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Finite element analysis of RC beams strengthened in flexure with CFRP rod panels

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HIGHLIGHTS

- CFRP rod panels have recently been developed for retrofit of concrete structures.
- Finite element (FE) models were developed to study RC beams bonded to CFRP rod panels.
- Two failure modes were simulated: intermediate crack-induced debonding, concrete cover separation.
- The FE models reported on vital data such as the tensile stress profile in the rods.
- Large shear and peeling stresses exist at or near the panels ends. Anchoring the panel's ends can reduce those stresses.

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ABSTRACT

The carbon fiber reinforced polymer (CFRP) rod panel technique has recently been introduced as an efficient and economical retrofit option for concrete structures. In a previous study, an experimental testing was carried out on RC beams strengthened with several rod panel configurations (continuous, overlapped, and overlapped with fabric end-anchorage). The current study presents comprehensive FE models of the tested beams, developed to provide an in-depth examination of the rod panel and its interaction with the concrete substrate. The FE models considered different material models and presented methodologies for simulating the failure modes experienced in the tests [intermediate crack-induced debonding (ICID) and concrete cover separation (CCS)]. Various comparisons with the experiments, such as ultimate load, load mid-span deflection history, failure mode, demonstrated the validity the FE models. This study reported on vital data, such as tensile stress distribution in the rod panel, maximum interfacial shear and normal stresses at the panel-concrete interface, and location of maximum stresses. It was found that high shear stresses exist at the end of the continuous and overlapped rod panels, and high normal stresses at the edge of the rod finger joint. Wrapping the panel's ends with fabrics resulted in reduction of end shear stresses and contributed to the prevention of CCS failure and the increase in the ultimate load. For field applications, the study recommends using the fabric wraps at the panel ends to prevent premature failures.

1. Introduction

During the last few decades, advanced composites in the form of fiber reinforced polymer (FRP) have emerged as one of the promising new construction materials. FRP composites offer many advantages such as high strength, lightweight, resistance to corrosion, good fatigue performance, and ease of handling and installation [1–3]. FRP could be used as an internal reinforcement for new construction of reinforced and prestressed concrete beams, girders, slabs, walls, and foundations [4–7]; as an additional reinforcement to strengthen or repair an existing concrete, steel, or masonry structure [8–12], or as an external confining reinforcement for reinforced concrete axial members [13–15].

One of the recently established innovative systems involving FRP composite is Carbon-FRP (CFRP) rod panels (CRPs) utilized for retrofit applications of concrete structures. CRPs are made from small diameter CFRP rods that are placed side by side at discrete spacing to form a panel [12,16–19]. When applying CRPs onto the substrate of members with large-spans or with limited accessibility, several short-length panels are used instead of continuous (full-length) panels, to reduce equipment and labor costs. The short-length panels are connected to each other via an overlapping or finger jointing mechanism.

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Few studies were undertaken to assess the bond properties and flexural effectiveness of CFRP rod panels in strengthening concrete members. For example, Jawdhari et al. [18] 6 carried out a bond study on small-scale CRPs adhered to concrete blocks to characterize the development length and other bond properties of two widely used panels, CRP 070 [made from 2 mm (0.078 in) rods at 6.35 mm (0.25 in) spacing], and CRP 195 [made from 4 mm (0.160 in) rods at 9.50 mm (0.375 in) spacing]. The development length was found to be 100 mm (4.00 in) and 119 mm (4.75 in) for CRP 070 and CRP 195, respectively. The bond strength per unit width of CRP was 563 kN/m (38.5 kip/ft) for CRP 070 and 712 kN/m (48.8 kip/ft) for CRP 195.

The response of full-scale RC beams strengthened in flexure with CRPs was experimentally investigated by Jawdhari [12]. The testing program included a control beam, and beams strengthened with CRP 070 or CRP 195 panels that were either continuous [one full-length panel, Fig. 1(b.1)], overlapped [two half-length panels in 150 mm finger joint at mid-span, Fig. 1(b.2)], or overlapped and anchored with CFRP fabric wraps at panels' ends. The results showed that the beams bonded with either full-length or overlapped CRPs failed at comparable loads by concrete cover separation; while no local debonding or any other signs of distress were seen at the finger joint region between the panels. Compared to the control specimen, the maximum load increase for strengthened beams ranged between 104 and 112% for continuous CRPs, 95–106% for overlapped CRPs, and 143–195% for overlapped CRPs with fabric wraps. In order to compare the performance of the CRP system with externally bonded (EB) FRP laminates, two additional RC beam specimens were tested. One specimen was strengthened with a continuous CFRP laminate and the other with lap-spliced CFRP laminate [12]. Detailed discussion on the capacity and failure modes observed during the experiments for the CRP and EB CFRP laminates is presented by Jawdhari [12].

