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Numerical investigation for the flexural strengthening of reinforced concrete beams with external prestressed HFRP sheets

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HIGHLIGHTS

- The flexural behavior of RC beams strengthened with prestressed HFRP is studied.
- Different material models are evaluated to describe the behavior of the beams.
- The model can be applied in analysis of other HFRP strengthened structures.

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ABSTRACT

Strengthening method of using HFRP (hybrid fiber reinforced polymer) has been considered to be an effective way to increase the strengthening efficiency. This paper focuses on simulating the flexural behaviors of RC (reinforced concrete) beam which strengthened by prestressed HFRP sheets. Finite element analysis is presented to validate against laboratory tests of five beams. All beams have the same rectangular cross-section geometry and are loaded under four point bending, but differed in the prestress and HFRP. The user-subroutine UMAT (User subroutine to define a material's mechanical behavior) is used for implementation of the whole model. Different material models are evaluated with respect to their ability to describe the behavior of the beams. The results show good agreement with the experimental data regarding load-displacement response, ultimate flexural capacity, ductility and failure mode. The result shows that prestressed HFRP can resist both live load and dead load of the strengthened beam, unload tensile stress of the steel and restore structural deformation, thus improve the performance of the strengthened beam.

1. Introduction

Civil structures, e.g. bridges, inevitably experience external perennial erosion environment, impact loading or other unexpectable overloading. Therefore, the loading capacities of civil structures might be weakened due to the aging and damage of the structure during their services. FRP (fiber reinforced polymer) strengthening has become a widely used structural strengthening technique to civil structures in recent years attributing its merits as good durability, high strength, low weight and ease of installation [1]. The earliest research on bonding FRP strengthening method was reported by Swiss Federal Laboratory in 1984 [2]. Since then numerous of experimental and modeling investigations of FRP strengthened RC structures has been carried out over the last decades [3,4]. Unidirectional FRP intrinsically has much higher tensile modulus and strength in fiber direction than other directions. This character mostly adapts it used in strengthening the tension face of bending structure, e.g. concrete beam or slab to elevate both their ultimate flexural strength capacity and post-cracking stiffness, and meanwhile stopping tensile crack extension in concrete [5,6]. It could be predicted that FRP strengthening has a high potential for becoming a primary strengthening scheme for deteriorated flexural loading structures [7].

Currently, carbon fiber, glass fiber and aramid fiber are the most widely employed fibers in FRP sheet for civil structure strengthening. Carbon fiber has the largest strength and modulus as well as stable and durable in erosion environment, however, with the cost of low elongation and high price. Glass fiber has best elongation but low modulus. Aramid fiber possesses the medial strength, modulus and toughness and the lowest price. Two or more reinforcing fiber types are usually employed in a FRP sheet in order to obtain the balanced mechanical and economical properties of FRP, which is also called hybrid FRP. In HFRP the advantages of

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different fibers could be fully used [8]. High modulus fiber provides the most stiffness and load carrying capacity in normal service condition. If some of it breaks due to large elongation, the load it carried before will be undertaken by low modulus fiber which still has strength allowance for its large critical elongation. As a result, the failure tolerance of the FRP is greatly improved. Besides, the cost is reduced for the low modulus fiber usually possesses high strength/price ratio [9]. Intraply hybrid and interlaminar hybrid are the two main hybrid modes for HFRP sheet and the former has been proven possessing better efficiency [10].

Ma Xiaosheng et al. [11] have conducted comparative tests of GFRP (glass fiber reinforced polymer), CFRP (carbon fiber reinforced polymer) and HFRP for strengthening concrete beams and columns. The balanced advantages of HFRP used for strengthening are discussed in terms of safety, durability and economy. Attari et al. [12] examined the efficiency of external strengthening systems for RC beams using HFRP fabric (Glass/Carbon). Their tests demonstrated the cost-effectiveness of twin layer glass-carbon HFRP fabric as a strengthening configuration for RC structures. In study of Yang et al. [13], HFRP is used to strengthen wood beams. They tried CFRP, GFRP and HFRP (Glass/Carbon), respectively. Similar to the results from RC structure strengthening, HFRP is also found provide a significant increase in moment bearing capacity and ductility of wood beam with lower cost. Out of the advantages of using HFRP as external bond, the most important one is the performance of the HFRP should support and contribute a good impact on the RC structure until its failure.

Concrete is brittle material and has low tensile strength and relatively high compressive strength. There will exit a big gap between tensile failure strains of concrete and HFRP, and this mismatching leads the strength of HFRP could not be fully used. Prestressed HFRP is a solution; however, the existing works on prestressed HFRP strengthening found in the literature mostly focus on experimental researches. The destruction of FRP strengthened RC structure is the outcome of complicated interactions of concrete, steel bar and FRP. In order to make full use of HFRP, the strengthening and load transfer mechanism, the matching of stiffness and strength of the strengthened structure need to be well understood.

