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FINITE ELEMENT MODELING OF RC CONNECTIONS STRENGTHENED WITH FRP LAMINATES*

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Abstract– Use of fiber reinforced plastic (FRP) composites for strengthening of beams and columns in RC structures has attracted great attention in recent decades. However, less attention has been paid to strengthening RC connections with FRP laminates. In the current study, a finite element (FE) modeling has been proposed for the non-linear analysis of RC joints covered with FRP overlays. The model consists of the effects of anchorage slip and anchorage extension of the steel reinforcement in the connection zone. As for the credibility of the method, some available experimental works were modeled and non-linearly analyzed using ANSYS. The results showed that the model can predict the experimental works with good accuracy. At the end and as a case study, a base joint specimen was strengthened with FRP laminates in 7 different cases and the specimens were analyzed using the aforementioned modeling. The results showed that good ductility and strength enhancement could be achieved by employing correctly configured FRP laminates.

Keywords– Anchorage slip, concrete, connection, ductility, finite element, flexural capacity, FRP, strengthening

1. INTRODUCTION

The use of FRP composites in strengthening reinforced concrete structures has been of great interest for civil engineers in recent years. Many researches have been directed to strengthening different reinforced concrete members such as beams, columns and slabs with FRP laminates; nevertheless, less attention has been paid to FRP strengthening of reinforced concrete joints. Parvin & Granata [1-5], Mosallam [6], and Gergely *et al*. [7] conducted some experimental and numerical studies on the subject of strengthening RC joints with FRP Laminates. They pointed out the increase in the strength of joints and decrease in the ultimate rotation of the joints as a result of FRP strengthening of RC connections.

Due to the complexity of the behavior of reinforced concrete joints, presenting an appropriate finite element modeling for the non-linear analysis of RC connections is of great importance. Such a model enables researchers to assess the behavior of any reinforced concrete joint with different dimensions and different configurations of strengthening laminates and eliminates the need of a similar assessment based on experimental laboratory tests that is very difficult due to the limitation in dimension, cost, and practical aspects.

The main objective of the current study has been focused on the introduction of a comprehensive non-linear finite element modeling for the analysis of RC joints using the available software. This model, when verified, could be utilized to predict the behavior of RC connections with different amounts of longitudinal and transverse reinforcements in the beam and column, and different configurations of FRP laminates in the joint region.

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2. FINITE ELEMENT MODELING

For non-linear finite element analysis, ANSYS software was used. To model the characteristics of concrete, a SOLID65 element was used. This element is capable of simulating the cracking and crushing of concrete, and to consider the reinforcement as volume fraction in 3 perpendicular directions, which could account for the modeling of the transverse reinforcement in the members. Furthermore, to model the longitudinal reinforcement and the FRP composites, LINK8 and SOLID45 elements, respectively were used [8].

As for failure criterion, the 5-parameter William-Varnk model was used. This model is able to account for the cracking of concrete in tension and crushing of concrete in compression; furthermore, it uses a smeared crack model. Some important parameters to perform the failure envelope in the model are the compressive strength of concrete, the modulus of the rupture, and the shear transfer coefficients for open and closed cracks. The latter coefficients may be taken as 1.0 and 0.2 to 0.25 for closed and open cracks, respectively, as recommended by kachlakev *et al*. [9]. Furthermore, since the crushing of concrete under pure compression rarely happens, the crushing could be eliminated from the concrete elements for better convergence in analysis.

As for the modeling of FRP composites in the software, an anisotropic material with the name of ANISO was used. The material in both compression and tension and in any direction of x, y and z uses a bi-linear stress-strain curve.

a) Modeling of anchorage slip

The anchorage slip and anchorage extension of the longitudinal reinforcement can significantly affect the behavior of reinforced concrete joints. They may also influence the rotation of the joint and even lead to brittle and sudden failure of the flexural concrete members as mentioned by Alsiwat & Saatioglu [10].

