Finite Elements in Analysis and Design 116 (2016) 12–20

Contents lists available at ScienceDirect

Finite Elements in Analysis and Design

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

A two-scale damage model for high-cycle fatigue at the fiber-reinforced polymer–concrete interface

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ARTICLE INFO

Article history:
Received 30 October 2015
Received in revised form
10 March 2016
Accepted 27 March 2016
Available online 12 April 2016

Keywords:
Damage
High-cycle fatigue
Finite element
Bond behavior
Fiber-reinforced polymer (FRP)
Concrete

ABSTRACT

This paper presents a new two-scale damage model of the fiber-reinforced polymer (FRP)–concrete bond under high-cycle fatigue. The material behavior is modeled as elastic-plastic coupled with damage for the microscale analysis and as elastic for the mesoscale analysis. A new damage law for the interface joint is described. The two-scale damage model has been implemented as a material model for a three dimensional an eight-node interface element of zero thickness and used to simulate a double shear joint specimen under high cycle fatigue. The numerical calculations were performed with a full incremental cycle solution and a new cycle jump approach.

1. Introduction

Repeated cyclic loading on reinforced concrete (RC) structures such as bridges can cause reduced service life and structure failure from fatigue even when the stress ranges applied to the structural components are very low. However, the use of fiber-reinforced polymer (FRP) composites to strengthen and increase the fatigue life (service life) of these structures is a promising technology, and this technique might be the optimal choice for consulting engineers. The bond between the FRP materials and the concrete must be durable to ensure that the strengthening system remains effective for its expected service life. Several test methods have been used to evaluate the bond behavior of externally bonded FRP composite sheets and plates under high- or low-cycle fatigue loading, including the single shear (single lap joint) test [1,2], the double lap joint test [3,4], the pullout specimen method for measuring peeling stresses [5], and the partially bonded beam test [6]. In the high-cycle fatigue test, the maximum applied fatigue load is lower than the limit of linearity (yield load of the joint), and the joint behavior is elastic. In contrast, the joint is in the non-linear phase in the low-cycle fatigue test. The behavior of the FRP–concrete bonded joints under high-cycle fatigue is classified into three phases, see Fig. 1. The damage in the first phase occurs mostly from microcracks that cause residual plastic strain with negligible stiffness degradation. In the second phase, macrocracks start to cause stiffness degradation, with keeping the ability of the joint to resist the applied load. Finally, debonding occurs (fracture process) from crack propagations that produce loss of both the stiffness and resistance capacity of the joint. The period of any phase and the possibility of their presence in the behavior of the joint is dependent on the maximum applied stresses as well as fatigue limit stress of the joints. Where, the first phase be prevalent of the joints behavior when the applied maximum stresses are a somewhat more than the fatigue limit stress.

A few models have been developed for FRP–concrete interfaces under fatigue load, and most researchers analyzing FRP-strengthened RC beams subjected to fatigue load have simulated the FRP–concrete bond as a perfect bond (full composite action) [7–9]. The models described in the literature are mainly based on the fracture mechanism, which is unsuitable for simulating high-cycle fatigue, especially in the first phase. Loo et al. [10] developed a model of the interface bond under fatigue load based on the degradation of the joint stiffness cycle, Eq. (1), where E_b and E_{bo} are the stiffness of the joint at cycle N and at the first cycle, respectively. $\Delta\tau_{ave}$ is average bond stress range, $\tau_{ave},\ f$ is average bond stress at failure, and the constants $\propto$, β and γ are

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http://dx.doi.org/10.1016/j.finel.2016.03.003
0168-874X/

parameters to fit the experimental data.

$$E_b = E_{bo}\left[1 + \propto (\log N)^{\beta}.\left(\frac{\Delta\tau_{ave}}{\tau_{ave}, f}\right)^{\gamma}\right] \quad (1)$$

This model did not produce good results when used to analyze the joint behavior with high-cycle fatigue.

Diab et al. [11] presented a model to assess the bonding fatigue behavior of the FRP–concrete interface. The model of the joint before the initiation of debonding and subsequent fatigue crack growth was based on the creep-fatigue interaction, which was represented by the degradation of the interfacial stiffness, Eq. (2), where K_{fo} and K_{ft} are the interfacial cycle-dependent stiffness at time zero and at time, and $\varnothing$ is creep-fatigue coefficient.

$$K_{ft} = \frac{K_{fo}}{1+\varnothing} \quad (2)$$

This is also not accurate for the first phase of high cycle fatigue.

In the present study, to get accurate results at the first phase of high cycle fatigue a two-scale model has been implemented for modeling FRP–concrete joints under high-cycle fatigue in the first phase when the stress level lower than the engineering yield stress. Plasticity coupled to a damage model for the microscale analysis and an elasticity model for the mesoscale analysis has been used. A double shear joint specimen under high-cycle fatigue using the three-dimensional finite element method (FEM) was modeled. After validating the model by comparison to experimental data, a parametric study was completed.

