Theoretical and Applied Fracture Mechanics 53 (2010) 113–126

Contents lists available at ScienceDirect

Theoretical and Applied Fracture Mechanics

journal homepage: www.elsevier.com/locate/tafmec

Fatigue crack growth of cable steel wires in a suspension bridge: Multiscaling and mesoscopic fracture mechanics

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ARTICLE INFO

Article history:
Available online 10 March 2010

Keywords:
Suspension bridge
Cable
Steel wire
Fatigue crack growth
Fatigue life
Cable tightening and loosening
Macro/micro dual scale crack model
Microcrack
Macrocrack
Mesoscopic fracture mechanics
Scale transition
Strain energy density factor
Restraining stress zone
Material microstructure parameters
Damage evolution

ABSTRACT

Intrinsically, fatigue failure problem is a typical multiscale problem because a fatigue failure process deals with the fatigue crack growth from microscale to macroscale that passes two different scales. Both the microscopic and macroscopic effects in geometry and material property would affect the fatigue behaviors of structural components. Classical continuum mechanics has inability to treat such a multiscale problem since it excludes the scale effect from the beginning by introducing the continuity and homogeneity assumptions which blot out the discontinuity and inhomogeneity of materials at the microscopic scale. The main obstacle here is the link between the microscopic and macroscopic scale. It has to divide a continuous fatigue process into two parts which are analyzed respectively by different approaches. The first is so called as the fatigue crack initiation period and the second as the fatigue crack propagation period. Now the problem can be solved by application of the mesoscopic fracture mechanics theories developed in the recent years which focus on the link between different scales such as nano-, micro- and macro-scale.

On the physical background of the problem, a restraining stress zone that can describe the material damaging process from micro to macro is then introduced and a macro/micro dual scale edge crack model is thus established. The expression of the macro/micro dual scale strain energy density factor is obtained which serves as a governing quantity for the fatigue crack growth. A multiscaling formulation for the fatigue crack growth is systematically developed. This is a main contribution to the fundamental theories for fatigue problem in this work. There prevail three basic parameters μ^*, σ^* and d^* in the proposed approach. They can take both the microscopic and macroscopic factors in geometry and material property into account. Note that μ^*, σ^* and d^* stand respectively for the ratio of microscopic to macroscopic shear modulus, the ratio of restraining stress to applied stress and the ratio of microvoid size ahead of crack tip to the characteristic length of material microstructure.

To illustrate the proposed multiscale approach, Hangzhou Jiangdong Bridge is selected to perform the numerical computations. The bridge locates at Hangzhou, the capital of Zhejiang Province of China. It is a self-anchored suspension bridge on the Qiantang River. The cables are made of 109 parallel steel wires in the diameter of 7 mm. Cable forces are calculated by finite element method in the service period with and without traffic load. Two parameters α and β are introduced to account for the additional tightening and loosening effects of cables in two different ways. The fatigue crack growth rate coefficient C_0 is determined from the fatigue experimental result. It can be concluded from numerical results that the size of initial microscopic defects is a dominant factor for the fatigue life of steel wires. In general, the tightening effect of cables would decrease the fatigue life while the loosening effect would impede the fatigue crack growth. However, the result can be reversed in some particular conditions. Moreover, the different evolution modes of three basic parameters μ^*, σ^* and d^* actually have the different influences on the fatigue crack growth behavior of steel wires. Finally the methodology developed in this work can apply to all cracking-induced failure problems of polycrystal materials, not only fatigue, but also creep rupture and cracking under both static and dynamic load and so on.

1. Introduction

Suspension bridges and cable-stayed bridges have prevailed in the modern long-span bridges because they can have a longer main span comparatively. Cables in a suspension bridge subject to loads

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doi:10.1016/j.tafmec.2010.03.002

including the dead loads and traffic loads and transfer them into the towers and anchors. Bridge cables are made of high strength steel wires. The strength of cable wires has increased significantly in the recent years. The range of minimum strength had fluctuated between 1470 MPa and 1570 MPa for more than 50 years. A leap of increase to 1770 MPa has taken place with the construction of the world's longest suspension span of 1991 m, the Akashi Kaikyo Bridge in Japan. The increase in the wire tensile strength is usually accompanied by reduction in ductility and increase in the wire susceptibility to delayed fracture, also known as hydrogen embrittlement. Inspection of suspension bridge cable wires has revealed deterioration with different degrees of severity. Deterioration of cable wires takes different forms such as stress corrosion cracking, pitting, corrosion fatigue and hydrogen embrittlement, which compromise the strength and ductility of wires leading to a reduced service life of bridge cables. Therefore, accurate assessment of steel wire fatigue lives is essential for the evaluation of the safe load carrying capacity of bridge cables.