To account for the anchorage slip and anchorage extension of the reinforcement in the current study, the non-linear spring model recommended by Soroushian *et al*. [11] was used. The following two sets of models were considered to reveal the effects of hooked reinforcement and straight anchored reinforcement: the pull out-slip relationship for the first set from the study conducted by Soroushian et al. [11], and the bond-slip relationship for the second set based on the study carried out by Ueda *et al*. [12].

3. MODELING OF AN EXTERNAL RC JOINT

An external reinforced concrete joint was selected and non-linearly modeled using the aforementioned procedure. The dimension and the reinforcement in the beam and column of the joint are shown in Figure 1. The compressive strength of the concrete was taken as 30 MPa, and the yield strengths of longitudinal and transverse reinforcements were taken as 420 MPa and 280 MPa, respectively.

To model the anchorage slip of the longitudinal reinforcement of the beam in the joint region, the bars were generated between separate nodes next to concrete nodes. Then, the bar nodes were connected to concrete nodes with non-linear spring elements of COMBIN39 in the software. The end supports of the top and bottom columns were fixed and a monotonic concentrated load applied to the tip of the beam. Finer meshes were chosen for the connection region due to the probability of stress concentration and more cracking. The mesh defined in the beam and column is shown in Fig. 1. To perform the non-linear analysis, the load was applied step by step and the modified Newton-Raphson method was used for the solution. To eliminate the effects of debonding of FRP laminates in FE analysis, i.e., the effects of local failure due to shear or normal stress concentrations at the end of the laminates, the maximum strain in FRP laminates was limited to the quantities which are suggested in ACI 440 [13].

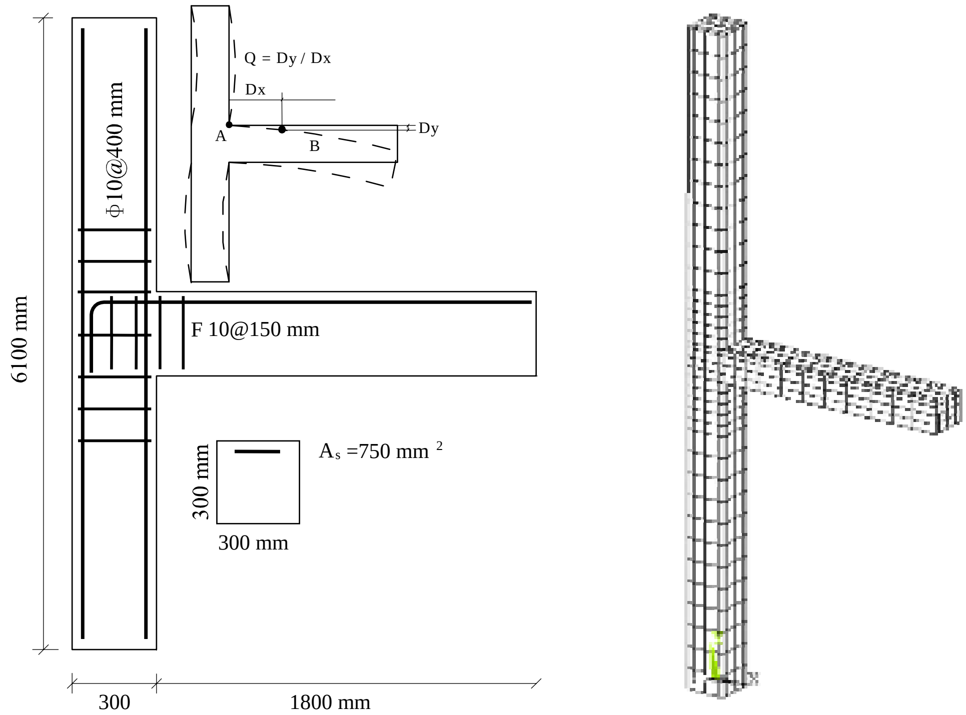
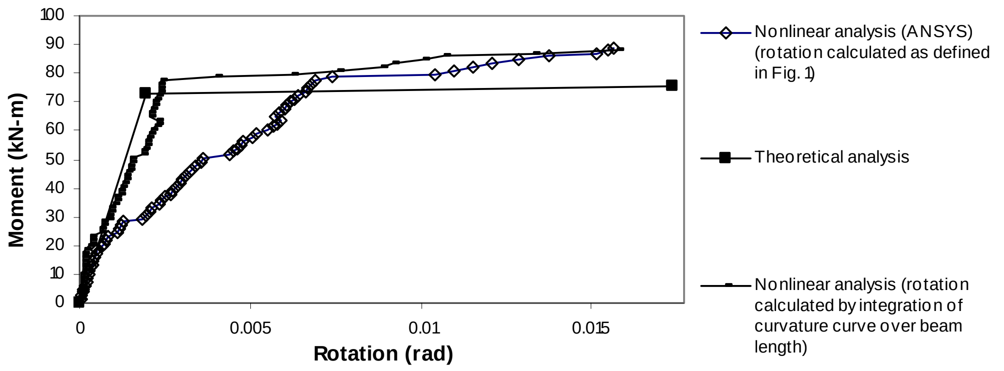