The damage process of concrete is complicated. Before the main crack is formed, there are initial damage and a large number of micro cracks that influence its modulus and strength. As for FRP, the failure mode is diversified, and its failure is a gradual process. Damage mechanics is an effective way to describe their mechanical behavior.

Dougill [14] first brought the concepts of damage mechanics to describe the damage of concrete. Nonlinear and stress state dependent mechanical response of concrete have been constituted in frameworks of elasticity damage [15], elastoplasticity damage [16], visco-elastoplastic [17] or fracture mechanics [18] have been proposed. Under compression, concrete characterizes notable plasticity in addition to damage attributing the crash of its porous micro structure, so volume compressible elastoplastic damage constitution is reasonably employed [19]. In the earlier studies, damage is presumed as a scalar. Many authors have commonly adopted an isotropic damage formulation, making use of a single scalar variable [20], and the damage evolution can be determined through experiments. Scalar models with two damage variables have also been proposed, in an attempt to distinguish between tension and compression damage mechanisms [21]. Later researchers introduce tensor into the damage model of concrete, anisotropic damage models have been proposed introducing 4th or more frequently 2nd order tensors [22,23]. Although these models are more consistent with the actual character of the concrete, the form of these models is complicated, along with a lot of hypothesis and parameters, and sometimes it is not easy to overcome some of the convergence problems related to the computational implementations. In spite of the enormous progress made in the field, currently there is not yet a scientific consensus about the damage theory of concrete.

Bonding strength of reinforcing steel bar and concrete has effect on the final strength of RC structure. Lutz et al. [24] proposed an RC finite element approach in which adhesion between rebar and concrete details to friction and mechanical bite. Wang et al. [25] proposed adhesive strength formula calculation according to the experiment test. Zhao et al. [26] suggested a bond stress-slip formula in their finite element analysis considering reinforcement corrosion.

FRP/concrete interface plays a critical role in the success of external bonding of FRP to RC structures for rehabilitating. The performance of FRP/concrete interface has been widely investigated through single-shear and double-lap shear experiments [27,28]. For numerical models, bonding FRP and concrete with common nodes is a simplified method once used [29] but can only be reasonable for the strong bonding condition. Various interfacial approaches, e.g. including combine spring element [30] and cohesive bonding [31] have been adopted more and more to simulate FRP gradually debonding process.

Although some experimental works have been reported on the performance of HFRP strengthened beams, few numerical efforts have been made to characterize its flexural behavior. Therefore, both experimental and numerical study are carried out in this paper. The nonlinear behavior of concrete, HFRP and interface are introduced in the FEM (finite element modeling) to predict overall flexural behaviors and failure modes of both un-strengthened and FRP-strengthened RC beams, and the result is validated with experimental results. The obtained results are meaningful for understanding the effects of prestressed HFRP strengthening on flexural performance of reinforced concrete beams

2. Material properties and constitutive models for HFRP-strengthened RC beams

2.1. Elasto-plastic damage constitution for concrete

Concrete is a multiphase material which consists of aggregate and hardened cement. Due to the inhomogeneity and existing of dispersed micro pores and cracks, it exhibits complicated mechanical behaviors. Concrete shows entirely different mechanical behavior and damage pattern under tension and compression. The tensile strength is much smaller than compressive strength. Concrete shows a strong brittleness under tension, while exhibiting significant plasticity under compression. Besides, it is usually hard to find a definite yield point in its compressive loading process. The yield strength of concrete is roughly estimated via engineering experience. Some researchers [32] presume that the plastic strain is produced once the load is applied; therefore the yield stress is zero. While some researchers [33] suggest that the yield stress can be obtained from the stress-strain curve of concrete, where significant nonlinear behavior is observed. Compressive strength of concrete will increase under multi-axial compression for concrete will be compacted under this loading state. On the contrary, tensile strength of concrete under multi-axial tension will decrease.

The nonlinearity of concrete is described with different material models, e.g. models of nonlinear elastic damage, elastoplastic and elastoplastic damage, as schematically illustrated in Fig. 1. Although all these models can simulate the stress-strain curve of the concrete well under monotonic loading before concrete reach its strength, nonlinear elastic damage model (Fig. 1(a)) can't reflect the accumulation of inelastic strain. The elastoplastic model (Fig. 1(b)) fails in reflecting softening behavior and the stiffness degradation in the process of unloading and reloading. The elasto-plastic damage model (Fig. 1(c)) reflects both the accumulation of plastic strain and the reduction of the elastic modulus. A modified elastoplastic damage constitutive model is proposed for concrete in this paper.

As concrete is a compressible porous material, the yield of concrete is postulated contributed by both effective stress and hydrostatic stress. The yield surface is a conical surface with axis of three principal normal stress $\sigma_1 = \sigma_2 = \sigma_3$. The yield criterion used here takes Drucker-Prager (D-P) [34] form:

$$f = \alpha I_1 + \sqrt{J_2} = f_y \tag{1}$$