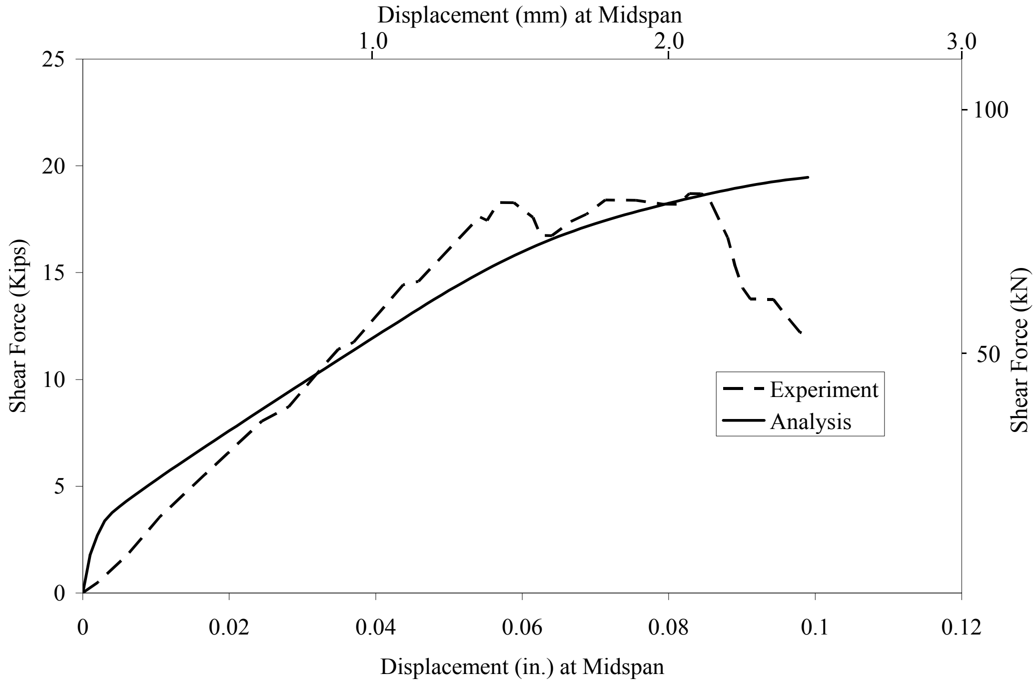

Figure 9 – Shear Force - Midspan Deflection for Beam Z31-FC

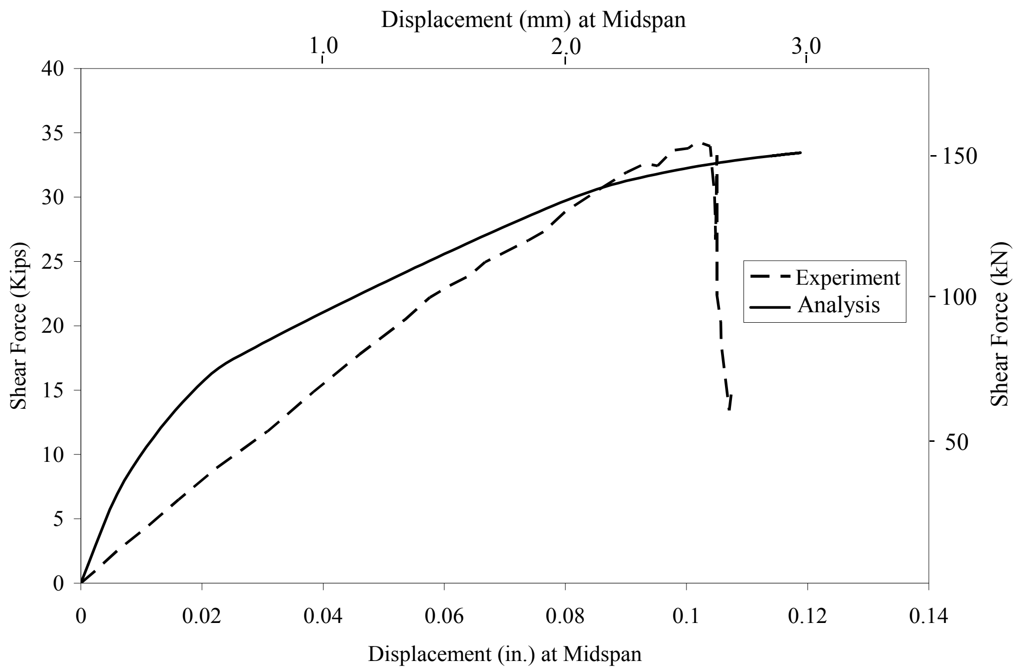

Figure 10 – Shear Force - Midspan Deflection for Beam Z31-F90

FINITE ELEMENT MODELING OF SHEAR DEFICIENT RC BEAMS STRENGTHENED WITH NSM CFRP RODS UNDER CYCLIC LOADING

R. Hawileh, J. A. Abdalla , M. Z. Naser , and M. Tanarslan

Synopsis: This paper presents Finite Element (FE) model to predict and analyze the cyclic loading response of reinforced concrete (RC) beams strengthened in shear with Carbon Fiber Reinforced-Polymer (CFRP) and Near-Surface Mounted (NSM) reinforcement. Four FE models were developed based on experimental tests conducted in a previous study. The first specimen was unstrengthened to serve as a control beam while the other two beams were strengthened with NSM CFRP bars with different spacing arrangements. The last beam specimen was strengthened with larger diameter CFRP bars. The developed FE models employed different nonlinear constitutive material modeling laws and techniques such as concrete cracking, steel yielding, bond-slip between CFRP bars and epoxy resin, and debonding between the epoxy resin and concrete surfaces. The predicted and measured load-deflection response envelop curves along with the associated hysteresis loops for each specimen were used as platforms to validate the accuracy of the developed models. The results indicate that there is a good match between the predicted results and measured data. It is concluded that the developed FE model is a suitable tool to predict the behavior of such strengthening systems when subjected to cyclic loading and could be used in lieu of expensive experimental testing especially in design-oriented parametric studies.