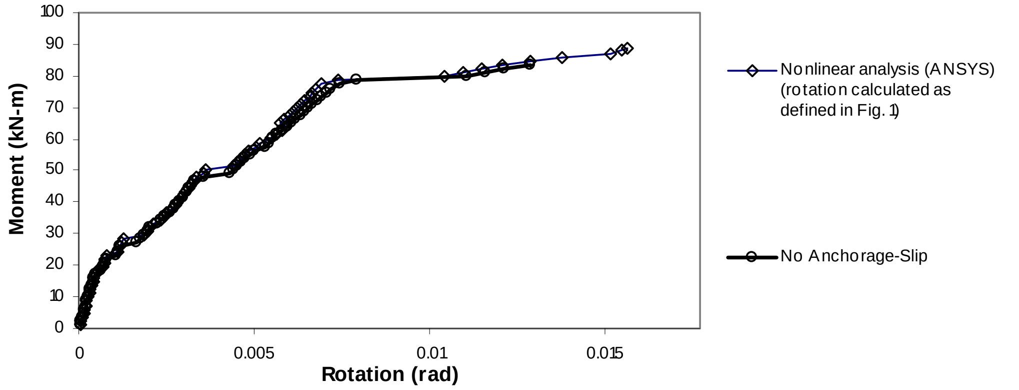
Fig. 1. Specification of the selected RC joint and its FE mesh

For verification of the results, the connection was theoretically analyzed and the moment-rotation diagram of the joint was drawn considering the effects of the anchorage slip. The theoretical analysis consisted of two stages. In the first stage, the resistant moment and the curvature for the beam section were calculated at cracking $(M_{cr}$ and $\phi_{cr})$, at the yield of the tensile reinforcement $(M_y$ and $\phi_y)$, and at ultimate $(M_u$ and $\phi_u)$. Then, the rotations corresponding to the cracking, yield of the tensile reinforcement, and the ultimate failure of the beam were calculated by integration from the relevant curvature variations over the beam length [14]. In the second stage, the effects of the anchorage slip were added to the calculated quantities in the moment-rotation diagram. To do so, the proposed bond stress-anchorage slip diagram in reference [10] was selected. The longitudinal reinforcement embedded in the column was divided into the segments corresponding to the elastic behavior, yield plateau, strain hardening and pull-out cone. Then the strain variation in each region was calculated by integration from strain variation over the length of the embedded reinforcement. Such as anchorage slip was calculated for the cases when the beam is at the verge of cracking, at the verge of yield of the longitudinal reinforcement, and at the ultimate failure. Finally, the corresponding rotations due to anchorage slip were calculated by dividing the anchorage slip to the depth of the neutral axis of the beam, and added to the similar quantities which were calculated in the first stage.

Figure 2 shows the moment-rotation diagram of the joint extracted from the results of non-linear FE analysis and theoretical analysis. In Fig. 2, there are two $M-\theta$ curves extracted from the FE analysis; in one of them the rotation (θ) is calculated as the ratio of the difference of vertical displacements of points A and B in Fig. 1 to their horizontal distance; and in the other one, the rotation is calculated as integration of the curvature over the length of the beam, as it is calculated in theoretical analysis. It is worthy to mention that the distance between points A and B was chosen long enough to include the plastic hinge zone in all specimens.



