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Full Length Research Paper

Numerical investigation on exterior reinforced concrete Beam-Column joint strengthened by composite fiber reinforced polymer (CFRP)

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In this paper, the effectiveness of composite fibre reinforced polymer (CFRP) layers for exterior beam-column connections was studied through a finite element model (FEM). ABAQUS environment (Hibbitt et al., 1988) was used for finite element analysis and a model based on a previous experimental test was made. The FEM results were validated by comparing with previous experimental test results. This model was developed to analyse rehabilitation of exterior beam-column connection. Five exterior reinforced concrete beam-column joint specimens, including a control specimen (non-retrofitted) and four retrofitted specimens with altered arrangements of CFRP were developed. From the realistic nonlinear analysis of reinforced concrete (RC) connections with FRP overlays, it was determined that L shape overlays from FRP composites at the beam-column, is an appropriate usage to increase ductility. In addition, U shape overlays under the beam and the use of FRP on both lateral sides of the beam are very good strengthening strategies for strength and ductility enhancement of the RC joints. However, FRP only on the top and bottom of the beam decreases the ductility.

Key words: Finite element (FE), reinforced concrete (RC), composite fiber reinforced polymer (CFRP), beam.

INTRODUCTION

The techniques of using fibre reinforced plastic for reinforcing the beam column joints have benefits including easy installation, protection against corrosion and high strength. Wrapping fibre sheets in two orthogonal directions in the joint area is the easiest way to strengthen the joints. Many fibre reinforced plastics are available on the market for strengthening reinforced concrete members. Carbon fibre reinforced polymer sheets are commonly used for retrofitting the structural elements. The exterior use of FRP expands the general performance of an RC frame structure without the need for an essential change to the original structure. Outside bonded FRP can be used in the repair of structures affected by seismic damage or vulnerable or substandard reinforced structures. FRP provides certain benefits, such as high strength to weight ratio, resistance to corrosion, quick and simple tender (Seible et al., 1999). FRP is expensive, but its use can be enhanced to reduce material wastage. In this paper, the efficiency and effectiveness of carbon fibre reinforced polymers (CFRP) in repairing and upgrading the shear strength and ductility of deficient exterior beam-column joints was studied. The three-dimensional domain model was for the analysis in this study and the processes of previous studies was followed (Ravari et al., 2011; Shariati et al., 2010; Ramli Sulong et al., 2010; Shariati et al., 2011).

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VERIFICATION OF FINITE ELEMENT MODELLING

Because of the problems of CFRP behaviour in composite sections and RC members, providing a suitable non-linear analysis of CFRP retrofitted joints is of interest. In this paper, a model was developed using ABAQUS environment (Hibbitt et al., 1988) and verified (Figure 1) and compared to the experimental results provided (Mahini and Ronagh, 2007). The experimental tests included exterior beam-column connections using a typical eight story RC structure situated in Brisbane, Australia as the example (Figure 2). Experimental results were performed to assess the skill of CFRP sheets in avoiding the plastic hinge development at the face of the column in the exterior RC joints.

Mahini et al. (2010) used a 1:2.2 scale exterior reinforced concrete beam-column joint. Figure 3 shows the test specimen details. The specimen consisted of a 180 mm wide and 230 mm

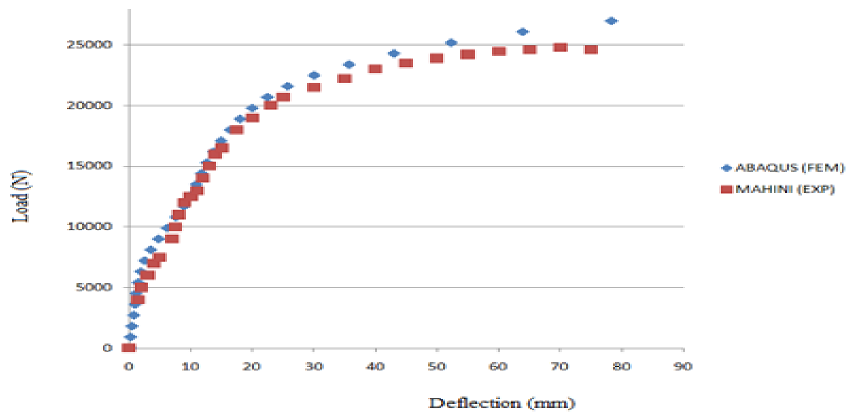

Figure 1. Verification of ABAQUS modelling with Mahini and Ronagh (2007) experimental tests.

