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Modeling and Analysis of Optimized Rectangular RC Columns Confined with CFRP Composites

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ABSTRACT

The structural behavior of rectangular reinforced concrete (RC) columns confined with different configurations of carbon fiber-reinforcement polymer (CFRP) sheets is investigated by using nonlinear finite element analysis (NLFEA). SOLID65, LINK8, SOLID45 and SOLID46 elements represented the concrete, steel bars, steel plates and CFRP sheets, respectively. Based on each simulated component's actual characteristics, the nonlinear material properties are defined for each type of element. The NLFEA results clearly confirmed that the use of CFRP composite strengthening system for RC columns improves the ductility and catastrophic axial strength capacity. The enhancement in the ductility and catastrophic axial strength increased with the increasing of the number of CFRP composite layers. The CFRP composite strengthening system of rectangular RC columns can be categorized as efficient and successful only if significant increase in the catastrophic axial strength capacity is achieved. As confirmed by the results of this study, NLFEA can efficiently simulate the structural behavior of rectangular RC columns confined with CFRP sheets. It is recommended that the NLFEA model be used in additional research studies to develop design guidelines and rules for RC structural elements strengthened with CFRP composites.

KEYWORDS: NLFEA, CFRP, Simulation, RC columns.

INTRODUCTION

Strengthening, repairing and seismic retrofitting of reinforced concrete (RC) structures with Carbon Fiber-Reinforced Polymer (CFRP) composites have become enormously promising due to their light weight, high strength and ease of application. There are many engineering strengthening applications in which CFRP was externally bonded onto the surface of RC elements to improve their ductility and strength (Richart et al., 1928; Saadatmanesh et al., 1994; Issa et al., 1994; Picher et al., 1996). In order to better understand the mechanical mechanism, the behavior of confined RC columns with CFRP sheets needs to be further investigated. Modeling of the complex nonlinear behavior of RC rectangular columns is a challenge in the FEA of structural concrete elements. Therefore, few researchers attempted to simulate the behavior of RC externally strengthened with FRP composites using FEA (Kachlakev et al., 2001; Tedesco et al., 1999; Feng et al., 2002; Al-Rousan, 2018; Al-Rousan et al., 2015; Al-Rousan, 2015; Al-Rousan et al., 2014; Al-Rousan and Haddad, 2013; Alrousan et al., 2012; Alrousan and Issa, 2011; Mohsen et al., 2009). In this study, the ANSYS finite element program (ANSYS, 2016) was used to simulate the behavior and the effectiveness of various configurations of CFRP confinement of rectangular RC columns. Actual geometry and steel reinforcing details of experimentally tested rectangular

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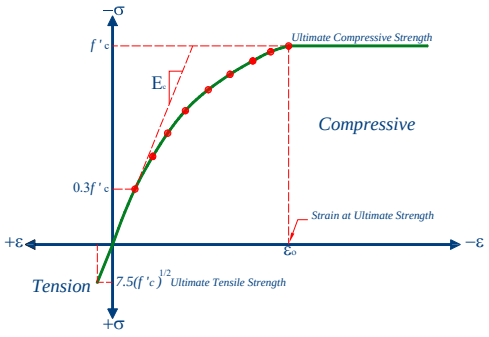
column specimens as well as the used strengthening configurations and the number of the externally bonded CFRP layers were considered in the NLFEA. Load-deflection response, load-strain response and failure mode were obtained for each specimen by NLFEA and compared to the corresponding experimental test results.

FINITE ELEMENT ANALYSIS

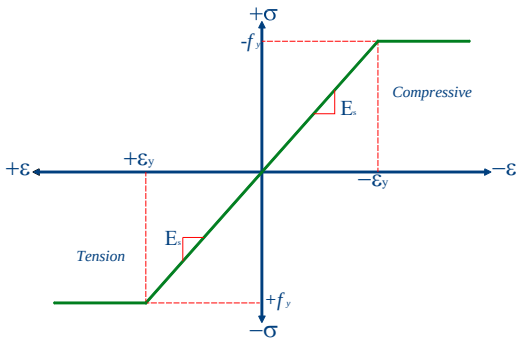
Element SOLID65 was used to model the concrete material without steel reinforcing bars. The element is capable of cracking in three orthogonal directions, crushing, creeping and plastically deforming (ANSYS, 2016). Ultimate uniaxial tensile strength of 4.5 MPa compressive strength of 55 MPa and initial Young's modulus (E_c) of 35063 MPa are needed to define a failure surface for concrete. William and Warnke (1975) defined the concrete criterion for failure of concrete due to a multiaxial stress state as shown in Figure 1(a). Also, Poisson's ratio of 0.2 and shear transfer coefficient (β_t) of 0.2 (Hemmaty, 1998) were used in this study.