(a)



(b)

Fig. 2. a) Moment-rotation curves for selected RC joint, b) Effect of anchorage slip on the moment-rotation curve

In Fig. 2, close agreement could be observed between the moment-rotation curves extracted from the theoretical analysis and the non-linear FE analysis with the same procedure of calculation of rotation as in the theoretical analysis. Furthermore, comparing the moment-rotation curves drawn from the results of FE analysis with and without the effect of anchorage slip in Fig. 2, shows that disregarding the anchorage slip of the longitudinal reinforcement in the analysis, significantly underestimates the final rotation and the ductility of the joint.

Figure 3 shows the strain variations in the longitudinal reinforcement of the beam, based on both non-linear FE and theoretical analyses. In the theoretical analysis, the effect of anchorage slip was considered. It could be observed that a good agreement exists between the curves, confirming the validity of the modeling and the analysis.

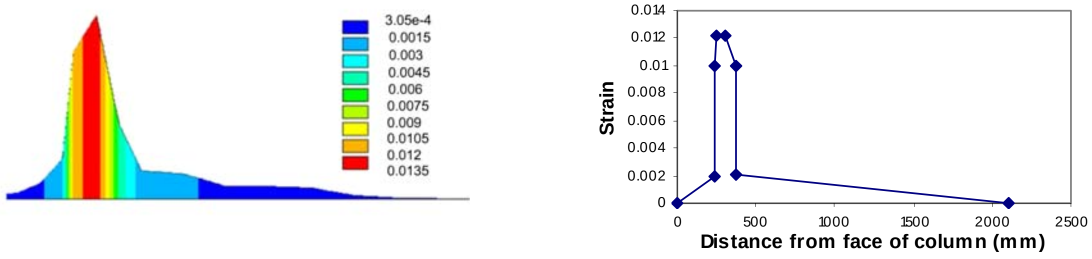


Fig. 3. Strain variations in longitudinal tensile reinforcement of the beam resulted from FE and theoretical analyses

4. MODELING OF AN FRP STRENGTHENED RC JOINT

For verification of the modeling and the analysis for the RC joint strengthened with FRP composites, an experimental study conducted on an FRP strengthened RC joint by Parvin & Granata [3] was selected. Figure 4 shows the dimension and the reinforcement of the specimen, as well as the arrangement of FRP laminates. Other characteristics of the materials could be found in the reference [3].

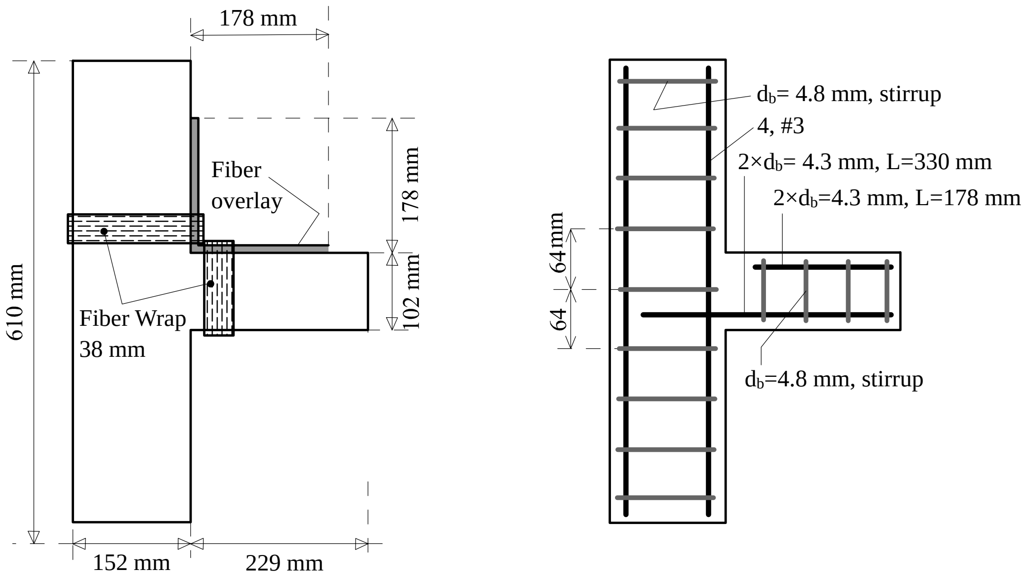


Fig. 4. Reinforcement specification of the RC joint and FRP strengthening plan [3]