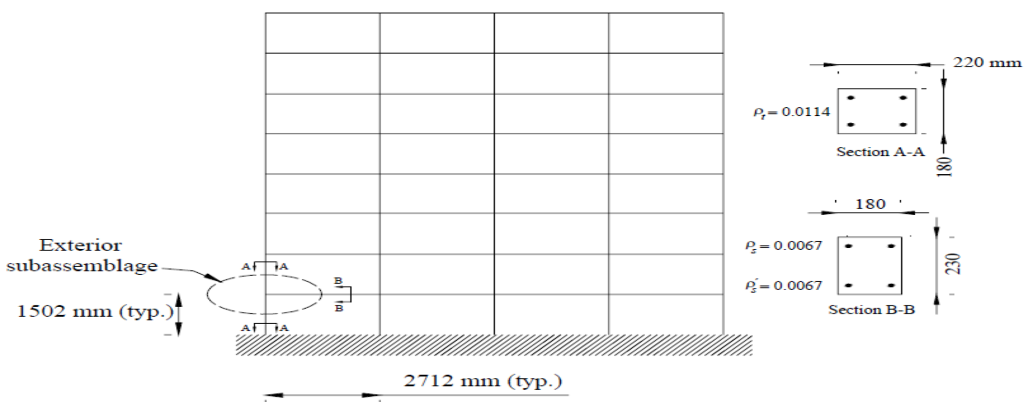

Figure 2. Eight-story RC building located in Brisbane, Australia column.

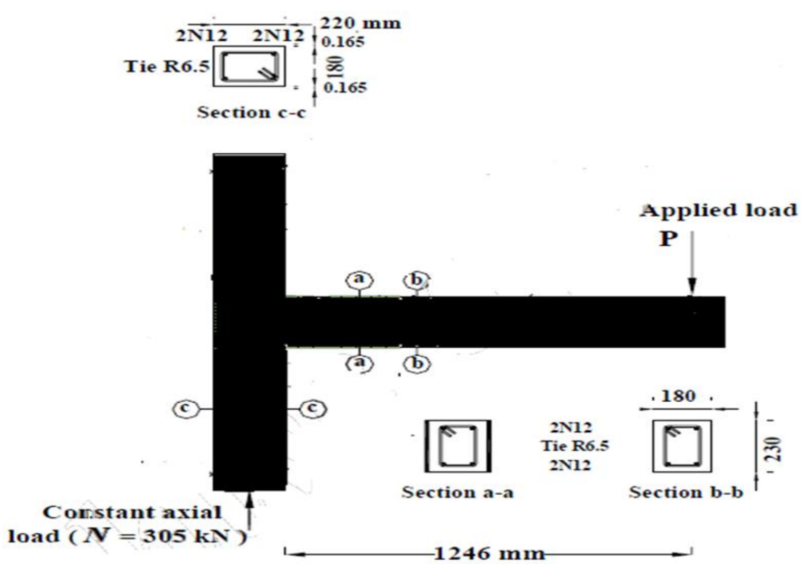

Figure 3. The test specimen details.