A 3-D spar element (LINK8) was used to model the steel bars with a uniaxial tension-compression behavior capable of plastic deformation (ANSYS, 2016). An elastic-perfectly plastic material was assumed for steel, which is identical in tension and compression as shown in Fig. 1(b). The Poisson's ratio and steel yield stress were 0.3 and 413 MPa, respectively. A SOLID45 (eight-node solid element) was used for the supports and load application steel plates (ANSYS, 2016) to provide an even stress distribution over the supports and loading area. A linear elastic material with an elastic modulus equal to 200 GPa and Poisson's ratio of 0.3 was assumed for steel plates. Finally, layered element (SOLID46) was used to model the CFRP composite sheet which has orthotropic material properties in each layer (ANSYS, 2016) with a thickness of 0.165 mm, elastic modulus of 228 GPa, tensile strength of 4275 MPa and ultimate tensile strain of 0.017 mm/mm in the fiber direction.

Firstly, a quarter of the column was simulated to study the behavior by taking benefit of symmetry of the column geometry and loading with proper boundary conditions which reduce the computer disk space requirements and computing time. At both column ends, one end was modeled as pin support, while translation and rotation in the loading direction were only allowed at the other column end. In order to determine the appropriate mesh density (Figure 2), a convergence study was carried out.



(a) Concrete

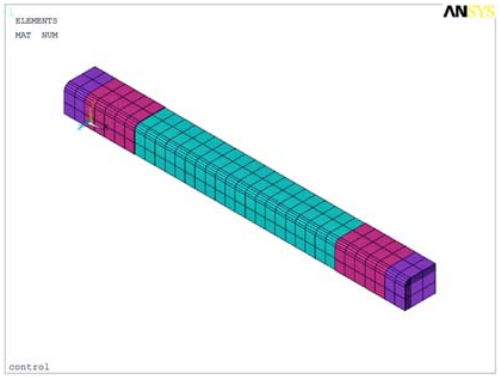


(b) Steel reinforcement

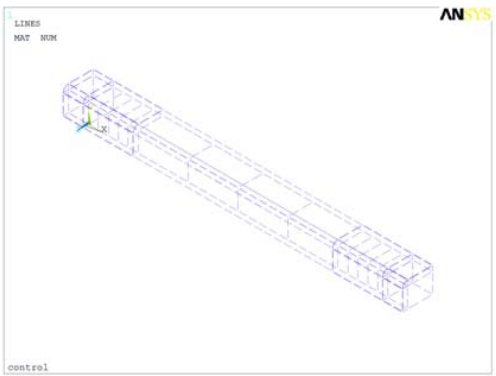
Figure (1): Stress-strain curve

Perfect bonding between concrete and steel reinforcement as well as between CFRP composite and concrete was assumed. Rectangular RC columns, with a length of 750 mm and a cross-section of 125×150 mm,

were simulated in order to model the response of confined rectangular RC columns with various configurations of CFRP sheets under axial loading. All the columns were reinforced longitudinally with 4 ϕ10 steel bars and laterally with steel ties of 5 mm diameter at a spacing of 125 mm except at the ends (25-mm spacing) and this is due to stress concentration at the ends. Also, these critical ends were additionally strengthened with two layers of CFRP composite sheets for a distance of 125 mm. The cross-section, reinforcement details and the CFRP composite confinement configurations of the columns are shown in Figure 3. The applied vertical load was divided up to failure into a series of small load increments of 0.45 kN. Convergence at the end of each load increment was checked by using Newton-Raphson equilibrium iterations. Failure of each column model was identified when the solution for a vertical load increment of 0.0045 kN was not converging.