The modeling of the different components of the specimen was performed as described in the previous sections. Considering the lack of tensile reinforcement at the end of the beam, the analysis stopped right after the occurrence of the first cracking at the end of the beam. This was mostly due to the instability caused by the sudden drop of the modulus of elasticity to zero after cracking started. To overcome this problem, a series of dummy elements of LINK8 with a very small cross sectional area of concrete with no cracking property were modeled in 3 directions between the end region of the beam and the column.

The far ends of the columns were fixed to the supports and the monotonic load was applied to the tip of the beam. Figure 5 shows the moment-rotation curves extracted from the non-linear FE analysis and the experimental data. Considering close agreement could be observed between the curves, it is concluded that the presented FE modeling is reliable.

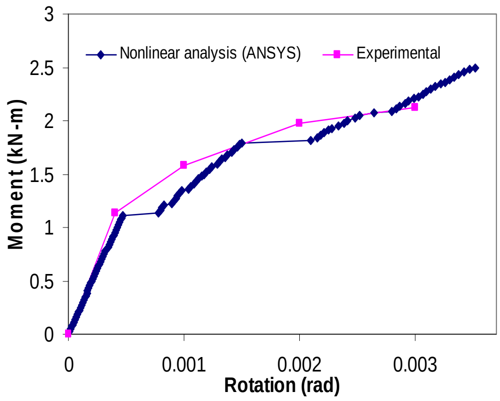


Fig. 5. Moment-rotation curve for the joint in Fig. 4 extracted from experiment [3] and calculated from FE analysis

5. CASE STUDY ON SOME STRENGTHENED SPECIMENS

As a case study on an RC joint strengthened with FRP laminates, a base joint with seven different strengthening designs was analyzed. The description of the base joint and the strengthened designs follows:

I. Control specimen: The control joint specimen known as “Base” is a connection composed of a column with a total height of 6 m and a beam of 2 m connected to the middle of the column. Both beam and columns are with the cross section of 400mm×400mm, the longitudinal reinforcement ratios for the beam (in tension zone) and column are $\rho_{beam} = 0.3\rho_{\max} = 0.8\%$ and $\rho_{column} = 4\%$, respectively. The transverse reinforcement for both beam and column in the connection region is $\phi 10@100\,\text{mm}$; while in the other parts of the beam and column, it is respectively $\phi 10@175\,\text{mm}$ and $\phi 10@400\,\text{mm}$. Note that the connection region is a limited length of the beam and column where the transverse reinforcement should be closely spaced according to ACI 318 to provide ductile behavior against earthquake. In the base specimen, the length of the connection region is calculated as 800 mm for the beam and 500 mm for the column.

II. Strengthened specimens: Four general strategies considered for strengthening the “Base” joint specimen with FRP sheets as follows:

1. L-shape overlays on the beam-column joint (Fig. 6a);
2. U-shape overlays under the beam (Fig. 6b);
3. FRP laminates on both sides of the beam (Fig. 6c);
4. Column wrapping (Fig. 6d).