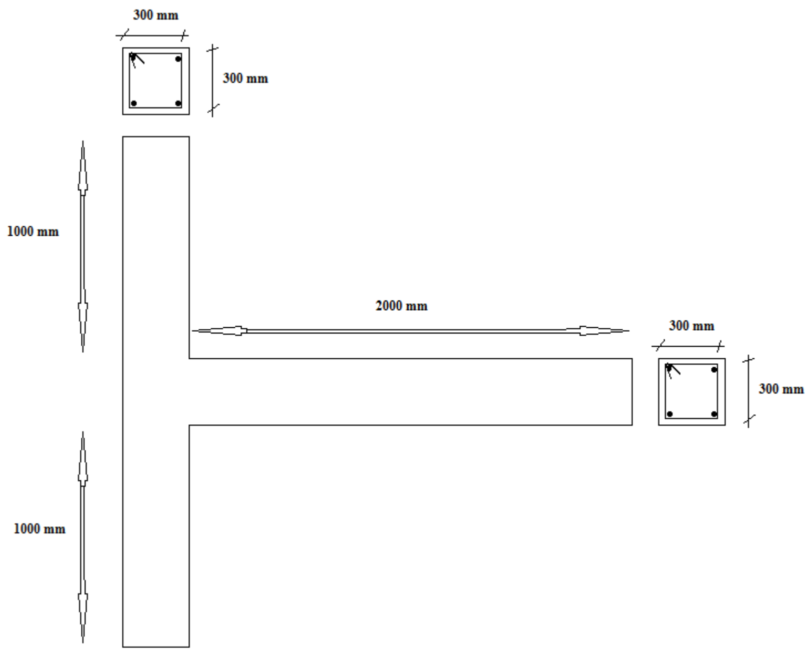

Figure 4. Details of control specimen.

deep beam with 220 × 180 mm column. Four N12 rebars (φ12 mm) were used for vertical reinforcement of the column and longitudinal reinforcement of the beam. R6.5 bars (φ 6.5 mm) were used for stirrups at a spacing of 15 mm in both beam and column. A concrete cover of 30 mm was considered for the beam and nonlinear finite element model, considered the geometric non-linearities and material inelasticity together.

Control specimen

The control joint specimen comprised a connection between a column with a total height of 2.3 m and a beam of 2 m connected to the middle of the column. Both beam and column have a cross section of 300 × 300 mm, the longitudinal reinforcement ratio for the beam (in tension zone) is 0.0056. The transverse reinforcement for both beam and column was φ10 at 100 mm (Figure 4).

Strengthen specimens

Four plain CFRP-retrofitted scaled-down joints of a typical ordinary moment resisting frame (OMRF) were tested under monotonic loads to failure, as shown in Figure 5. The chracteristics of these specimens are described in Table 1.

Material properties

Concrete

Concrete was modelled using a solid element with eight nodes with three translation degrees of freedom at each node. The concrete solid element in the ABAQUS model is called C3D8R. The material behaviour was incorporated in the FE model for both the elastic and manufacturer. The value for ν = 0.3 was used for the isotropic inelastic stages. The concrete had a uniaxial compressive strength considered as 40 MPa and ε_0 = 0.003, νc = 0.2.

The concrete damaged plasticity model (CDP) was used for defining concrete material behaviour in the inelastic range. This model was developed by Lee and Fenves (1998). The main failure mechanisms of concrete in CDP include (1) tensile cracking and (2) compressive crushing of the concrete. The program computes the concrete compressive stress-strain curve based on the input of stress versus inelastic strain.

The concrete behaviour under axial tension is assumed to be linear until the formation of the initial cracking at the peak stress known as failure stress. Post failure stress is defined in the program in terms of stress versus cracking strain. This behaviour allows for the effect of the interaction between the concrete and the reinforcement rebar through introducing tension stiffening to the softening side of the curve.

Rebar reinforcement

An elastic-perfectly plastic material was used for steel with an equal behaviour in tension and compression. The elastic modulus (Es), yield stress (Fy) and density (γ) were presumed to be 209 GPa and 500 MPa, 7800 Kg/m^3, respectively. The steel reinforcement assigned has a Poisson's ratio of 0.3. Full bond contact between the steel reinforcement and the concrete is presumed. The embedded element option was used for connecting the reinforcement element to the concrete element, steel reinforcement was used as the embedded element and concrete was used as the host element.

