Fourth International Conference on FRP Composites in Civil Engineering (CICE2008)
22-24July 2008, Zurich, Switzerland

Behavior of RC beams strengthened with CFRP plates using the finite element modeling

A.I.M. Al-Janabi, S.A. Ahmed & A.R. Safi
Civil Engineering Department, Faculty of Engineering, Al-Tahadi University, Sirt, Libya

ABSTRACT: During the last decade, strengthening of RC structures with CFRP (carbon fiber reinforced polymer) composite has become very popular. In the present work, numerical analysis was performed using the ANSYS finite element software to predict the performance of RC beams strengthened with CFRP plates. The concrete was modeled as 3-dimentional solid elements having nonlinear properties. The reinforcing steel was modeled as linkage elements with elastic-plastic behavior. The CFRP was modeled as plane shell elements attached to the concrete surface. The efficiency of the present model was measured by comparing its results with the available experimental results; good agreement was found between the numerical and experimental studies. The influences of CFRP plate length factor, concrete strength and steel reinforcement area on the performance of RC strengthened beams were investigated. It has been shown that the use of CFRP strengthening can significantly increase the ultimate load carrying capacity as well as the stiffness of RC beams. The major effect was found at a plate length factor of 0.8. The effect of CFRP strengthening on the behavior of beams with low area of steel reinforcement was more pronounced than that of beams with high area of steel reinforcement.

1 INTRODUCTION

Repair and strengthening of various RC members using FRP materials is becoming more and more popular in structural retrofitting field. CFRP plates are now identified as an effective way to enhance strength and ductility of RC members, due to its superior properties.

Extensive experimental works on different RC members strengthened with CFRP plates were carried out (Hosny et al. 2006; Mohamed & Alwifati 2005; Nguyen et al. 2001). These works showed that the proper use of CFRP plates increases stiffness, ductility and load-carrying capacity of the strengthened members. However, research is still required for full understanding of the problem.

Recently, many attempts have been made to use the finite element (FE) modeling for the problem using various softwares; such as DIANA, LUSAS, LS-DYNA and ABAQUS (Ross et al. 1999; Rahimi & Huchinson 2001; Tavarez et al. 2003; Hu et al. 2004). However, most of these works were dedicated for the purpose of comparison with experimental studies. Therefore, they were done on members with scaled down dimensions, such as those normally used in the experimental studies.

The main objective of the present study was to apply the non-linear FE modeling to RC beams with prototype dimensions. The CFRP plates were externally bonded at the tension side of the beam, and the modeling was carried out using the 3-dimensional nonlinear FE ANSYS software. Numerical study was performed on selected cases from the previous experimental works to check the validity of the model. The effects of some influencing parameters including CFRP plate length factor, concrete strength and steel reinforcement area on the behavior of strengthened beams were studied.

2 FINITE ELEMENT MODELING

The RC beams used in the analysis were simply supported and strengthened with external CFRP plates attached to their bottom. The plates covered all or only part of the beam span. The loading condition considered was two-point loads symmetrically positioned about the beam center line. Because of symmetry only one-quarter of the beam was considered by using the appropriate boundary conditions about axes of symmetry.

To model the beams within the ANSYS environment, the concrete was modeled using the Solid 65 three-dimensional element. The nonlinear stress-strain behavior of concrete in compression was modeled using the relation given by Thorenfeldt et al. (James et al. 2005), see Figure 1. In tension, it was modeled as linear elastic up to the tensile strength of concrete. The steel reinforcement was modeled using Link 8 element with elastic perfectly plastic behavior, as shown in Figure 2.

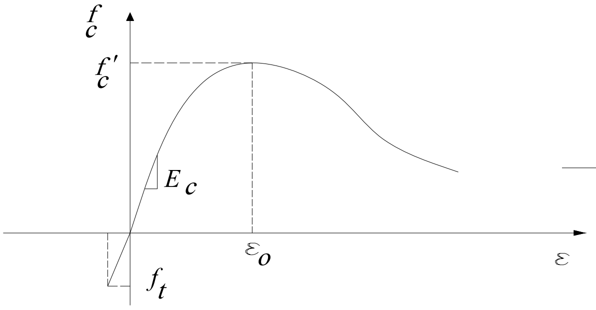

Figure 1. Stress-strain relationship of concrete.

