TECHNICAL NOTE

CONTINUUM DAMAGE MODEL OF LOW-CYCLE FATIGUE AND FATIGUE DAMAGE ANALYSIS OF WELDED JOINT

GUANG-XU CHENG,† JIAN-ZHENG ZUO, ZHI-WEN LOU and ZHEN-BANG KUANG
Department of Engineering Mechanics, Xi'an Jiaotong University, Xi'an, Shaanxi Province, 710049, P.R. China

Abstract—We know from experimental phenomena that the ductility of materials decreases with increasing numbers of cycles in the process of cycle fatigue loading, from which a new fatigue damage variable \( D^* \) based on the material ductility property is defined. Then a continuum damage mechanics model for low-cycle fatigue is derived from the new damage variable and is used to study the fatigue damage of welded joint. Damage evolution equations for the weld metal, heat-affected zone and base metal of 16MnR steel are obtained, respectively. The theoretical and experimental results show that the new damage variable \( D^* \) has a definite physical meaning and can be measured by a simple procedure and it can be related to the mechanical property of material directly. Copyright © 1996 Elsevier Science Ltd

1. INTRODUCTION

Most of the steel structures are fabricated by welding. Therefore, the overall safety of steel structures will be evaluated in the welded joint as well as in the base plate. The welded joint in the structure is composed of the solidified weld metal, heat-affected zone and base plate, and is a highly heterogeneous medium. The welding zone has different mechanical properties from the base metal and is presumably the location of toughness degradation. Statistically, failures of most welded structures are caused by fatigue damage or fatigue fracture. Therefore, many works have been devoted to investigating the fatigue damage of welded joint. It is noted that the fatigue damage behaviour of welded joint is different from that of homogeneous base metal.

In the past, works on fatigue problem for welded structures focused on the fatigue strength and fatigue crack growth behaviour caused by welded defects. Generally, the welded defects were simplified to macrocracks. The fatigue crack growth was studied by use of the fracture mechanics approach and other methods. However, because of the characteristics of the welding procedure, the welding zones easily produce metallurgical discontinuities, such as, microcracks, porosity or microvoids, non-metallic inclusions, microstructure alteration of heat-affected zone, etc. Really, welding zones may be considered as the initial damage collecting zones of microscopic defects. In other words, welding procedure may cause initial damage in the base metal. This initial damage zone and mechanical discontinuous behaviour must lead to the mechanical properties deterioration in the welded joint. Under the action of cycle loading, the damage process and final fracture of structures are the evolution processes of this initial damage. Fracture mechanics deals mainly with the load carrying capacity of structures containing major cracks \([1]\). It does not investigate the fatigue damage evolution for microdefects distributed in materials. In fact, most fatigue failure events are not all from fatigue crack growth directly from internal welded defects of the structure. Usually, the cracks are formed on the surface of the weld toe which has stress concentration, then the crack growth leads to complete structure fracture. Comparing to crack propagation, the damage process occupies most fatigue life of the structure. Therefore, it is very important to investigate the damage process and physical mechanism of damage evolution before the macrocrack formed in the welded zone. However, owing to the complexity of microscopic defects, it is as yet very difficult to individually and specially investigate the influence of microscopic defects on the fatigue damage of a material. Recently, the development of continuum damage mechanics (CDM) has provided a method for solving the fatigue damage problem. The task of CDM is to analyze the damage evolution process of the microcracks, voids and microstructure heterogeneity segregation before macrocrack initiation by introducing a damage variable \( D \) into the constitutive relation of material. The purpose of this work is to analyze the fatigue damage of welded joint through a new damage variable presented by the authors, and to develop a low-cycle fatigue model by CDM. It is also our purpose to study the crack initiation process from the experimental and theoretical analysis with damage mechanics, and to establish a fatigue life prediction method suitable for the welding structure.

2. A NEW FATIGUE DAMAGE VARIABLE BASED ON THE MATERIAL DUCTILITY

The first step of establishing a damage mechanics model is to define an appropriate damage variable which can be used to describe material damage evolution well. Many damage variables have been presented in literatures. For example, the damage variable may be defined in terms of the variation of elastic modulus \( E \) \([2]\), expressed by the variation of cyclic plastic response \([3]\) and measured through the variation of voltage potential \( \Delta V \) \([4]\). Although several damage variables and

†Present address: Department of Chemical Engineering, Xi'an Jiaotong University.
damage measurement methods have been proposed, no one of them is perfect [3]. This fact urged the authors to define a new damage variable in terms of material ductility. From the experimental results of fatigue damage, a fatigue damage model was presented based on the concept of ductility exhaustion. The concept of ductility exhaustion was explained in detail in refs [5–7]. The main point of view of the ductility exhaustion model is that the inherent ductility in the material is exhausted after cycle loading, when the deterioration of ductility reaches a critical value, the material will have fatigue damage failure.