(a) Quarter of the column



(b) Steel reinforcement

Figure (2): Typical finite element meshing of a quarter of the column

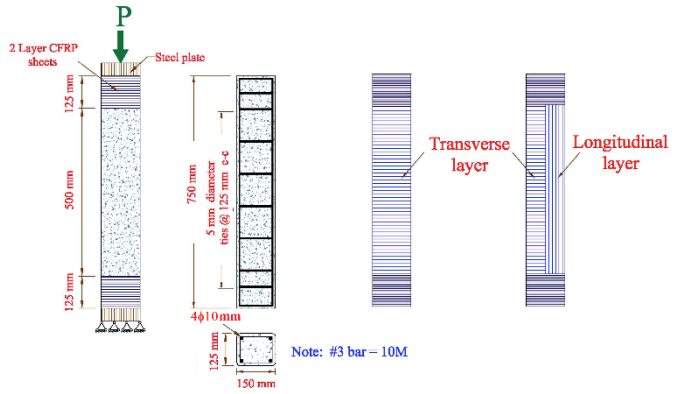


Figure (3): Cross-section and reinforcement details

RESULTS AND DISCUSSION

Load-Displacement Response

The characteristics of the CFRP-confined columns were evaluated based on the catastrophic load-displacement behavior. Figure 4 shows the NLFEA axial load *versus* axial displacement curves of the simulated columns. The catastrophic loads were 1072, 1588, 1659, 1757, 1817, 1912, 1968 and 2046 kN, as shown in Table 1. The corresponding increase in the catastrophic axial load with respect to the control specimens was about 48%, 55%, 64%, 70%, 78%, 84% and 90%, respectively. The catastrophic axial load–displacement curves shown in Figure 4 reveal that there is a significant increase in the catastrophic axial load as well as in the ultimate axial displacement when confining the columns with CFRP sheets. Figure 4 also shows that the increase in the ultimate loads and displacements is directly related to the increase in the number of CFRP sheet layers.

Load-Strain Response

The axial and circumferential strains at the critical region of the columns were plotted *versus* the axial load, as shown in Figure 5. The axial load-axial strain response followed a similar trend as the axial load-axial displacement for each specimen type. At failure, the circumferential strain readings of the confined columns were greater than 0.017 mm/mm, which is the maximum strain capacity of the carbon fiber. The circumferential strain results are coinciding with the observed failure mode of the confined columns; the failures did not occur before the fracturing of the CFRP sheets. This reveals that the effectiveness of the CFRP confinement was good. Based on the NLFEA results shown in Figures 4 and 5, it can be observed that confinement of rectangular RC columns with CFRP significantly enhances its strength and ductility performance under axial loading. Typical distributions of CFRP sheet and concrete strains at control and confinement columns are shown in Figures 6-13.

Table 1. ANSYS results at failure

Confinement configuration	Catastrophic load, kN	Percentage of increase in ultimate load with respect to control specimen (%)
Control (unconfined)	1072	---
1 layer in the transverse direction (1T)	1588	48.1
1 layer in the transverse direction and 1 layer in the longitudinal direction (1T1L(OUT))	1659	54.8
2 layers in the transverse direction (2T)	1757	63.9
1 layer in the longitudinal direction and 1 layer in the transverse direction (1T1L(in))	1817	69.5
3 layers in the transverse direction (3T)	1912	78.4
1 layer in the longitudinal direction and 2 layers in the transverse direction (2T1L(in))	1968	83.6
4 layers in the transverse direction (4T)	2046	90.6