Carbon fibre reinforcement polymer (CFRP)

The CFRP is designated as a linear elastic orthotropic material, because the composite is unidirectional and the behaviour is essentially orthotropic. The modulus in the fibre direction is a significant factor, because the composite is mainly stressed in the

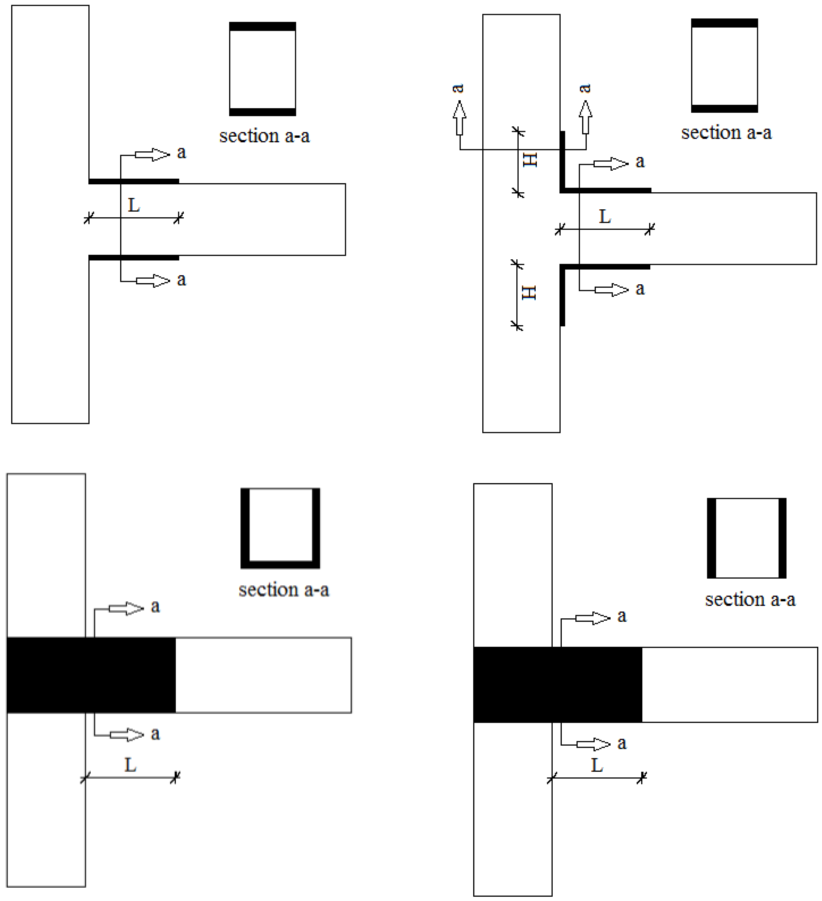

Figure 5. Strengthening design with FRP.

Table 1. Characteristics of strengthen specimens.

Specimen name	Top and bottom of beam length (mm)	I-shape length (mm)	U-shape length (mm)	Both sides length (mm)
SC	-	-	-	-
S1	450	-	-	-
S2	-	450	-	-
S3	-	-	-	750
S4	-	-	450	-

fibre direction. A value of 165 Gpa is assigned for the elastic modulus in the fibre direction where the unidirectional CFRP material is used in the experimental study. This modulus of elasticity was specified by the model. For the orthotropic material model, E11 was set to 138 GPa, E22 = 14.5 GPa and G12 = G13 = 5.86 GPa and G23 were set to 3.52. For CFRP-concrete interface, full bond assumption was made for the interaction between FRP and concrete surfaces.

Boundary conditions

The boundary conditions were set in the model to mimic the experimental test conditions. The bottom of the column was restrained in five (5) degrees of freedom in the Ux, Uy, Uz, Rx and Ry directions. In this scenario, the column was allowed to rotate in the Rz only. The pin-pin axial link at the top of the column in the model was assumed as a roller support that is released at the Uy and Rz. The remaining four boundary conditions Ux, Uz, Rx and Ry at the top of the column are restrained against movement.