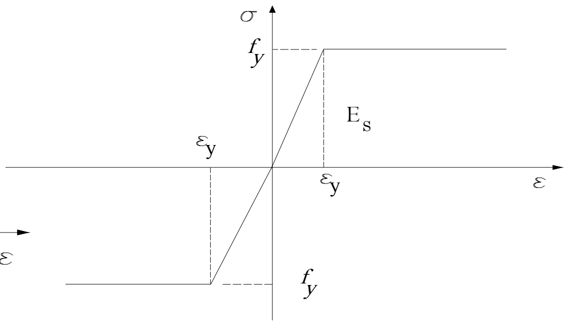

Figure 2. Stress-strain relationship of steel reinf.

The CFRP plate was modeled as a three-dimensional Shell 41 element with linear stress-strain relation up to failure in tension without any strength in compression (Fig. 3). Full bond between concrete and CFRP plate was assumed.

To distribute loads and reactions on concrete, thick steel plates of appropriate dimensions were used under the load and under the beam at the supports, see Figure 4. These plates were modeled with the three-dimensional Solid 45 element with elastic properties.

The total number of elements in the problems investigated varied from 1305 to 4058 element (Fig. 4).

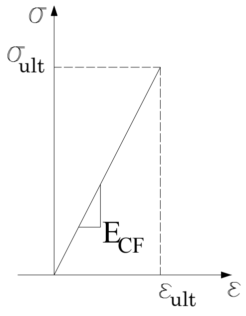

Figure 3. Stress-strain relationship of CFRP.

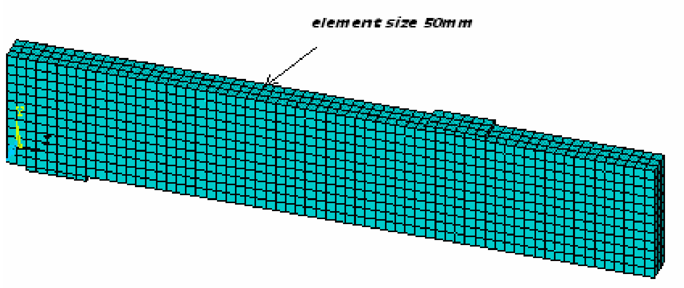

Figure 4. Meshing of the problem.

3 CALIBRATION CASE STUDIES

The validity of the model was calibrated against results of previous experimental studies covering RC beams with or without CFRP plate strengthening.

3.1 *Case I: work of Buckhouse (1997)*

A full-scale RC beam without CFRP strengthening was tested under third-point loading by Buckhouse (1997) and the test results were reported by Wolanski (2004). The beam dimensions were 250×450 mm cross-section and 4.5 m span.

The experimental and the FE results of the load mid-span deflection curve are shown in Figure 5. As shown, the entire load mid-span deflection response produced using ANSYS model was similar to the experimental response. To facilitate direct comparison of the results shown in Figure 5, the loads at the first crack, yield and ultimate were calculated using the present model and compared with those predicted experimentally (Buckhose 1997), hand computed and reported by Wolneski (2004), see Table 1. Also, the deflections at first crack and at ultimate were predicted and compared with the same three sources. As shown in Table 1, results of the loads and deflections computed by the present model agreed well with the experimental, hand computation and previous study results.

Table 1. Results of the loads and deflections.