From the viewpoint of the damage variable in CDM, any state parameter may be used to measure the fatigue damage, as long as the parameter varies monotonically with cycle loading. Therefore, it is known from the ductility exhaustion model that both material fracture strain $\varepsilon_f$ and reduction of section area $\Psi$ may be used as the damage variable. Under the hypothesis of isotropy, a new damage variable is defined as

$$D^* = \frac{\varepsilon_f - \bar{\varepsilon}_f}{\varepsilon_f} = 1 - \frac{\bar{\varepsilon}_f}{\varepsilon_f}.$$  

(1)

In order to make the experimental measurement easier, using the relationship of $\varepsilon_f = \ln(1/(1 - \Psi))$, we define the new damage variable by $\Psi$, i.e.

$$D^* = 1 - \frac{\ln\left(\frac{1}{1 - \Psi}\right)}{\ln\left(\frac{1}{1 - \Psi}\right)}.$$  

(2)

where $\varepsilon_f$ and $\Psi$ are original fracture strain and reduction of section area before cycle loading, respectively. $\bar{\varepsilon}_f$ and $\bar{\Psi}$ are remaining fracture strain and remaining reduction of section area after some loading cycles, respectively.

It is known from eq. (2) that if $\Psi = \Psi_f$, then $D^* = 0$, which corresponds to the undamaged state of material; when the material reaches the complete damage state, the ductility of material is fully exhausted, $\Psi = 0$ or $D^* = 1$. This is consistent with the definition of the damage variable in classical damage mechanics [2].

3. LOW-CYCLE FATIGUE DAMAGE EVOLUTION

According to Lemaitre's theory [2, 8], low-cycle fatigue (LCF) damage evolution can be described by a suitable dissipation potential. We choose the dissipation potential $\phi$ as follows:

$$\phi = \frac{A(R)}{\beta^2} \left( \frac{Y}{A(R)} \right)^{\beta} f(D).$$  

(3)

Here, $Y$ is the damage strain energy release rate, $R$ is the ratio of minimum strain to maximum strain. $A(R)$ and $\beta$ are temperature dependent material constants. $f(D)$ is a function of damage variable $D$. According to our experimental results, the ductility of materials decreases with increasing cycle numbers. So, the inherent ductility of material may influence the fatigue damage evolution. In order to consider the effect of inherent ductility of material on the damage evolution, $\Psi$ is introduced into damage function $f(D)$ by the authors and it will give a true physical meaning to damage evolution (it should be noted that the original material ductility $\Psi$ is constant). We choose the damage function $f(D)$ as follows

$$f(D) = [1 - (1 - D)^{1 + \gamma}]^\gamma.$$  

(4)

The law of damage evolution may be derived from $\phi$ as

$$\dot{D} = -\frac{\partial \phi}{\partial Y} = \left( -\frac{Y}{A(R)} \right)^\gamma f(D)$$

$$= \left[ \frac{\Delta \sigma_{i}^2}{A(R)(1 - D)} f \left( \frac{\Delta \sigma_m}{\Delta \sigma_{m}} \right) \right]^\gamma f(D).$$  

(5)

where $f(\Delta \sigma_{mi}/\Delta \sigma_{m}) = 2/3 (1 + v) + 3(1 - 2v)(\Delta \sigma_{mi}/\Delta \sigma_{m})^2$. $v$ is Poisson's ratio, $\sigma_m = 1/3 \text{tr}(\sigma)$ is hydrostatic stress and $\Delta \sigma_m$ is von Mises equivalent stress amplitude. For the one-dimensional stress state, $\Delta \sigma_m = 1/3 \Delta \sigma$, $\Delta \sigma_{m} = \Delta \sigma$. $f (\sigma_m/\Delta \sigma_m) = 1$. we have,

$$D = \left[ \frac{\Delta \sigma}{A(R)(1 - D)} \right] f(D).$$  

(6)

In the case of proportional loading per cycle, as $D$ varies very slightly in a cycle, the variation of $(1 - D)$ in a cycle can be neglected. So the damage during one cycle may be obtained from eq. (6).