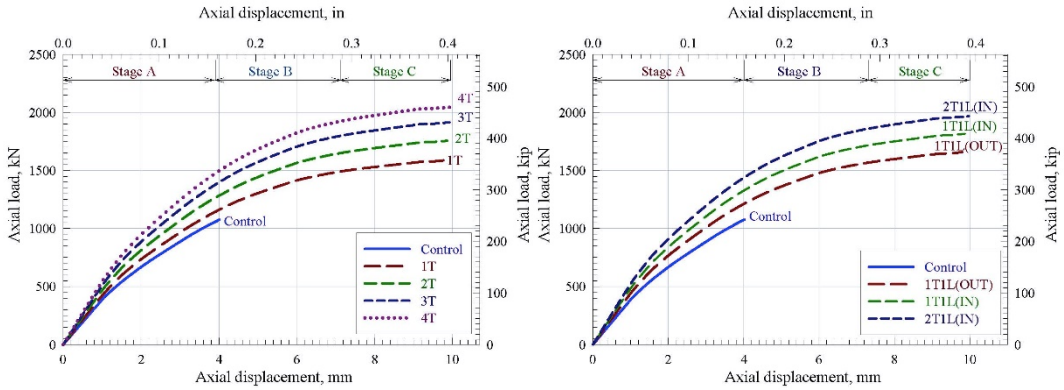


Figure (4): Axial loads *versus* axial displacements

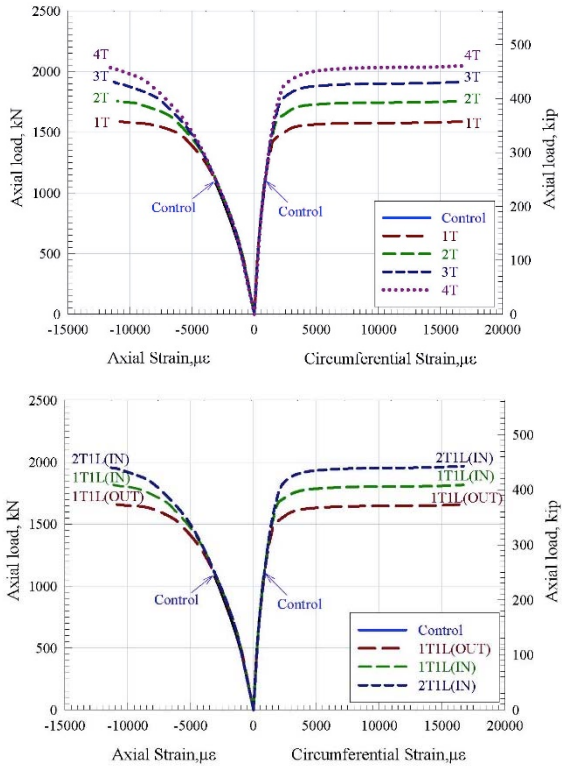


Figure (5): Axial load *versus* axial and circumferential strain curves

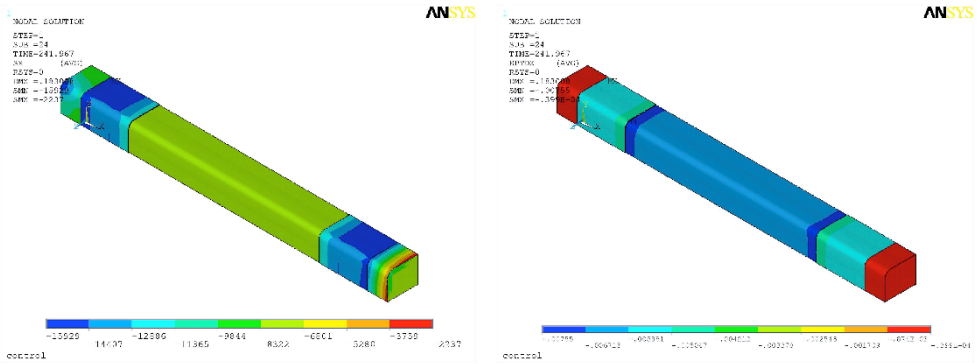


Figure (6): Strain and stress contours of control column

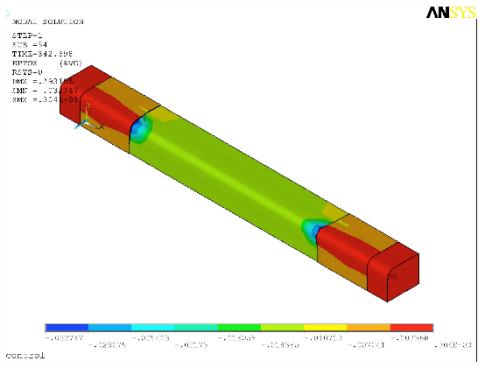


Figure (7): Strain contours with one layer in the transverse direction

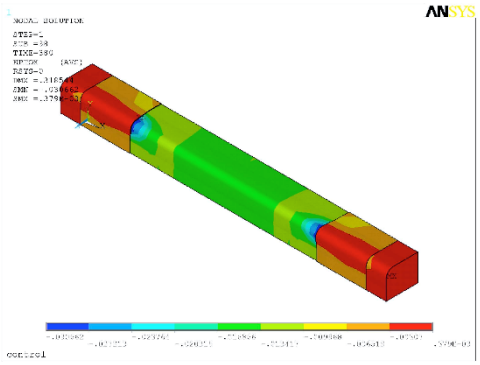


Figure (8): Strain contours with 2 layers in the transverse direction

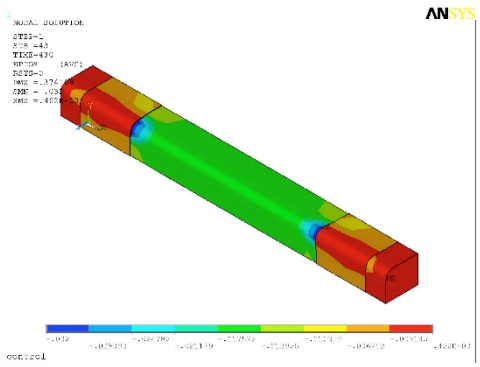


Figure (9): Strain contours with 3 layers in the transverse direction

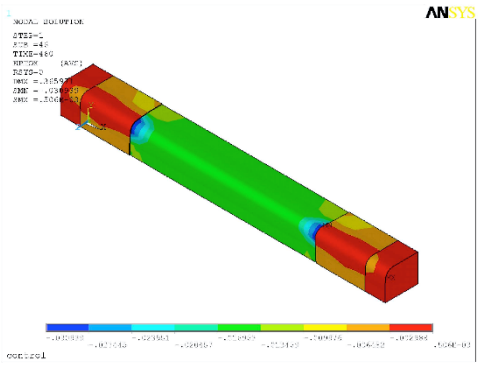


Figure (10): Strain contours with 4 layers in the transverse direction

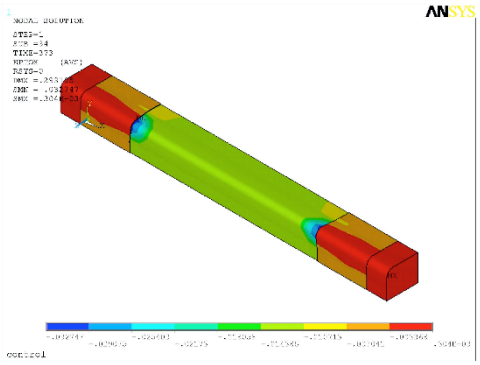


Figure (11): Strain contours of column with one layer in the longitudinal (out) and one layer in the transverse direction

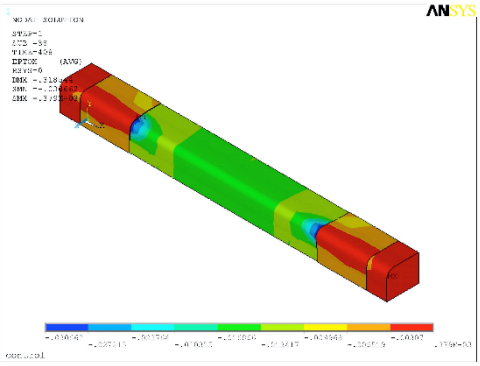