Loads

In order to incorporate the gravity and lateral loads in the finite element (FE) model, two steps were defined in the FE simulation. The gravity load was simulated in the first step as a uniform pressure applied at the top of the column. The lateral load was incorporated in the second step of the FE analysis as a monotonic incremental displacement applied tangential to the end surface of

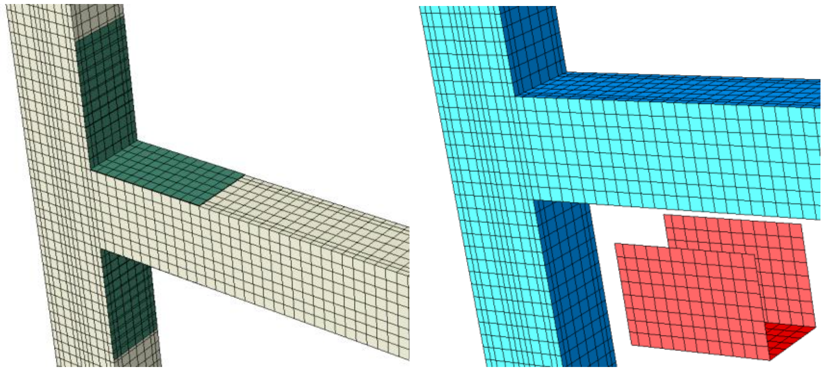

Figure 6. Meshed structure for the beam-column joint.

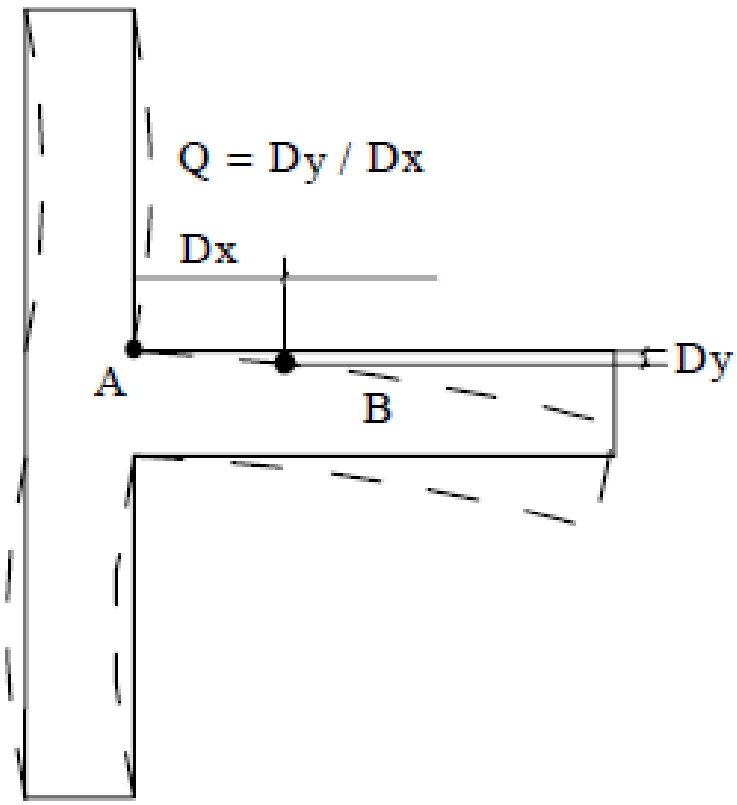

Figure 7. Ductility determination method for connection.

the beam until failure of the specimen.

The finite element mesh

In order to obtain accurate results from the FE model, all the elements in the model were purposely assigned the same mesh size to ensure that two different materials each share the same node. The type of mesh selected in the model was structured. The mesh element for the concrete, rebar and FRP laminate element were 3D solid, 2D truss and shell, respectively. Figure 6 shows the meshed structure for the beam-column joint model.

RESULTS AND DISCUSSION

The rotation (θ) is considered as the ratio of the alteration of vertical displacements of points A and B in Figure 7 to their horizontal distance as calculated in theoretical analysis. It is appropriate to mention that the space between points A and B was chosen to be long enough to comprise the plastic hinge zone in all specimens (Figure 7).