Keywords: shear failure, reinforced concrete beams, computational modeling, fiber-reinforced polymers (FRP), strengthening, near-surface mounted (NSM), cyclic loading.

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INTRODUCTION

Fiber reinforced polymer (FRP) materials deliver a new choice for strengthening and rehabilitation of reinforced concrete (RC) structures due to their superior mechanical properties, light weight, and ease of installation. Extensive research has been carried out to evaluate the contribution of externally bonded FRP laminates to the shear capacity of RC Beams (Chajes et al., 1995; Norris et al., 1997; Khalifa and Nanni, 2002; Alzoubi and Zhengliang; 2007, Lee et al., 2008; Tanarslan et al., 2008; Hawileh et al., 2010)[1-7]. Results have shown that achieving the full capacity of FRP is almost impossible due to FRP debonding from the concrete surfaces. Several researchers conducted several experimental and numerical studies to investigate the failure mode of FRP debonding (Zhao et al., 2005; Consenza et al., 1997; Al-Mahaidi et al., 2001; Sabrina et al., 2010; Al-Tamimi et al., 2011; Naser et al., 2011; Ombres, 2010; Lu and Ayoub, 2008; You et al., 2009)[8-16]. Debonding usually initiates at the interface between the FRP laminate and concrete surfaces. This failure mode happens when the shear stress in the laminate approaches the ultimate bond strength of the epoxy material. Thus the member will fail before mobilizing the full tensile strength of the FRP material. Thus, FRP strengthened systems is governed by the bond strength of the adhesive and the bonding area of FRP. In addition, exterior affects like high and low temperature, freeze/thaw, accidental impacts and fire will influence the performance of such externally strengthened members.