	Present FE model	Experimental (Buckhouse)	Hand computed	Reported (Wolneski)
1st crack load (kN)	23.1	20.0	22.8	23.2
1st yield load (kN)	62.3	60.0	–	61.4
Ultimate load (kN)	73.8	72.6	64.9	72.6
Deflection at 1st crack load (mm)	1.3487	1.3665	1.3437	1.3564
Deflection at ultimate load (mm)	94.0308	92.7100	–	91.0844

Figure 6 shows the crack patterns of the tested beam, produced using the present model, at various load stages. The first cracks occurred at the bottom of the beam in the constant moment region (near the mid-span of the beam) at a load of 23.1 kN (Fig. 6a). These cracks were of flexural nature and they occurred in the vertical direction. At a load of 35.6 kN (nearly half the ultimate load), the flexural cracks spread in the upward vertical direction in the constant moment region (Fig. 6b). In addition, diagonal tension cracks (due to shear force) outside the constant moment region also occurred. At the ultimate load, the flexural cracks in the constant moment region increased in the vertical direction and nearly covered the full depth of the beam (Fig. 6c). Similarly, diagonal tension cracks spread and became closer to the support.

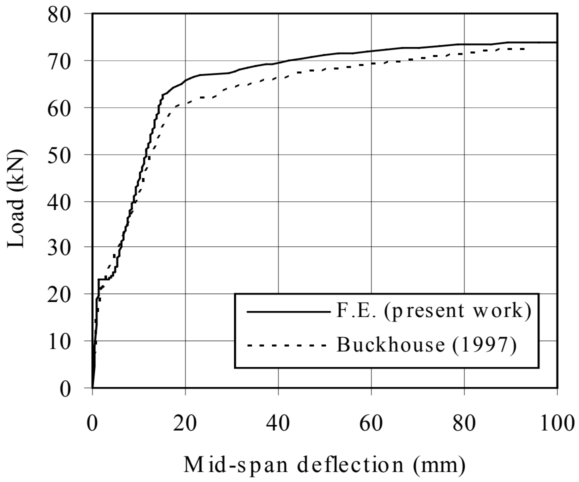

Figure 5. Experimental and FE load mid-span deflection of unstrengthened RC beam.

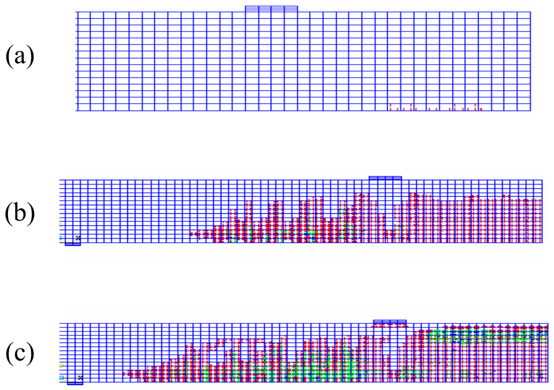

Figure 6. Crack patterns at various loads of unstrengthened RC beam.

3.2 *Case II: work of Nguyen et al. (2001)*

Four RC beams were tested by Nguyen (2001), one of them (CB1) was considered as the control beam without CFRP strengthening, while the other three (A950, A1100 and A1500) were strengthened with CFRP plates. The shown number beside the letter A gives the length the CFRP plate, while its width and thickness were kept constant at 80 and 1.2 mm, respectively. All beams had cross-sectional dimensions of 120×150 mm and length of 1500 mm. They were simply supported over 1330 mm span and tested under two-concentrated loads 450 mm apart.

Table 2 shows the FE ultimate loads for control and strengthened RC beams, together with the predicted and experimentally measured ones, as given by Nguyen (2001). The predicted ultimate loads for beams with CFRP plate were computed based on full composite action between CFRP plate and RC beam. As can be seen the FE ultimate loads of the four tested beams were slightly less than the experimentally measured ones; the difference between them was about 5% in case of control beam and ranged between 5-18% in case of CFRP strengthened beams. This difference may be attributed to the complex nature of modeling, e.g. the strain hardening of the steel reinforcement was not included in the model and the complex behavior of concrete model.

Table 2. Results of the ultimate loads.