This study aims at developing comprehensive three-dimensional (3D) FE models capable of predicting the behavior of RC beams strengthened in flexure with CFRP rod panels. The FE models are developed for the specimens in Jawdhari study [12]. The CRP strengthened beams in the experiments failed in one of two failure modes: concrete cover separation (CCS) and intermediate crack-induced debonding (ICID). The study also aims at numerically simulating these failure modes. Due to difficulty of instrumenting the small diameter rods with strain gages, the experimental investigation was limited in its capability of presenting some test data, such as the tensile stress distribution in the rods, and interfacial stresses at the CRP-concrete interface. Within the validated FE models, such data can be easily extracted and presented, hence providing a valuable platform to thoroughly examine the behavior of CRP bonded RC members.

2. Summary of experimental program

The FE models in this study are developed for the experimental tests carried out by Jawdhari [12] to investigate the effectiveness of CRPs for flexural retrofit of reinforced concrete (RC) beams. The experimental program consisted of seven specimens (control beam, and six strengthened beams). Strengthened specimens consisted of beams bonded at the soffit with one of the following reinforcements: continuous CRP 070, overlapped CRP 070 [two half-length panels with 150 mm finger joint at mid-span], overlapped CRP 070 anchored at ends with fabric wraps, continuous CRP 195, overlapped CRP 195 [two half-length panels with 150 mm finger joint at mid-span], and overlapped CRP 195 anchored at ends with fabric wraps (Fig. 1). In the overlapped panels, one of the panels was furnished with an extra rod to provide symmetric behavior on both sides of the finger joint. The total FRP areas of CRP 070 and CRP 195 panels were 64 mm^2 (100×10^{-3} in^2) and 173 mm^2 (268×10^{-3} in^2), respectively.

The beams were 3042 mm (120 in) long and had a square cross-section of 152×152 mm (6×6 in). They were tested under statically increasing four-point bending loads. Flexural reinforcement consisted of two 10 mm-diameter steel rebars on the tension side and two 10 mm-diameter rebars on the compression side. Shear reinforcement consisted of 3 mm-diameter steel stirrups located within the shear span. Away from the supports, the stirrups were spaced at 152 mm (6 in) in the shear span, while for locations near the supports and loading points, the stirrup spacing was reduced to 76 mm (3 in).

For the specimens with CFRP fabric wraps at panels' ends, the wrap was composed of two plies with total thickness of 1 mm (0.04 in) and width of 300 mm (12 in). The wrap has a length of 225 (9 in) toward the beam's center, and 75 mm (3 in) outside the panels' end as shown in Fig. 1(b.3). The tested specimens, their dimensions, loading configuration, lay-out of internal reinforcement, and details of CRP reinforcement, are presented in Fig. 1.

Instrumentation of the specimens consisted of two LVDTs to measure the mid-span deflection, one LVDT to check for any potential movement of the loading frame, and several electric strain gages on the surface of the adhesive embedding the rod panels, to measure the strain profile along the length of the rod panel. Table 1 lists the material properties for concrete, steel reinforcement, CFRP rods and fabric, and adhesive. The properties are obtained from experiments, or design codes, or from the literature. Section 3.4 (material properties) provides details and references to the materials used in the modeling.

3. Finite element modeling

3.1. Element selection

The FE models were generated in the general-purpose software ANSYS [20]. Due to symmetry of the tested beams in the transverse direction, only half of the beam was modeled (Fig. 2). A quarter-beam model was not applicable for all specimens due to the presence of the extra rod in the overlapped panels. Concrete volume was modeled using the 8-node Solid 65 element. The element has three degrees of freedom at each node, translations in the global *x*, *y*, and *z* directions, and it can represent concrete's inherent nonlinear properties such as cracking in three orthogonal directions, crushing, creep, and plastic deformations [20].

The 8-node Solid 185 element was used to represent the embedding adhesive layer, fabric wraps, and steel plates at the loading points and supports. The element's nodes are defined by three translational degrees of freedom similar to those of Solid 65, and is capable of considering nonlinear properties such as multi-linear material behavior, plasticity, stress stiffening, and large deformations [20].

The reinforcing element (REINF 264), having two nodes along the element's length and three translational degrees of freedom per node, was used to model the internal steel reinforcement (flexural rebars and shear stirrups) and the CFRP rods. The reinforcing element displays only axial properties (tension-compression stiffness), with the ability of simulating the plastic response of various materials. REINF 264 element is assigned to a base (solid) element, such as (Solid 65, and solid185), and it interacts with the base element via the global nodes of the base element. The inputs for REINF264 element are: orientation, location relative to the base element, cross-sectional area, and material model. A perfect bond assumption, at the interface between concrete base elements (Solid 65) and steel reinforcing elements, and also at the interface between adhesive base elements (Solid 185) and CFRP rod