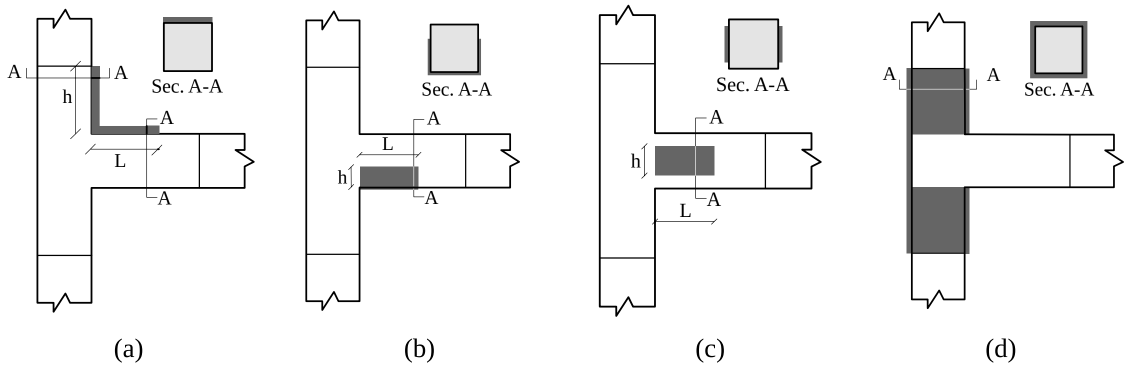


Fig. 6. Strengthening designs with FRP overlays

Combining the four aforementioned strategies, 7 cases were defined for strengthening the “Base” specimen as given in Table 1. The thickness of FRP laminates was assumed 3 mm for all cases. Other characteristics of CFRP laminates are given in Table 2. Note that the characteristics given in Table 2, satisfy the consistency conditions which are necessary for a non-isotropic material like ANISO in the analysis as described in reference [8] and stated by kachlakev *et al*. [9].

Table 1. Characteristics of the strengthened specimens

Joint name	L-shape overlay	U-shape laminate		Both sides laminates		Column wrapping
	L (mm)	L (mm)	h (mm)	L (mm)	h (mm)	
S1	400					No
S2	400					Yes
S3		400	200			No
S4		400	200			Yes
S5				400	400	No
S6				400	400	Yes
S7						Yes

Table 2. Mechanical properties of CFRP laminates used for FE modeling [9]

Modulus of elasticity (GPa)	In fibers direction	$E_x=62$	Compressive strength (MPa)	In fibers direction		$\sigma_x = 10$
	Perpendicular to fibers direction	$E_y=4.8$		Perpendicular to fibers direction		$\sigma_y = 152$
		$E_z=4.8$				$\sigma_z = 232.94$
Tensile strength (MPa)	In fibers direction	$\sigma'_x = 935$	Shear modulus (MPa)	$G_{xy}=3270$	Poisson's ratio	$\nu_{xy} = 0.22$
	Perpendicular to fibers direction	$\sigma'_y = 26$		$G_{xz}=3270$		$\nu_{xz} = 0.22$
		$\sigma'_z = 14$		$G_{yz}=1860$		$\nu_{yz} = 0.30$

6. RESULTS OF THE ANALYSIS

Different results including the ultimate load, stresses in concrete and reinforcements, stresses in FRP laminates, the crack pattern at various stages and the ductility of each specimen were investigated.

Figure 7 shows the moment-rotation curves for the Base and the strengthened specimens. Some other results including the flexural capacity of the joint, the ductility factor and the ultimate rotation for all specimens are given in Table 3.