Beam	Concrete strength (MPa)	Predicted ultimate load (kN)		Experimental ultimate load (kN)	FE ultimate load (kN)	Failure mode
		Without CFRP	With CFRP			
CB1	32.1	42.1	-	42.3	40	Flexural
A950	32.1	42.1	82	56.2	51	Peeling of CFRP
A1100	32.1	42.1	82	57.3	54	Peeling of CFRP
A1500	44.6	44.1	100	118	96	Flexural

4 PARAMETRIC STUDY

The present model was used to study the effect of plate length factor, concrete strength and steel reinforcement area on the structural behavior of RC beams strengthened with CFRP plates. A full-scale RC beam with the dimensions and reinforcement details shown in Figure 7 was used in this investigation, except in case of studying the effect of steel reinforcement where the area of steel was changed according to case of study. The width of CFRP plate was constant and equal to the total width of the beam, and its thickness was 1.2 mm.

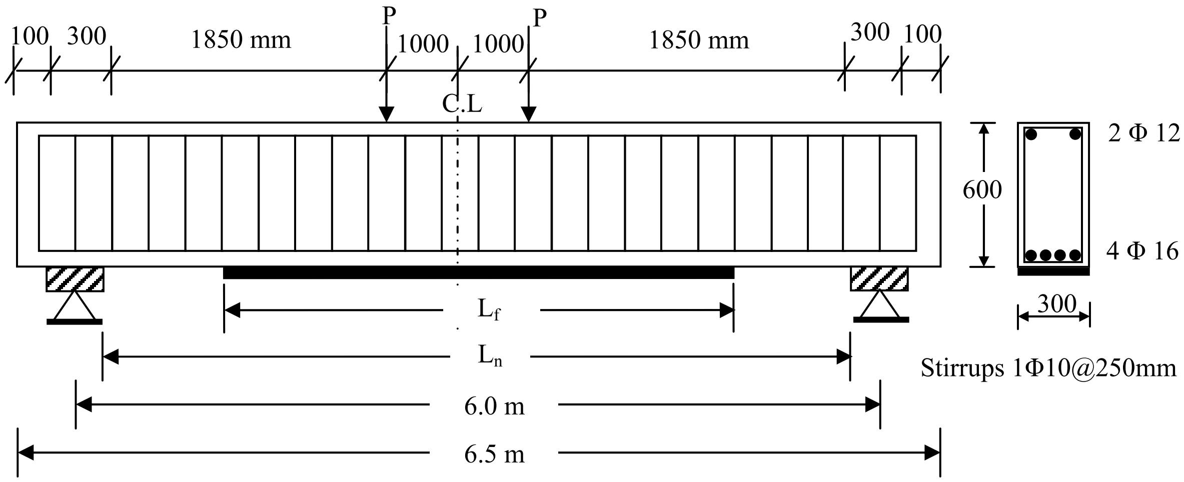

Figure 7. Dimensions and reinforcement details of the full-scale beam used in the present study.

4.1 *Effect of plate length factor (α)*

The plate length factor is the ratio between the length of the CFRP plate and clear span of the beam (L_f/L_n). The effect of the plate length factor on the ultimate load capacity of strengthened beam is shown in Figure 8. As can be noticed in this figure, increase of α from 0.50 to 0.80 gave a significant increase in the ultimate load, from 137 kN to 223 kN. However, increasing of α from 0.8 to 1.0 showed a very slight increase in the ultimate load, from 223 kN to 224 kN.

For further investigation, Figure 9 shows the stress distribution along CFRP plates at the ultimate loads. As shown, the stresses in CFRP plates were of maximum value at the beam mid-span and decreased to a very small value at end of CFRP plates. For short CFRP plates (α = 0.5 - 0.6), the stresses developed in CFRP plates were small due to peeling of the CFRP plates as a result of their short development lengths. The behavior showed that the concrete cover at end of CFRP plate suffered from cracking and the stresses in shear reinforcement, in the same region, were close to yielding.