2. Damage constitutive equation

Damage to a material refers to gradual deterioration of mechanical strength from the development of microcracks and micro-cavities [12]. Most models of damage in a material introduce a damage variable [13]. The damage variable is the ratio of the effective area or volume of the intersections of all microcracks or micro-cavities to the total undamaged area or volume. We designed the damage model according to this definition.

A suitable damage model for the joint interface represented by an interface element under fatigue load must allow for the different materials of the joint and must relate directly to the accumulated microplastic strain. In addition, the parameters must be easy to determine from static test. To meet these criteria, we need to describe the behavior of the joint under monotonic load. Fig. 2 shows the schematic of the general behavior of the FRP–concrete joint under static load constructed from an experiment [14], where the stress is the applied average bond stress and slip represents the slip of FRP with respect to the concrete block. The joint behavior has two stages, the elastic stage and the fracture stage. The fracture stage starts after the maximum load is reached, which means that the damage behavior of the bond occurs only during the elastic stage and thereby the first phase of fatigue joint behavior take place at entire this stage only. The fatigue behavior phases can be represented, schematically, with regard to static behavior in Fig. 2(b). To describe this damage behavior, we define the damage variable D_j for the 3-D joint as a function of the total strain (elastic and accumulated plastic strain) within the elastic stage as

$$D_j = \left(1 - \frac{\varepsilon_{j3}}{L_{e,j}}\right)^{\left(\alpha - \frac{1}{\alpha}\right)}, \quad (3)$$

where ε_{j3} is the current total strain (interface slip which has the dimension of length) in normal and shear directions (j). $L_{e,j}$ is the total length of the elastic stage obtained from static tests of FRP–concrete joints with different modes, by this parameter the state of stress (mode I, mode II, mode III) is taken into the damage. α is the damage exponent that determines the shape of the damage evolution curve and should be greater than one.

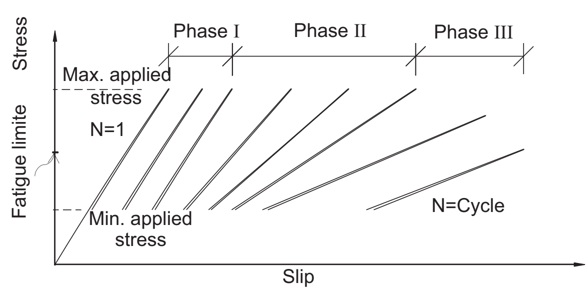

Fig. 1. Typical bond stress-slip relationship in FRP–concrete joints under high-cycle fatigue.

3. Material models

In the FEM analysis, concrete and FRP are modeled at the mesoscale, the scale of the representative volume element. The behavior of material at this scale is linear elastic. The bond between the concrete and FRP, which is represented by the interface element, is treated with a two-scale damage model. The two scale model is considered as inclusion within in an elastic meso-matrix [15] as shown in Fig. 3. This inclusion is modeled as elastic-plastic coupled with damage.

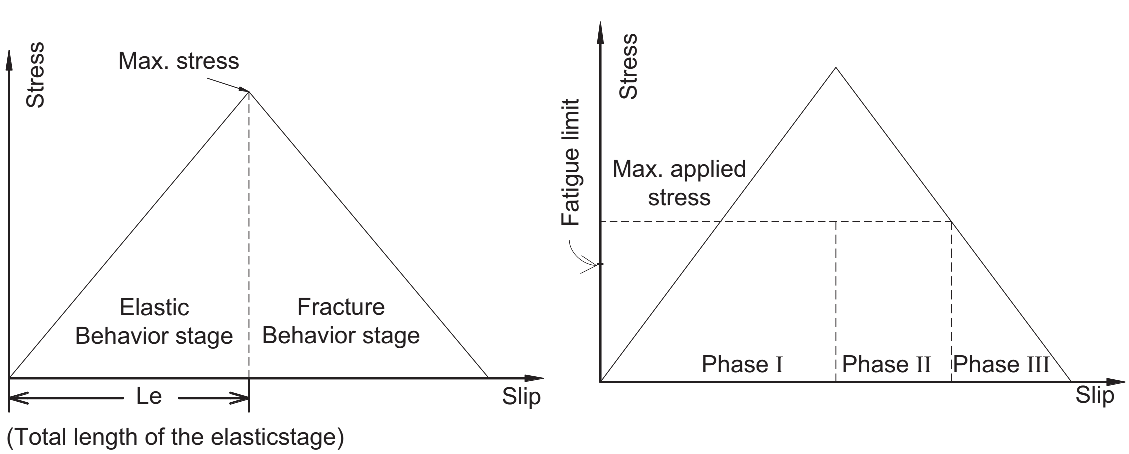

Fig. 2. Typical FRP–concrete joint behavior under static load (a) static stages (b) fatigue phases in static stress-slip space.