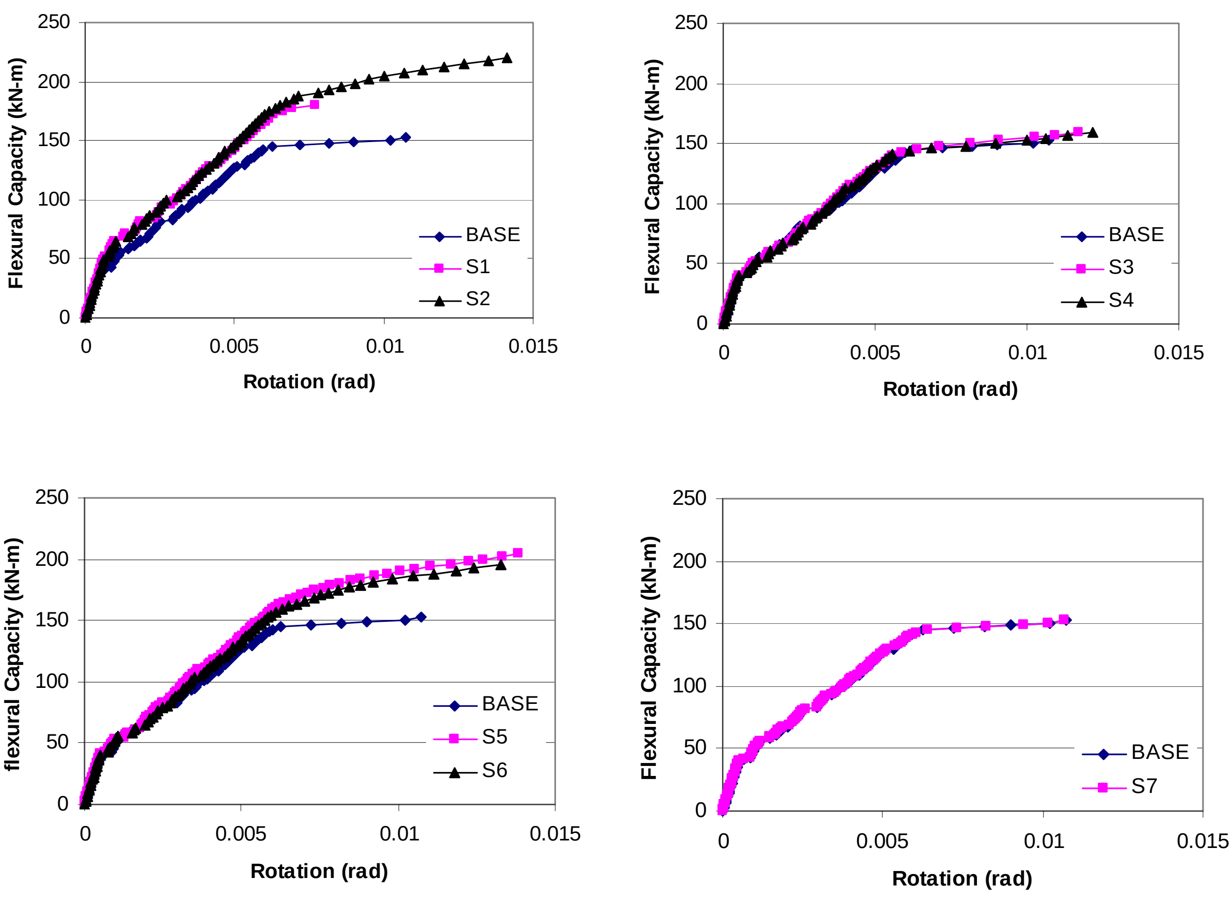


Fig. 7. Moment-rotation curves for the base specimen and the strengthened specimens (extracted from non-linear analyses)

Table 3. Selected results from the non-linear analyses of strengthened specimens

Joint name	Ductility factor	Flexural capacity (kN.m)	Ultimate rotation (rad.)
Base	1.8	153	0.0107
S1	1.25	179.9	0.0077
S2	2.35	219.74	0.0141
S3	2.15	159.81	0.0117
S4	2.23	159.2	0.0122
S5	2.22	204.05	0.0107
S6	2.27	195.1	0.0109
S7	1.83	153	0.0107

7. DISCUSSION ON THE RESULTS

a) Flexural capacity

The results show that the flexural capacities of the strengthened specimens have increased compared to that of the base specimen. The increase in flexural capacities of specimens S1 and S2 is due to the tensile action of L shaped laminates in the tensile face of the beam; however, in specimens S3 and S4 with U shape FRP laminates, it could be contributed to the prevention of crack propagation, as well as the confinement of the concrete in the compression zone of the beam. Nevertheless, no increase in flexural capacity was observed in specimen S7, since only column wrapping with FRP laminates had been added to this specimen, which is not effective in the flexural capacity of the beam.

b) Ductility enhancement

It could be observed from Table 3 that the highest ductility factor is related to strengthened specimen S2 and then to specimen S6. The high growth of ductile behavior in specimen S2, may be attributed to the simultaneous column wrapping and use of FRP overlays, which cause the end part conditions of the beam to be close to fix support.