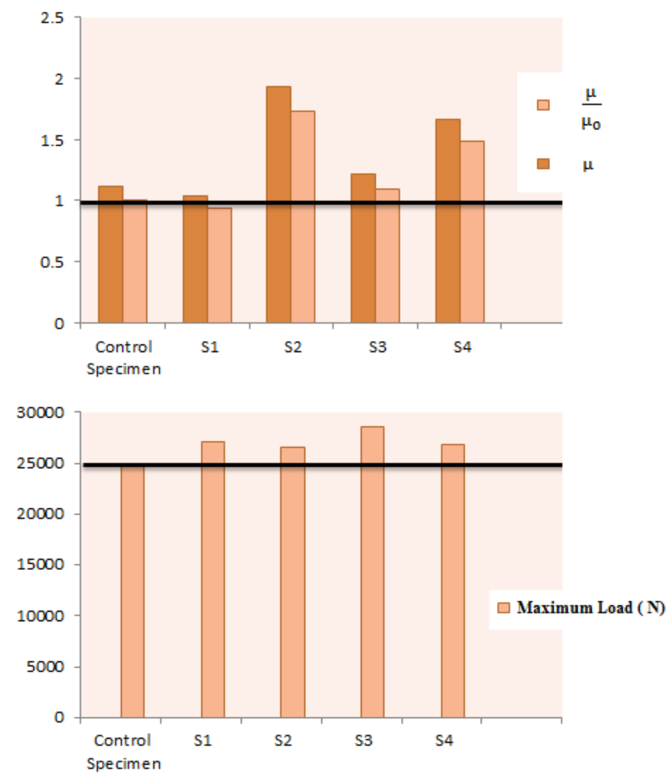

Figure 8. Maximum load, Ductility (μ_0), and relative specimens' ductility to control specimen's ductility $(\frac{\mu_0}{\mu})$.

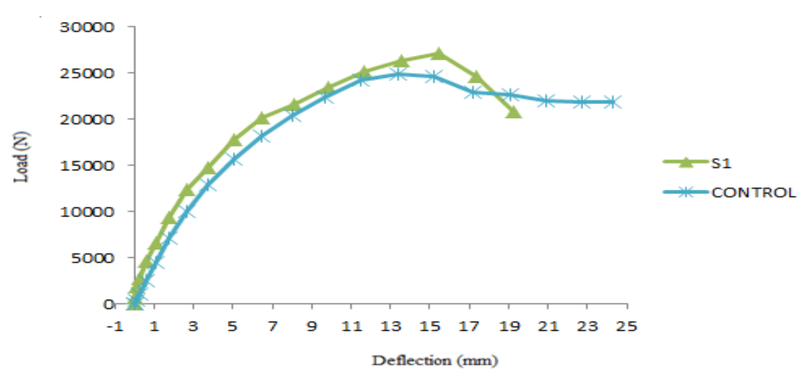

Figure 9. Load-deflection curves for the control specimen and specimen S1.

$$\mu=\frac{\theta_u}{\theta_y} \quad (1)$$

Different results including the ultimate load, stresses in concrete and reinforcements, stresses in FRP laminates and the ductility of each specimen were investigated. Figures 9 to 12 show the load-deflection curves for the control specimen and the strengthened specimens. Certain other results including the flexural capacity of the joint, the ductility factor for all specimens are given in Table 2 and Figure 8.

Conclusions

The effectiveness of composite fibre reinforced polymer (CFRP) layers for exterior beam-column connections was

