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Nonlinear 3D finite element modeling of RC beams strengthened with prestressed NSM-CFRP strips

Hamid Y. Omran, Raafat El-Hacha *

Dept. of Civil Eng., Univ. of Calgary, 2500 Univ. Drive N.W., Calgary, Canada T2N 1N4

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ABSTRACT

This paper demonstrates a comprehensive 3D nonlinear Finite Element (FE) analysis of Reinforced Concrete (RC) beams strengthened with prestressed Near-Surface Mounted (NSM) Carbon Fiber Reinforced Polymer (CFRP) strips. Debonding effect at the epoxy-concrete interface was considered in the model by identification of fracture energies of the interfaces and appropriate bilinear shear stress-slip and tension stress-gap models. Prestressing was applied to the CFRP strips by adopting the equivalent temperature method. A constitutive confined concrete model for flexural member was generated from unconfined concrete curve and assigned to the concrete materials. The results from the FE model were validated with experimental data available in the literature. Comparison between FE and test results confirms excellent accuracy of the proposed model. An optimum prestressing level in the NSM-CFRP strips was determined that enhances the beam performance under service and ultimate loads by maintaining the amount of energy absorption in the strengthened beam equal to the un-strengthened control beam.

1. Introduction

Upgrading Reinforced Concrete (RC) members using Fiber Reinforced Polymer (FRP) reinforcements has become one of the most commonly used strengthening methods in recent years. FRP strengthening methods are classified in two general techniques: Externally Bonded (EB) and Near-Surface Mounted (NSM). Currently, prestressing is employed the with the NSM-FRP strengthening technique to enhance the flexural performance of strengthened beam [1–3].

Numerical and analytical investigations of FRP strengthened concrete members, with more focus on the EB technique, have been extensively pursued parallel to the experimental work and practical applications. Many researchers simulated the behavior of EB strengthened RC flexural members using 2D/3D FE models considering perfect bond between interfaces (concrete–epoxy and epoxy-FRP) due to the fact that debonding failure was not observed in relevant tests [4–11]. However, a few researchers considered the debonding effects in 2D FE modeling of EB strengthened RC beam [12–15]. On the other hand, FE modeling of NSM-FRP strengthened RC beams is rarely carried out [16–18]. Soliman et al. [18] employed experimental shear stress-slip curve to consider the local debonding in the FE model of non-prestressed NSM-FRP strengthening technique. In the NSM-FRP strengthened RC beam, the debonding occurs at the concrete–epoxy interface which is the weakest interface and the main reason for shortage of research in this field is the identification of appropriate bond behavior that can be reasonably applicable to the NSM technique. Some researchers have investigated the bond-strength behavior in EB technique, the most well-known ones are the proposed models by Chen and Teng [19] and Lu et al. [20]; however, these models are derived based on the geometry of the EB plate and are not accurate for NSM technique. Seracino et al. [21] derived an equation to calculate the debonding resistance of NSM and EB plate-to-concrete joints based on the geometry of the interface debonding failure plane. Although FE modeling of prestressed EB-FRP strengthened beams has rarely been performed even with considering complete bond [22], FE modeling of prestressed NSM-FRP strengthened RC beams has never been investigated taking into account the debonding effects.

Three main objectives are outlined for this paper:

(1) To develop a 3D nonlinear FE model to simulate the exact behavior of RC beams strengthened with prestressed-NSM-CFRP strips. The FE model was verified with experimental test results available in the literature [23]. The FE model accounts for the debonding behavior at the concrete–epoxy interface considering a bilinear shear stress-slip model and a bilinear normal tension stress-gap model derived from

* Corresponding author. Tel.: +1 403 220 4817; fax: +1 403 282 7026.
E-mail address: relhacha@ucalgary.ca (R. El-Hacha).

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fracture energies of the interface. From an extensive literature survey, only one reference was found which considered both models in the FE modeling of EB FRP strengthening technique [15], however, no work has been done with the NSM-FRP strengthening technique by considering both models (bilinear shear stress-slip and bilinear normal tension stress-gap). Also, the prestressing is enforced to the CFRP strips using the equivalent temperature method.

(2) To analyze the flexural behavior of strengthened RC beams using prestressed NSM-CFRP strips in terms of load–deflection curve, bond performance, strain profile, failure mode, and energy absorption by considering different parameters including the effects of prestressing and debonding.

(3) To achieve a practical optimum prestressing level in the NSM-CFRP strips that enhances the beam performance under service and ultimate loads by maintaining the amount of energy absorption in the strengthened beam equal to the un-strengthened beam.

2. Experimental program overview

Five RC beams were tested [23]: one un-strengthened control beam, and four strengthened beam with prestressed NSM-CFRP strips. Each beam was strengthened using two 2 × 16 mm CFRP strips glued together from the width and embedded in one groove pre-cut in the concrete cover on the beam's tension soffit. The beams were, 5000 mm long, simply supported with rectangular cross section of 200 × 400 mm. Various prestressing levels of 0%, 17%, 29.3%, and 51% of the ultimate tensile strain of the CFRP strips were enforced to the NSM-CFRP strips (corresponding to prestrain of 0, 0.0034, 0.00587, and 0.0102 equivalent to a prestressing force of 0 kN, 28.4 kN, 49.03 kN, and 85.2 kN, respectively). The CFRP strips were prestressed using an innovative anchorage system that consisted of two steel anchors bonded to the ends of the CFRP strips using epoxy and movable brackets temporary mounted on the beam. More details on the system can be found in Refs. [2,23]. The beams were tested under monotonic static loading in four-point bending configuration [23].

