to simulate the stress states under the combination of normal stress and shear stress, which was a very common phenomenon in steel bridges. Different artificial corrosion pits were manufactured to consider the effect of an actual marine atmospheric environment. To date, the fatigue damage analysis of these welded joints with artificial corrosion pits has never been investigated. First, artificial corrosion tests and fatigue tests of full penetration load-carrying fillet cruciform welded joints with a 45° inclined angle were carried out. Second, a new damage variable based on the crack size was defined to assess the stiffness degradation. The material parameters of the fatigue damage evolution equation were obtained from the fatigue experimental data. The CDM model combined with numerical simulations was used to describe the fatigue damage evolution process. Finally, the fatigue life prediction equations of welded joints with different levels of corrosion were obtained. A comparison between the fatigue life predicted results and the test results was made. Finally, it was proved whether the crack size can be used as the damage variable.

2. Fatigue damage model

2.1. Damage variable

Material damage is a progressive internal deterioration process under external loads. When the effective cross-sectional area does not resist the loading, the material completely fails. A damage variable is used to reflect the degradation of the material. In 1958, Kachanov [1] defined it as follows

$$D = \frac{A-\tilde{A}}{A} \tag{1}$$

where A is the overall cross-sectional area and $\tilde{A}$ is the effective cross-sectional area. When $D = 0$ and 1, it is the undamaged state and failure state, respectively. The concept of effective stress is introduced to describe the effect of damage on the strain. The effective stress $\tilde{\sigma}$ acting on the effective area is defined as

$$\tilde{\sigma} = \frac{\sigma}{1-D} \tag{2}$$

Lemaitre [31] introduced the concept of strain equivalence. The strain with a damaged state under applied stress is equivalent to the strain with an undamaged state under effective stress. Then, the elastic constitutive model of isotropic damaged material can be written as

$$\varepsilon_{ij} = \frac{1+\nu}{E}\left(\frac{\sigma_{ij}}{1-D}\right) - \frac{\nu}{E}\left(\frac{\sigma_{kk}\delta_{ij}}{1-D}\right) \tag{3}$$

where ε_{ij} is the elastic strain tensor, σ_{ij} is the Cauchy stress tensor, ν and E are Poisson's ratio and Young's modulus for undamaged material, respectively, and δ_{ij} is the Kronecker delta.

The measure of a traditional damage variable based on the elastic modulus or cross-sectional area is difficult and inaccurate. A new damage variable based on crack size is defined to assess the stiffness degradation. Semi-elliptical surface crack growth in a finite thickness plate is shown in Fig. 1. The damage variable D can be expressed as

$$D = \frac{A}{A_\mathrm{k}} = \frac{\pi ac/2}{\pi a_\mathrm{k} c_\mathrm{k}/2} = \frac{ac}{a_\mathrm{k} c_\mathrm{k}} \tag{4}$$

where A, a and c are the crack area, depth and half-width, respectively, and A_k, a_k and c_k are the crack area, depth and half-width for fatigue failure, respectively.

2.2. Fatigue damage evolution equation

Chaboche and Lesne [32] proposed a nonlinear cumulative fatigue damage model under various loading situations. It can be used to describe the degradation process of materials and the expression is written as

$$\frac{\mathrm{d}D}{\mathrm{d}N} = \left[1-(1-D)^{1+\beta}\right]^{\alpha}\left[\frac{\Delta\sigma}{M_0(1-b\sigma_\mathrm{m})(1-D)}\right]^{\beta} \tag{5}$$

where $\Delta\sigma$ and σ_m are the stress range and mean stress, respectively, and b, β, M_0 and α are material parameters. The parameter α is written as

$$\alpha = 1-H\left\langle\frac{\Delta\sigma-\sigma_{-1}}{\sigma_\mathrm{b}-\Delta\sigma}\right\rangle \tag{6}$$

where σ_{-1} is the fatigue limit, σ_b is the tensile strength, and H is the material parameter. The symbol $\langle\rangle$ is defined as $\langle x\rangle = 0$ if $x < 0$ and $\langle x\rangle = x$ if $x > 0$. Integrating from $D = 0$ to $D = 1$, Eq. (5) gives the number of cycles to failure, and fatigue life N_f can be expressed as

$$N_\mathrm{f} = \frac{1}{1-\alpha}\frac{1}{1+\beta}\left[\frac{M_0(1-b\sigma_\mathrm{m})}{\Delta\sigma}\right]^{\beta} \tag{7}$$

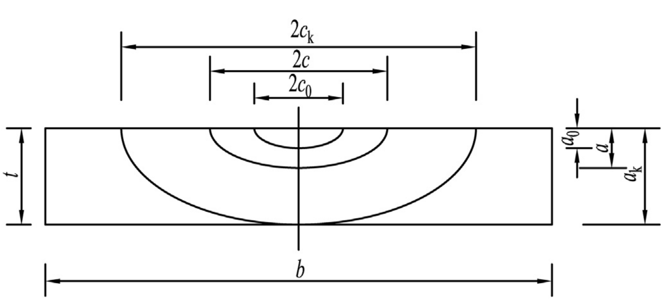

Fig. 1. Semi-elliptical surface crack growth in a finite thickness plate.