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Investigation of the strengthening effect of DFRCC applied to plain concrete beams

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Abstract

One of the most important characteristics of Ductile Fiber Reinforced Cementitious Composite (DFRCC) is its strain hardening behavior up to 5–6% *strain* under tensile loading. In this study, the strengthening effect of DFRCC, applied to the tension region of plain concrete beams, is both numerically and experimentally examined. More specifically, 10%, 20%, and 30% of the beam height are replaced with DFRCC to measure the strengthening effect of the composite beam. From four-point bending tests and numerical simulations, the load–deflection behaviors are investigated and compared. To assess the effect of ultimate tensile strength, strain capacity and strain hardening slope of DFRCC, numerical simulations are carried out with DFRCC strain capacities ranging from 1% to 5%. From these studies, it is shown that DFRCC significantly contributes to the deflection capacity, load carrying capacity and failure modes of concrete beams.
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Keywords: Ductile fiber reinforced cementitious composite; Strain hardening; Strain capacity; Strengthening effect; Numerical model

1. Introduction

Multitudes of concrete structures were constructed during the 1960s and 1970s. After 30–40 years of service life, time has come to make a decision whether to repair or replace many of these concrete structures. For the successful repair of structures, structural health evaluation, methodology of repair, and selection of repair materials are three important factors [1,2]. Many different materials have been developed for the purpose of repairing deficient structures. They range from Portland cement-based materials to polymer-based materials. However, polymeric materials have been utilized in limited applications as a repair material for concrete structures because, in part, of concerns about the long-term compatibility between the concrete substrate and the repair material.

Compatibility between substrate and repair material is the most important factor in selection of repair material. Cement-based materials are suitable for repairing concrete structures due to their mechanical and physical properties (e.g. coefficient of thermal expansion, fracture energy, permeability), as well as other important considerations such as cost, availability, and constructability [3–6].

Recently, different types of cement-based composites have been developed to control mechanical properties, such as elastic modulus, ultimate tensile strength, and strain capacity. This is possible through characterization and engineering of the three main phases of the composite: matrix, fiber and fiber–matrix interface. For this reason, composites can be tailored for unique applications by maximizing their mechanical properties and characteristics. Recently, Ductile Fiber Reinforced Cementitious Composites (DFRCC) with moderate elastic modulus, moderate tensile strength, and high tensile strain capacity have been developed based on micro mechanical models [7–11]. One of the most promising areas of application of this material is using the material to the repair of concrete structures.

The present paper investigates the importance of the ductility of DFRCC when it is used as repair material on concrete structures under flexural loading. A lattice-type

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model was developed to study damage in concrete and cement-based composites [12–15]. At this stage, strain hardening behavior of DFRCC has been implemented in the model and the simulation results (Group B beams) are compared with experimental data (Group A beams). Composite beams are also numerically simulated with DFRCC having different strain capacities to investigate the effect of ultimate tensile strength and strain hardening slope (Group C and D beams).

2. Numerical modeling

2.1. Background of numerical method

Lattice models have been widely used for simulation of brittle failure of materials [16–19]. In the most basic case, crack growth is modeled by removing (from the mesh) the element with the highest stress-to-strength ratio. The computation is repeated until failure in the complete mesh is obtained. The fracture is based on the maximum tensile stress that occurs in the outermost fiber of a frame element due to moment and normal force at nodes *i* and *j* as shown:

$$\sigma = \frac{\beta}{(1-\Omega)}\left(\frac{F}{A} + \alpha\frac{\max(|M_i|,|M_j|)}{W}\right), \tag{1}$$

where F is the axial force in the frame element, M_i and M_j are the bending moments at nodes i and j of the frame element, respectively. The parameter A is the section area of frame element with width b and depth h, and W is the element section modulus ($bh^2/6$). Ω is a damage parameter which is initially set to zero for all elements; $\Omega = 1$ corresponds to element removal from the lattice (i.e. complete damage). The constant α is a parameter to control the influence of flexure on the fracture and β is a parameter for scaling the element effective stress to global stress levels. The significance of parameters α and β was discussed in Refs. [20–22].

The lattice model is based on the iteration of linear elastic lattice behavior when nonlinearity is introduced. Once an element is removed from the system, the solution is repeated linearly to get another point on the load–deformation curve. As will be shown later, the model can realistically describe the cracking patterns. The model's main drawback, however, is its highly irregular macroscopic stress–deformation relation particularly in the post-peak region.

Cement-based materials such as concrete and DFRCC always fail due to tensile cracking at the microlevel. In this study, therefore, the ADLE (Axial Deformation Link Element) model [12–15] was introduced to investigate the fracture behavior of the materials. This model considers only axial deformation between two neighboring points. At each load stage, the effective stress σ acting in each element is computed according to Eq. (1) when $\alpha = 0$. The ADL element with the highest ratio $R = \sigma/\sigma_f$ experiences a fracture event when $R \geqslant 1.0$, where σ is the axial stress in the element and σ_f is the tensile strength of the material. Element internal forces associated with this change are released, with both the element and system stiffness matrices reformed. To model the macroscopic nature of the material and fracture process better, the stiffness of fracturing elements was gradually reduced via damage parameter Ω depending on the component type. The ADLE model adopts the fictitious crack model with post-peak softening curve to overcome the weakness of a lattice type model as mentioned earlier. This model reveals a realistic stress–strain response similar to that observed experimentally for concrete material.

2.2. Constitutive relations of concrete and DFRCC

The softening behavior of the concrete is implemented through the stress-crack separation relations in order to arrive at a mesh–objective representation of fracture [23]. It is assumed that the stress–strain relation for the elements is linearly elastic up to its tensile strength of the phase considered, followed by softening. Hence, the elastic parameters required to establish the first part of the relation are elastic modulus (E) and tensile strength (f_t). The inelastic parameters associated with the softening part of the curve are fracture energy (G_F) and the shape of the stress–separation curve. When these parameters are specified, a complete constitutive relation can be established for each individual element based on its length. Unlike concrete materials, however, DFRCC exhibits tensile strain-hardening characteristics. A constitutive relation for an ordinary DFRCC is shown in Fig. 1.

The tensile stress increases linearly up to first cracking strength f_t, after which DFRCC undergoes strain-hardening up to the ultimate tensile strength $\beta_s f_t$. The ultimate tensile strength parameter β_s can change according to the characteristics of DFRCC. During strain-hardening, multiple micro-cracks are successively formed and finally those cracks become nearly equally spaced in parallel. In the strain-softening region, transmitted tensile stress decreases after strain-hardening. During strain-softening, the "strain" is not uniquely defined, but depends on gauge length. Deformation at this stage is more appropriately described by crack opening displacement, and begins to localize in the transition from uniform deformation field (multiple cracking deformation) to the crack opening displacement of a single crack.

The first step of numerical procedure is data input for mesh generation and material property assignment. For the mesh generation step, axial deformation link elements (ADLE) are generated and each element is assigned with material properties such as elastic modulus, first cracking strength, ultimate tensile strength, and fracture energy [23,24]. In this material property assignment process, material properties vary about their mean values with 10% coefficient of variation (c.o.v). This deviation of material properties is provided by Monte Carlo simulation using a normal distribution. From the previous research, c.o.v has a slight effect on the response. The predicted response

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