Fig. 1 depicts the details of the strengthened beams. Fig. 2 represents the stress–strain curve of the internal steel reinforcements determined from the uni-axial tension tests [23]. The concrete material possesses a Young's modulus of 27.84 GPa, a maximum compressive strength of 40 MPa, and a strain at ultimate strength of 0.002233, which are the average values obtained from the compression tests of concrete cylinders [23]. Modeling of the concrete stress–strain behavior is described in

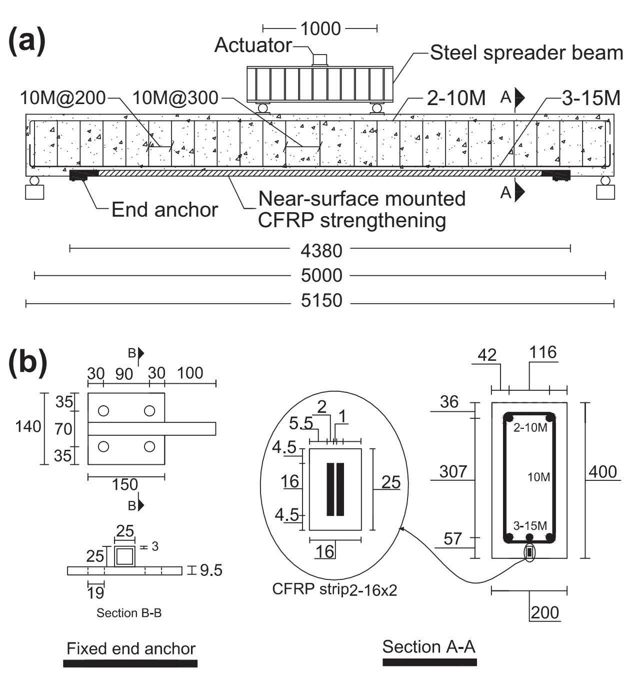

Fig. 1. Geometry of the tested beams: (a) elevation and (b) cross-section, grooves, and end anchor.

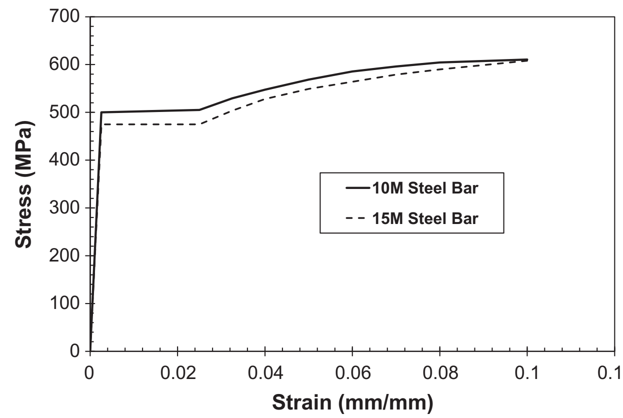

Fig. 2. Stress–strain curves of steel bars.

Section 3.4.1. The employed CFRP strip was type Aslan 500 produced by Hughes Brothers with a tensile strength of 2610 MPa, an ultimate strain of 0.02, and a Young's modulus of 130.5 GPa determined from the tension test [23] with a linear-elastic behavior up to failure. Two types of epoxy adhesives were used: Type A (Sikadure® 330) with a Young's modulus of 4.5 GPa and an ultimate tensile strength of 30 MPa [24] used in the end groove regions (around and inside the end anchors), and epoxy Type B (Sikadure® 30) with a Young's modulus of 4.5 GPa and ultimate tensile strength of 24.8 MPa [25] used to fill in the intermediate groove regions between the end anchors.

3. FE analysis

3.1. Finite element model

The developed FE models are 3D and all materials including concrete, CFRP strips, longitudinal steel reinforcements, stirrups, epoxy adhesive, bolts, and end anchor were simulated using appropriate elements available in the ANSYS program library [26]. To reduce the computer computational time, modeling time, and volume of the results' file, only one quarter of the beam was modeled due to the symmetry in geometry and loading conditions, as shown in Fig. 3. Out of two mesh generation techniques: solid modeling and direct generation, the latter was employed to generate the FE model due to intricacy of the NSM strengthened beams. The direct generation technique has the advantage of complete control over the geometry of every node and every element; even if it is too time consuming for generating large-scale model and the modeler needs to focus more on every detail of the mesh.

3.2. Debonding model

To implement debonding aspects in the FE model, the concrete–epoxy interface, which is the weakest layer, is modeled using contact pairs and Cohesive Zone Material (CZM) model. In most studies, debonding was analyzed based on shear stress-slip (bond-slip) of the interfaces [12–14,18]. In this study a normal stress-gap model is employed in addition to the shear stress-slip model enabling mixed-mode debonding. It should be noted, the rational of considering both models provides an opportunity to accurately analyze the debonding behavior; considering only the shear stress-slip model leads to a mode of separation of the interface surfaces in which relative tangential displacement (slip) dominates the separation normal to the interface (gap); on the other hand, considering just the tension stress-gap model leads to a mode of failure in which the separation normal to the interface dominates the slip tangent to the interface. Therefore, defining the debonding based on only one of these two models means ignoring the effect of the other and generating a difference with reality where both models contribute to debonding. The bilinear shear