The limiting lives of either the suspension or the cable-stayed bridges are predominantly determined by the aging of the cables [1]. Cables having different length sustain different stresses and strains, their ultimate lives will not only differ but they will change differently because of the changing environment. Some experiment-based investigations have been made [2–4]. Monte Carlo simulation was investigated to show the relationship between the fatigue lives of short-prestressing strand test specimens and strand stay cables. Cable lives were calculated by using statistics determined from the results of fatigue tests of prestressing strand specimens [2]. A model was developed based on some fatigue tests for predicting free-bending fatigue life of axially preloaded spiral strands clamped at the end [3]. Discussed in [4] was the buffeting-induced fatigue damage problem of steel girders located in strong wind regions. Some fatigue experiments for bridge cables have also been completed recently in China such as [5–7]. Moreover, the problem of fatigue limit and fatigue life prediction in high strength cold drawn eutectoid steel wires was studied in [8]. The degradation of bridge cable wires due to stress corrosion and hydrogen embrittlement was explored in [9]. Discussed in [10] was the assessment method of cracking potential in bridge cable wires. The wire fractures in locked coil cables were investigated in [11]. Bridge Technology Consulting of New York State made an investigation which focused on fracture toughness identification of main cable wires at the Mid-Hudson Suspension Bridge in 2007 [12]. The fracture strength of cracked steel wires under different crack shapes and sizes was calculated in [13]. The effect of crack shape and size on estimating the fracture strength and crack growth fatigue life of bridge cable steel wires was assessed in [14]. The fatigue crack growth behavior of cables and steel wires in a cable-stayed bridge was predicted in [15].

However, the fatigue problem has yet remained challenge although it is an old problem. In summary, a fatigue process is usually divided into two stages in an arbitrary way. The first stage is called as the fatigue crack initiation while the second stage is the fatigue crack propagation. Different methodologies are respectively applied to two different periods. For the fatigue crack initiation period, Miner's fatigue cumulative damage theory including various improved versions is often used [16]. Miner's theory is an empirical approach which greatly depends on the fatigue experiments. For the fatigue crack propagation period, Paris's equation is often adopted, which gives a relationship between the fatigue crack propagation rate da/dN and the crack intensity factor range ΔK based on the fatigue tests [17]. Paris's equation is only valid for the macroscopic fatigue crack stable growth known as region II. In fact, the growth of a fatigue crack from micro to macro is a continuous physical process that should be analyzed within a unified theoretical framework. The fatigue crack initiation period deals with the nucleation, collecting and growth of microdefects. On the other hand, the fatigue crack propagation period is the crack growth at the macroscopic scale including the crack stable and instable propagation. The problem how to link two different stages (or scales) has remained open. It is a scale transition problem that should be solved by developing the multiscaing theories. Many efforts have been done in this field. For instance, a self-consistent micromechanical description of orthotropic texture evolution in the context of a constrained single slip model for planar crystalline polymers is proposed in [18]. The quasicontinuum (QC) method was combined with continuum defect models to establish a coupled atomistic/continuum model of defects in solids [19]. The effect of microcracking on the mechanics of fatigue crack growth in austempered ductile iron was considered in [20]. The effect of microstructure on mixed-mode (mode I + II), high-cycle fatigue thresholds in a Ti–6Al–4V alloy over a range of crack sizes from tens of micrometers to in excess of several millimeters was investigated in [21]. Shown in [22] was microcracking in brittle materials results in a reduction of the stress intensity factor (SIF) and energy release rate (ERR). A three-dimensional finite element simulation was performed to study the growth of microstructurally small fatigue cracks in aluminium alloy 7075-T651 in [23]. A micromechanical description of small fatigue crack growth was presented based on the successive blocking of the monotonic plastic zone (MPZ) and cyclic plastic zone (CPZ) of a crack at microstructural barriers such as grain boundaries and phase limits in [24].

Otherwise, some advances in multiscaling fatigue theories can be found in [25,26]. In the recent years, a notable work on developing the multiscaling crack models has been done in [27–30]. A dual scale stress intensity factor or energy density factor has been proposed to describe a crack from micro to macro. The single scale crack model cannot explain the scale transition between two different scales. Multiscaling of fatigue crack growth rates for metal alloys is revealed by the spread of the test data in three different regions known as I, II and III. It has been shown that when a dual scale crack model is adopted, three regions I, II and III are shown respectively to lie on a straight line with different slope and y-intercept that corresponds to different mean stress σ_m and stress amplitude σ_a [30]. This implies that the scale effect can be taken into account in a multiscale crack model. To reiterate, a micro-/macro-crack model will be used in this work to analyze the fatigue crack growth behavior of the cable steel wires in a real suspension bridge. A wide variation of the tightening and loosening of the tension in cables is expected to occur due to many reasons. The large variations of fatigue lives for the cable wires are identified for several different scenarios of cable tightening and loosening. The results can be used to develop inspection procedures for the health well-being of the bridge.

2. Underlying physical model

Macro/micro dual scale crack model is based on the concept of restraining stress zone as shown in Fig. 1. Fig. 1a shows a plate under the uniaxial tension without damage. Now it is assumed that there is a cut in the center of plate as shown in Fig. 1b. The restraining stresses would prevail on the cut surfaces denoted by σ_0. If the ratio of restraining stress to applied stress σ_0/σ_∞ is equal to 1, say $\sigma_0 = \sigma_\infty$, case (b) is then equivalent to case (a) (i.e., no damage). If $\sigma_0 = 0$, case (b) is then identical to case (c) as shown in Fig. 1c known as a mode I crack at the macroscale. Hence, it is pertinent to use the stress ratio σ_0/σ_∞ to quantify the damage degree of a material. The value of σ_0/σ_∞ would be 1–0. $\sigma_0/\sigma_\infty = 1$ implies that the material has no any damage. On the other hand, $\sigma_0/\sigma_\infty = 0$ means that there is a macroscopic crack with free crack surfaces.