Figure (12): Strain contours of column with one layer in the longitudinal direction (in) and one layer in the transverse direction

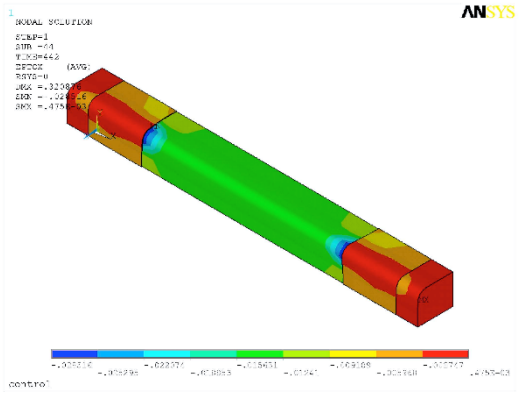


Figure (13): Strain contours of column with one layer in the longitudinal direction (in) and two layers in the transverse direction

CONCLUSIONS

Externally bonded CFRP sheets are very effective in enhancing the axial strength and deformation capacity of concrete columns. Increasing the number of CFRP sheet layers leads to a significant increase in the catastrophic axial strength and a slight increase in the catastrophic displacement. Also, two CFRP sheet layers represent the optimum number of CFRP layers based on the load-strain behavior. Catastrophic axial loads and strains at failure were recorded for the confined RC columns wrapped with CFRP in comparison with the unconfined ones. This finite element model can be used in additional studies to develop design rules for strengthening RC columns using CFRP composites.

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