On the other hand, for α = 0.7 and 0.8, the stresses in CFRP plates were high and nearly equal. When the value of α was increased from 0.8 to 1.0, a further increase in the CFRP stresses was obtained, however, there was not any increase in the ultimate load capacity (Fig. 8). This means that the maximum benefit from CFRP plate development length was achieved at α = 0.8. Extending the CFRP length factor beyond this value had not any beneficial effect. In this case the behavior indicated flexural failure as a result of yielding of tension reinforcement.

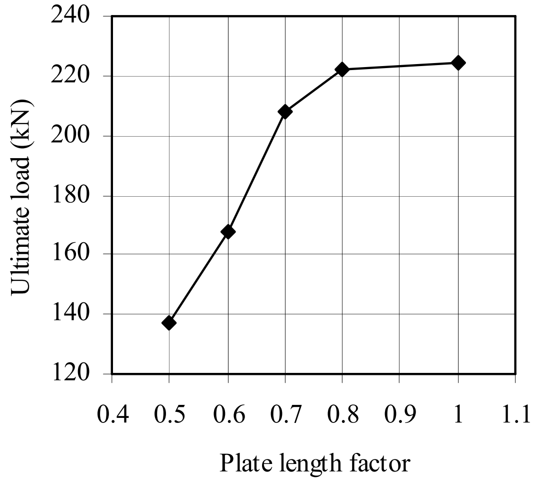

Figure 8. Effect of plate length factor on ultimate load capacity.

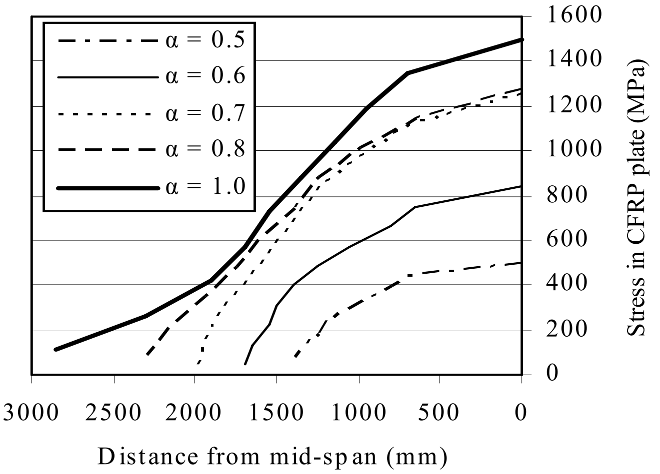

Figure 9. Stress distribution along the CFRP plate at the ultimate loads.

4.2 *Effect of concrete strength*

Figure 10 shows the load mid-span deflection of RC beams made from two grades of concrete compressive strength, 30 and 40 MPa, and strengthened with CFRP plates having plate length factor of 0.5 and 0.8. The results showed that increase of α from 0.5 to 0.8 have increased the ultimate load carrying capacity of the strengthened beams by about 70%, irrespective of concrete compressive strength. This means that CFRP strengthening have similar effect for different grades of concrete.

4.3 *Effect of steel reinforcement area (A_s)*

Two sets of RC beams were reinforced with three different areas of steel and analyzed using ANSYS FE model, see Table 3. The results showed that the effect of CFRP strengthening on beams with low A_s was higher than that with high A_s. For example, the increase in the load carrying capacity of beam with A_s=804 mm^2 was about 150%, when A_s was doubled to 1608 mm^2 the increase in the ultimate load capacity was only about 75%.

Table 3. Effect of As on ultimate load of RC beams.