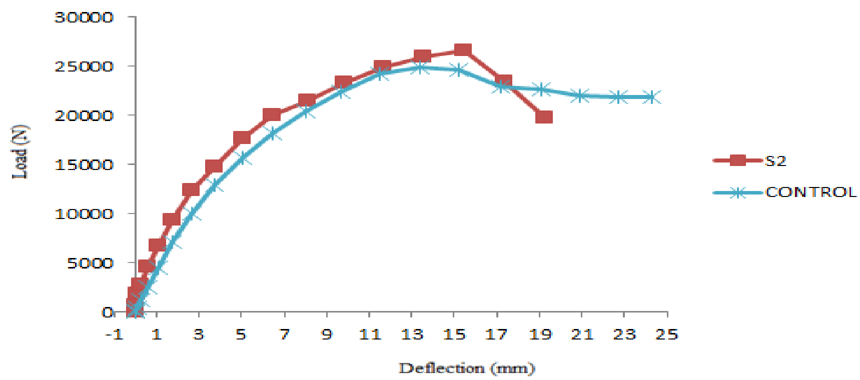

Figure 10. Load-deflection curves for the control specimen and specimen S2.

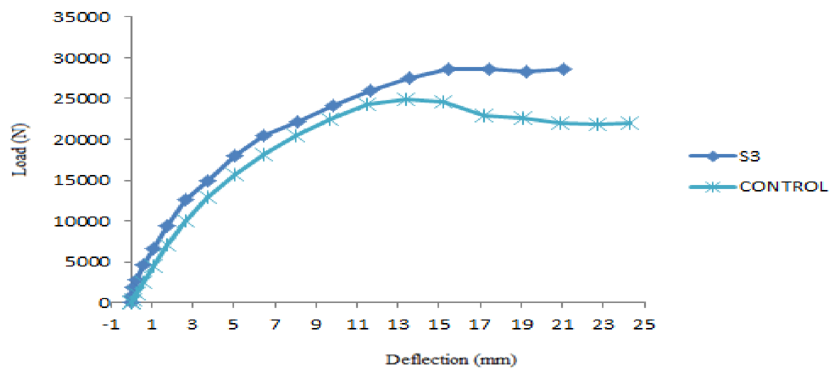

Figure 11. Load-deflection curves for the control specimen and specimen S3.

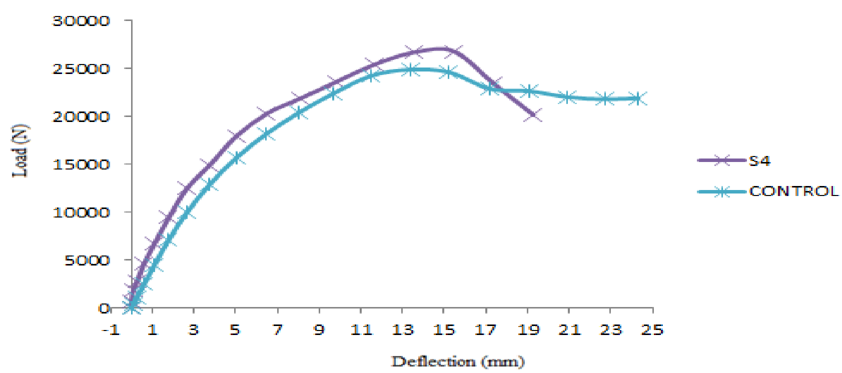

Figure 12. Load-deflection curves for the control specimen and specimen S4.

studied through a finite element model (FEM) based on a previous experimental test. Five exterior reinforced concrete beam-column joint specimens, including a control specimen (non-retrofitted) and four retrofitted specimens with different configurations of CFRP were developed. These specimens analysed to find out an effective way to improve the seismic performance of the joints in terms of the lateral strength and ductility. The different configurations of CFRP considered for the specimens were by attaching to the top, bottom and lateral sides of the beams. The results show that respectable ductility and strength enhancement could be attained by engaging

Table 2. Ductility factor for specimens.

	SC	S1	S2	S3	S4
Ductility (μ_0)	1.118	1.042	1.935	1.222	1.667
Maximum strength	24917	27111	26586	28551	26814

configured CFRP laminates correctly. Also, from the realistic non-linear analysis of RC connections with FRP overlays, it was determined that L shape overlays from FRP composites at the beam-column is an appropriate usage to increase ductility. In addition, U shape overlays under the beam and the use of FRP on both lateral sides of the beam are very good strengthening strategies for strength and ductility enhancement in the RC joints. However FRP only on the top and bottom of the beam decreases the ductility.

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