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A study on the simulation method for fatigue damage behavior of reinforced concrete structures

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ABSTRACT

This paper mainly focuses on developing an efficient simulation method for fatigue behavior of reinforced concrete structures (RC structures), through which the damage state and the potential fatigue damage failure pattern of the RC structures could be obtained in finite element analysis (FEA). In order to accomplish such object, fatigue behavior of RC structures is studied using the entire history of damage accumulation for both concrete and steel bars. A bi-scalar damage-plasticity constitutive model for concrete and a single-scalar damage constitutive model for reinforcement are first introduced to characterize the fatigue damage state of the structure. Then, a two-scale temporal expediting computational technique is developed for the material constitutive models, by which the original material models could be split into a micro periodic time scale portion and a macro homogenized time scale portion. Through this calculation technique, the original increment-by-increment FEA procedures could be transferred to the two-time scale calculation, which would greatly enhance the efficiency of the structural fatigue simulation. By combining the material constitutive models and the expediting calculation technique with FEA, a set of numerical examples and comparisons are performed, specifically, a column-drilled shaft connection in bridge structure is simulated, which validates the effectiveness and reliability of the current simulation method for the fatigue behavior of RC structures.

1. Introduction

Many reinforced concrete structures (RC structures) are subjected to cyclic live loads during their service life, such as wind power tower bases, bridge decks, pavement of high-speed rails, etc. In many circumstances, fatigue or time-delayed fracture will occur in these kinds of structures. Starting from the research of Considére [4] and Joly [16] the fatigue problem of concrete materials and structural members has long been studied [12,30]. However, the fatigue damage behavior and fatigue life predictions of concrete materials and reinforced concrete structures still pose a great challenge to the researchers. To-date, the design codes for fatigue of concrete materials and RC structures are mainly based on the experimental S-N or ε-N curves, which provides a general way to predict the fatigue life and degradation of the structure [35]. However, the fatigue test-based empirical models [2,13,5,21,40] can hardly indicate the damage development and its spatial distribution in the RC structures. Hence, they seem unable to provide the comprehensive information of the fatigue damage of the whole structure.

To obtain the spatial distribution of the physical quantities (e.g. displacement, stress, strain, damage, etc.) and the whole degradation behavior of a structure due to fatigue loads, finite element analysis (FEA) was carried out [28,37], in which two important ingredients, namely, the material constitutive model and the computational technique, should be studied in-depth. In the aspect of material model, both fracture and damage theories have been used to describe the mechanical properties of concrete for fatigue simulations. By referring to the classical Paris' law [29] which is used for metal in the beginning, several fracture models [34,3,37] were developed for concrete material. Considering the nonlinearity within the fracture processing zone of the concrete cracks [14], the cohesive crack models [15,27,41] were introduced later on. However, these fracture mechanics based models mainly focus on single macro cracking behavior of concrete, which is unable to describe the effect of multiple micro cracks and the corresponding

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damage mechanisms and states. Hence, they are not suitable for fatigue simulation of large-scale structures. A more reliable theoretical framework, namely the continuum damage mechanics, was later adopted to modeling the fatigue behavior of concrete [25,1,26,24]. Based on the irreversible thermodynamics, damage variables are introduced to describe the material degradation caused by the propagation of micro cracks which strongly interact and intersect with each other. Then, the constitutive model for concrete fatigue simulation could be created according to the Clausius-Duhem inequality [23] and a proper damage evolution law. By combining the constitutive model with FEA, several fatigue simulations on concrete material were performed [26,24].

Although the fatigue damage models and finite element method have long been developed, a proper fatigue simulation on RC structures was seldom reported. One reason is that, the fatigue damage accumulations for both concrete and steel are seldom considered at the same time in the FEA. Most importantly, most of the fatigue simulations on concrete or RC structures merely used the default increment-by-increment calculation procedure in FEA software, by which a lot of calculation time is needed. Thus, these simulations could only consider simple cases, for example, the material or element cases under low cycle fatigue (usually less than 5000 loading cycles). When considering fatigue problem of large-scale RC structures and higher cycles (e.g. the intermediate or high cycle fatigue) the traditional simulation method will meet great difficulties.

To solve this problem, the temporal expediting computational techniques must be studied. One kind of the damage constitutive model-based speeding computational techniques is the so-called 'cycle jump' method [6–8,18]. According to this method, the damage evolution rate of every spatial integration point could be calculated through one or a few loading cycles [10,9] as the following equation shows:

$$\dot{d} \approx \frac{\Delta d}{\Delta N} = d_{N+k}(x_a) - d_N(x_a), \quad k = 1, 2, 3 \ldots \tag{1}$$

in which $d_N(x_a)$ is the damage variable of the integration point a at the N-th cycle; N is the number of loading cycles; and k denotes the cycle number from the N-th cycle. Then, the jumping cycles, ΔN, could be obtained by setting a proper Δd.