$$\frac{\delta D}{\delta N} = \left[ \frac{\Delta \sigma}{A(R)(1 - D)} \right]^\gamma \left[ 1 - (1 - D)^{1 + \gamma} \right] \gamma.$$  

(7)

Integrating eq. (7) with initial and final conditions $D \mid \nu = 0 = D; D \mid \nu \rightarrow \infty = D = 1$, respectively, we obtain the following damage evolution law:

$$D = 1 - \left[ \left( \frac{N}{N_i} \right)^{1 - \nu} \right]^{1 + \gamma}.$$  

(8)
Table 1. The compositions and mechanical properties of 16MnR steel

<table>
<thead>
<tr>
<th>Elements (%)</th>
<th>Mechanical properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Mn</td>
</tr>
<tr>
<td>0.18</td>
<td>1.54</td>
</tr>
</tbody>
</table>

Table 2. Welding conditions

<table>
<thead>
<tr>
<th>Welding Voltage (V)</th>
<th>Welding Current (A)</th>
<th>Welding Velocity (cm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First welding layer</td>
<td>30 ~ 40</td>
<td>620 ~ 630</td>
</tr>
<tr>
<td>Second welding layer</td>
<td>35 ~ 40</td>
<td>630 ~ 640</td>
</tr>
<tr>
<td>Third welding layer</td>
<td>35 ~ 40</td>
<td>630 ~ 640</td>
</tr>
</tbody>
</table>

Considering the critical damage value \(D_c < 1\) for most practical engineering materials, the fatigue damage evolution equation may be rewritten as follows:

\[
D^* = D^t \left\{ 1 - \left[ \left( \frac{N}{N_t} \right)^{\frac{1}{\gamma \cdot \phi}} \right]^{\gamma \cdot \phi} \right\}.
\]

(9)

To obtain the damage life \(N_t\) corresponding to the critical damage state, we integrate eq. (7).

\[
\left[ \left[ \frac{\tau^D}{\sigma^D} \frac{d\left( 1 - (1 - D)^{\frac{1}{\gamma \cdot \phi}} \right)}{\left[ 1 - (1 - D)^{\frac{1}{\gamma \cdot \phi}} \right]} \right] \right]_N = \int_0^{N_t} \left( 1 + \beta \right) \left( \frac{\Delta \sigma}{A(R)} \right) \frac{d\sigma}{\psi}.
\]

Thus,

\[
N_t = \left[ \left( 1 + \beta \right) \left( 1 - \frac{\Delta \sigma}{A(R)} \right) \right]^{-1}.
\]

(10)

In eq. (10), function \(A(R)\) may be determined using the linear form of \(A(R) = A_0 (1 - B \epsilon_{\text{um}})\), coefficients \(A_0\) and \(B\) may be obtained from fatigue experiments.

It is known from eq. (9), that the damage evolution equation is non-linear and only one parameter \(\beta\) needs to be determined from experiment, as long as the experimental data of \(D^*\) vs \(N/N_t\) are obtained. The \(\psi\) value may be obtained accurately by the least square method.

4. EXPERIMENTAL RESULTS

4.1. Experimental details

The test material is 16MnR pressure vessel steel. The compositions and mechanical properties of the steel are given in Table 1. The welded joint was welded by auto-submergy arc welding procedure under the welding conditions shown in Table 2 and Fig. 1. The welded joint consists of three zones macroscopically, i.e. weld metal zone, heat-affected zone (HAZ) and base metal.

In order to study the fatigue damage behaviour of the welding zones, respectively, the so-called hour-glass type fatigue specimens were used. The test part of the specimen is a cylindrical bar of 7.0 mm in diameter and 30 mm in length, and the minimum cross-section (6.0 mm in diameter) is placed on the centre of the weld metal (called weld specimen), or heat-affected zone (called HAZ specimen) or base metal (called base metal specimen), respectively, as shown in Fig. 2. The fatigue tests were performed on a closed-loop, servo-hydraulic INSTRON-1341 test machine by means of constant total strain-controlled. The constant strain amplitude of 0.66% and strain ratio \(R = 0\) were employed for all specimens. The tests were divided into two groups. In the first group, undamaged specimens (no cycle loading before tensile) were directly subjected to monotonic tensile load until fracture to obtain the reduction of section area \(\psi\). In the other groups, the

Fig. 1. Welded plate and its geometry size.
specimens were subjected to cycle loading to a certain number of cycles firstly, then the damaged specimens were tensioned to fracture by monotonic loading to obtain the remaining reduction of section area $\bar{\phi}$.