The latter provides the necessary conditions for the longitudinal reinforcement of the beam to yield right after the strengthened length, which may be interpreted as movement of the plastic hinge. The relative increase in ductility factors of the specimens S3 to S6 is basically due to the confinement of the compression concrete of the beam caused by the FRP laminates over the compression region of the beam, which leads to the improvement of the ductility of the beam and the whole connection. It could be seen from Table 3 that the column wrapping with FRP composites increases the ductility of the joint compared to the similar specimens without column wrapping.

c) Ultimate rotation

The ultimate rotation in strengthened specimen S1 has decreased compared to that of the base specimen, while it has increased or has not changed in the other strengthened specimens as shown in Table 3. In fact, the L shape overlays without column wrapping have diminished the rotation of the joint. However, the column wrapping with FRP laminates has provided a more ductile behavior for the whole connection with a higher ultimate rotation.

d) Mode of failure

Mode of failure in connections is from the most important behavioral characteristics which are determinative for ductile behavior and energy absorption in the joint. Scrutiny in the results of the analyses showed 3 types of failure in the connection specimens as follows:

1. Flexural failure at the end of the beam at the face of the column (full flexural cracks at the end of beam). This type of failure was observed in specimens “Base”, S3, S4, S6 and S7.
2. Flexural failure in the beam at a distance equal to the length of strengthening overlays from the face of the column. This type of failure was observed in specimens S1and S2.
3. Shear failure of the joint as shown in Fig. 8 (diagonal cracks in conjunction with the beam and column). This type of failure was observed in specimen S5.

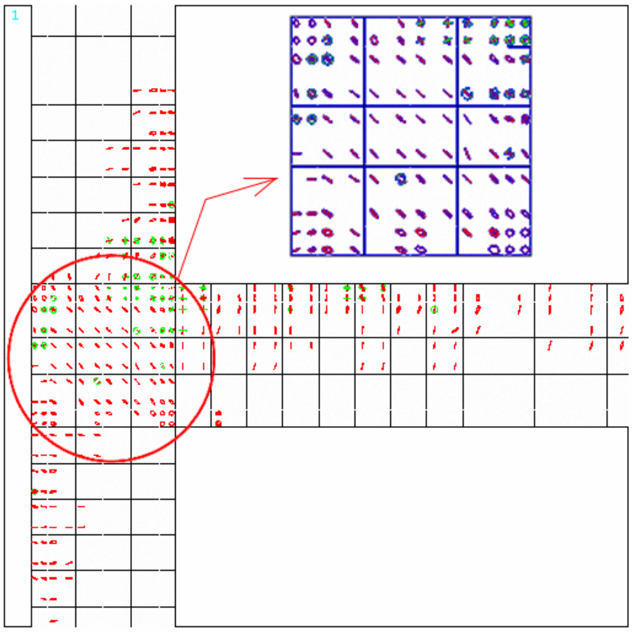


Fig. 8. Pattern of cracks in the joint under ultimate load and the consecutive shear failure of the joint

8. SUMMARY AND CONCLUSIONS

In this paper, an attempt was made to introduce a rational and comprehensive procedure for modeling FRP strengthened RC connections for non-linear FE analysis. Appropriate elements from the software were chosen to account for the realistic behavior of each component in the connection, and the modeling and the analysis procedure were verified using some existing experimental data. A case study on a typical RC connection with some particular strengthening strategies with FRP laminates was performed. The results of this study could be summarized as follows:

1. Realistic non-linear analysis of RC connections with FRP overlays could be performed using available software.
2. The modeling of anchorage slip in the embedded reinforcement is possible using non-linear spring models.
3. Ignoring the anchorage slip of the longitudinal reinforcement of the beam embedded in the column in FE analysis leads to underestimating the ultimate rotation of the joint up to 25%.

L shape overlays from FRP composites at the beam-column connection, plus column wrapping with FRP laminates and U shape overlays under the beam are very good strengthening strategies for strength and ductility enhancement in the RC joints.

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