The above extrapolation algorithm contributes to high efficiency in fatigue simulations. However, the integration needs extra control to ensure the accuracy [11], and it is very sensitive to the threshold of Δd [9]. Thus, it may not be a unique computational method for fatigue simulation.

As a matter of fact, the fatigue life of material spans years or even decades, while the loading and response cycles could be in the order of seconds. Therefore, it is a multi-scale problem in time domain. Based on such understanding, some researchers [28,10] proposed a more reliable speeding calculation method, namely, the two-scale temporal asymptotic homogenization method. By this method, the original constitutive models could be split into a homogenized portion described by macro time coordinate t, and a periodic portion described by micro time coordinate τ. On the basis of such time separation, a relatively large time step could be adopted in the FEA and the simulation does not need to do the integration of every time increment in every loading cycle. This calculation technique has been successfully applied to simulate some simple fatigue problems without considering plastic deformation [28,10]. However, it has never been used for RC structures. The most possible reason is that, governing equations in macro and micro time scales have to be derived for different types of constitutive models according to the theoretical framework. For concrete material, not only damage but plastic deformation accumulates due to fatigue [24]. Hence, the time separation of the concrete damage-plasticity constitutive model is more complex and difficult than the elastic-damage material models.

With the inspirations from the previous work, this paper intends to present an efficient and reliable method for the fatigue simulation of RC structures. In the simulation, fatigue of both concrete and reinforcement are taken into consideration. To consider the fatigue behavior of concrete, a damage-plasticity constitutive model [24] is introduced, and the fatigue damage accumulation of reinforcement is considered by adopting a typical fatigue damage evolution model for steel [9]. To enhance the computational efficiency in FEA, the two-scale temporal asymptotic homogenization theoretical framework is introduced. On the basis of this framework, governing computational equations in macro and micro time scales for the currently adopted damage-plasticity material model are developed. Then through combing the material models and the corresponding calculation technique with FEA, a set of procedures for simulations and comparisons are illustrated, which validates the effectiveness and reliability of the current method for the simulation of fatigue behavior of RC structures. According to these studies, the two-scale temporal asymptotic homogenization framework could be expanded to consider both of the damage and plasticity accumulations for RC structures which are little reported in literature. At the same time, the damage accumulation process and its real-time spatial distribution in the RC structures could be gained in an efficient way, based on which, the fatigue failure pattern of the RC structures could be reasonably predicted.

2. Theoretical framework of the two-scale temporal asymptotic homogenization expediting calculation technique

According to the two-scale temporal asymptotic homogenization theory, multiple time scales are adopted to describe slow degradation of material properties (e.g. fatigue damage, plastic deformation, etc.) due to fatigue, as well as to resolve the response (e.g. stress, strain, etc.) within a single load cycle [28]. The original time coordinate in common FEA could be split into a macro (slow) homogenized time coordinate t, and a micro periodic time (fast) coordinate τ. These two time coordinates are related by a small positive scaling parameter ϵ:

$$\tau = \frac{t}{\epsilon} \tag{2}$$

Then the periodic response fields φ (e.g. fatigue stress, fatigue strain, etc.) as is shown in Fig. 1 could be further expressed as the function of the multiple time scales:

$$\varphi^{\epsilon}(\boldsymbol{x}, t) = \varphi(\boldsymbol{x}, t, \tau(t)) \tag{3}$$

in which $\boldsymbol{x}$ represents the spatial coordinates; and the variable with superscript 'ϵ' means that the multi-time scale is taken into account.

The time variation of structural response in both time scales could be obtained through taking time differentiation of Eq. (3):

$$\dot{\varphi}^{\epsilon}(\boldsymbol{x}, t) = \varphi_{,t}(\boldsymbol{x}, t, \tau(t)) + \epsilon^{-1}\varphi_{,\tau}(\boldsymbol{x}, t, \tau(t)) \tag{4}$$

where the superposed dot denotes the total time derivative of a variable; the subscripts '$,t$' and '$,\tau$' represent the partial derivative of t and τ, respectively; Then the decomposition of the response into a macro- and micro-time scales could be gained by adopting the temporal smoothing operator [28]:

$$\varphi^{\epsilon}(\boldsymbol{x}, t, \tau) = \langle\varphi\rangle(\boldsymbol{x}, t) + \Phi(\boldsymbol{x}, t, \tau) \tag{5}$$

in which $\langle\cdot\rangle = 1/\tau_0 \int_0^{\tau_0} \cdot d\tau$ is the temporal smoothing operator; $\langle\varphi\rangle$ denotes the macro-time portion of the response φ; τ_0 denotes the micro time period; and Φ represents the micro-time portion of φ.