4.2. Fatigue damage evolution of welded joint

From the experimental results of low-cycle fatigue damage tests for welded metal, heat-affected zone and base metal, respectively, the new damage variable defined in eq. (2) was used to evaluate the damage behaviour of welded joint, and the damage parameters $D_c$ and $\beta$ were determined through the experimental data. Consequently, we get the following damage evolution laws

$$
D_c = 0.707 \left[ 1 - \left( \frac{N}{N_f} \right)^{2.3487 \times 0.599} \right] 
$$

(11a)

Fig. 3. The comparison of damage evolution curves derived from eqs (11) with experimental results.
Fig. 4. Microscopic fractographs of SEM.
Weld metal: \( D^* = 0.817 \left\{ 1 - \left[ \frac{N}{N_i} \right]^{1.227} \right\}^{1/3} \) \( (11b) \)

Heat-affected zone: \( D^* = 0.788 \left\{ 1 - \left[ \frac{N}{N_i} \right]^{1.249} \right\}^{1/3} \) \( (11c) \)

The values of \( D^* \) calculated from eqs \((11)\) are plotted against the cycle fraction \( N/N_i \) as shown in Fig. 3. It is found that the calculating values of damage evolution law by the above fatigue damage model are in good agreement with the experimental results. Evidently, the damage evolution law of weld metal, heat-affected zone and base metal are different. By comparing, we find that the damage rate of heat-affected zone rises steeply, the damage rate of base metal rises comparatively slowly. The reason is that the physical mechanism of damage is different in these three zones. Therefore, it is necessary to analyze deeply the damage mechanism of welded zone by microscopic analysis method.

4.3. Microscopic analysis of fatigue damage mechanism

According to the general micro-mechanism of the fatigue damage under the strain-controlled cycle condition, the fatigue damage initiates from the local weak zone in practical material. So it is needed to analyze the fracture surface of fatigue damaged specimens by Scanning Electronic Microscope (SEM). The microscopic fractographs of fatigue damage for these three welding zones at critical damage state are shown in Fig. 4. Obviously, the damage appearance of weld metal is mainly of dimples, and there are a large number of non-metallic inclusions or secondary particles. Fatigue damage initiates firstly from the boundary of particles, which urges microcrack initiation. Because plastic deformation in inclusions is more difficult than that in matrix, inclusions separate with matrix at one or two points along the tension direction. It can be seen that the inclusion–matrix interface is the local weak zone of weld metal. The stress concentration effect of inclusions causes the intersection slip to concentrate in the local region. The microplastic deformation accumulation and material ductility exhaustion lead to the separation of inclusions from the matrix interface.

For the heat-affected zone, there are a lot of large grains and local brittle phase due to heat cycle in the welding process. The slip occurs more easily in the interior of the grain than at the grain boundaries, the inhomogeneous slip and local plastic strain concentration occur at the grain boundaries. The dislocation stuffing is formed on the boundaries, which causes stress concentration on the boundaries. When the peak stress overtakes the critical stress value, the grain boundaries will separate from each other. For a large grain, the dislocation stuffing is stronger. Consequently, the material needs to exhaust more ductility and the damage initiates at the grain boundary prior to the small grain.

For the base metal, the material has good ductility. Plastic deformation is in progress through slip. When the cycle number is not too large, the slips occur only in individual grains and distribute uniformly. As the cycle number increases, some of the existing slip bands are widened, as well as some new slips occur. When two slip bands intersect in the grain, the stuff of the slip band results in the microcrack initiation.

5. CONCLUSIONS

1. Based on the model of ductility exhaustion, a new damage variable \( D^* \) is defined. Theoretical analysis and experimental results prove that the damage variable has a clear physical meaning and it may be used to analyze the fatigue damage behavior of materials.

2. A non-linear continuum damage model for low-cycle fatigue is derived on the basis of CDM theory. The present model can describe the LCF damage evolution of welded joint. The damage evolution equations of weld metal, heat-affected zone and base metal were measured through fatigue damage tests, respectively. The values of damage \( D^* \) calculated from eqs \((11)\) are in good agreement with the experimental results.

3. The fatigue damage variable and damage evolution equation established by employing the ductility exhaustion model have a definite physical meaning.

Acknowledgements—The authors would like to express their appreciation of the financial support by the National Laboratory of Structure Strength and Vibration, Xi’an Jiaotong University.

REFERENCES


(Received 2 March 1994)