A_s (mm^2)	Ultimate loads (kN)		Increase in ultimate load (%)
	Beams without CFRP	Beams with CFRP	
804	89	223	150
1206	126	271	115
1608	173	303	75

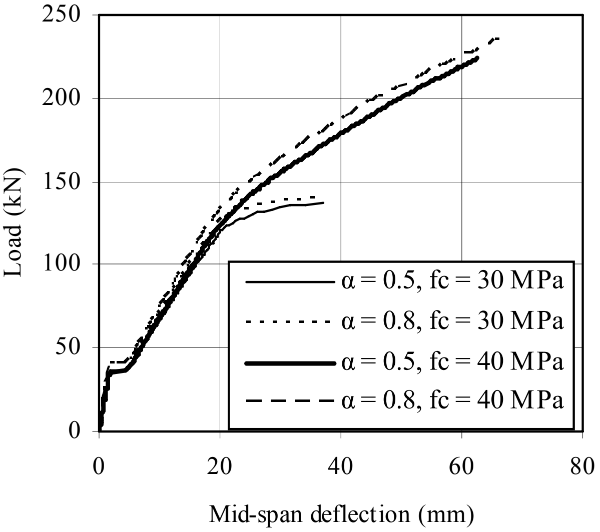

Figure 10. Load mid-span deflections of RC beams with two grades of concrete.

5 CONCLUSIONS

A numerical study was carried out for RC beams strengthened with CFRP plates using the three-dimensional finite element adopted by ANSYS. Results of the present model showed good agreement with the experimental values. It has been found that as the CFRP plate length increases, the stiffness and the ultimate load carrying capacity of the strengthened beams increase. This was true till a plate length factor of 0.8, after that the increase was negligible. This means that there is no benefit in increasing the CFRP plate length more than 0.8 of the clear span. When the concrete strength was increased from 30 to 40 MPa, quite similar behavior was observed; the increase in the ultimate load was about 70% in the two cases. Study of the effect of CFRP strengthening on beams having different tensile steel reinforcement area showed that beams with higher tension steel area gained smaller % increase in the ultimate load capacity, when strengthened with similar CFRP plates.

6 REFRENCES

Buckhouse, E.R. 1997. External Flexural Reinforcement of Existing RC Beams Using Bolted Steel Channels. M.Sc. Thesis, Marquette University, Milwaukee, Wisconsin.

Hosny A., Rahman, A.A., Sayed-Ahmed, E.Y., and Alhlaby, N.A. 2006. CFRP Strengthening of Prestressed-Precast Hollow Core Slabs to Resist Negative Moments. Proceeding of the 10th ASCE, Kuwait, 551-558.

Hu, H.T., Lin, F.M., and Jan, Y.Y. 2004. Nonlinear Finite Element Analysis of RC Beams Strengthened by FRP. Journal of Composite Structures, 63, 271-281.

James, G.M., and James, K.W. 2005. Reinforced Concrete: Mechanics and Design. 4th Edition, Prentice Hall, Upper Saddle River, New Jersey.

Mohamed, M.M., and Alwifati, A.M. 2005. Study of RC Beams Strengthened With CFRP Plate. M.Sc. Thesis, Dept. of Civil Engineering, Al-Fateh University, Tripoli, Libya.

Nguyen, D.M., Chan, T.K., and Cheong, H.K. 2001. Effect of Plate Length on the Strength of RC Beam Bonded with CFRP Plates. Journal of Composites for Construction, 5(1), 12-17.

Rahimi, H., and Hutchinson, A. 2001. Concrete Beams Strengthened With Externally Bonded FRP Plates. Journal of Composites for Construction, 5(1), 44-56.

Ross, C.A., Jerorme, D.M., Tedesco, J.W., and Hughes, M.L. 1999. Strengthening of RC Beams With Externally Bonded Composites Laminates. ACI Structural Journal, 96(2), 212-220.

Tavarez, F.A, Bank, L.C., and Pleshe, M.E. 2003. Analysis of FRP Grid Reinforced Concrete Beams", ACI Structural Journal, 100(2), 250-258.

Wolanski, A.J. 2004. Flexural Behavior of RC and Prestressed Concrete Beams Using FE Analysis. M.Sc. Thesis, Dept. of Civil Engineering, Marqutte University, Milwaukee, Wisconsin.