Embedding of FRP bars into pre-cut grooves bonded with epoxy adhesive or cement grout to strengthen RC structural members have been recently proposed as an alternative to externally bonded FRP systems. The technique was named as Near Surface Mounting (NSM) (De Lorenzis and Teng, 2006)[17] and has several advantages when compared to externally bonded FRP composites, mainly: a) The risk of debonding from the concrete substrate is reduced, b) The NSM bars are protected by the cover so they are less exposed to exterior environmental effects, c) concrete surface preparation is no longer needed but pre-cut grooves have to be prepared to mount the FRP bars inside them. It should be noted that the success of the NSM technique depends on the bond between the FRP rods and concrete. Bond performance of NSM systems have been evaluated by several researchers using different experimental programs of bond tests (De Lorenzis and Nanni, 2002; Kotynia, 2011; Anwarul, 2009)[18-20]. The results of these experimental programs for testing the bond between CFRP rods and concrete have showed that NSM CFRP rods have a great anchorage capacity to concrete as compared to externally bonded FRP systems.

Although, there are several experimental and numerical studies that investigated the flexural performance of RC beams in flexure (Al-Mahmoud et al., 2007; Rizkalla, 2004; Rasheed et al., 2010; Hawileh, 2010; Taljsten et al., 2003; El-Hacha and Rizkalla, 2004; Al-Mahmoud et al., 2009; Badawi and Soudki, 2009)[22-28], still limited information is available in the literature (De Lorenzis and Nanni, 2001; De Lorenzis and Nanni, 2001; Rizzo and De Lorenzis , 2009)[29-32] on the performance and capacity of RC beams strengthened with NSM CFRP rods in shear. Tests on shear deficient beams had been conducted under monotonic loading in all previous studies (De Lorenzis and Nanni, 2001; De Lorenzis and Nanni, 2001; Rizzo and De Lorenzis , 2009)[29-32]. Although several investigators have experimentally investigated the performance of NSM strengthened RC beams under monotonic loading, however the literature still lacking in terms of studies addressing the performance of NSM strengthened RC beams under cyclic loading (Capozucca, 2009; Oudah and El-Hucha; 2012; Tanarslan, 2011)[33-35]. Moreover, the authors' literature review revealed that very few studies have been conducted in using finite element in modeling and simulation of behavior of NSM strengthened RC beams under cyclic loading.

The cyclic loading response and behavior of RC beams, deficient in shear and strengthened with NSM-CFRP rods was examined in an experimental program, conducted by Tanarslan (2011)[35] in a previous investigation. Spacing of CFRP bars and CFRP bar diameter were the main variables of the experimental program. Test results had shown an increase in capacity to every beam specimen strengthened with NSM CFRP bars. The aim of this research is to numerically predict via finite element (FE) analysis, the response and load-carrying capacities of the specimens tested by Tanarslan (2011)[35]. The obtained and predicted load-deflection response envelop curves and load-deflection hysteresis loops for each specimen were used as benchmarks for comparison. The results show that there is a good agreement and high correlation between the finite element predicted results and the experimentally measured data. Thus, the presented FE model herein could serve as a valid tool to investigate the performance of RC beams strengthened with NSM reinforcement under cyclic loading.

RESEARCH SIGNIFICANCE

The Near Surface mounted (NSM) strengthening system has been recently used in strengthening and retrofitting of structural members in flexure and shear. Most of the research studies investigated the performance of flexural strengthening of RC members. The literature is lacking experimental and numerical studies on the cyclic behavior of RC beams strengthened in shear using NSM CFRP bars. Further experimental, analytical, and numerical investigation is warranted in this area. The aim of this paper is to numerically predict by developing a finite element (FE) model that is capable to predict the response of such strengthened RC beams under cyclic loading.

SUMMARY OF EXPERIMENTAL PROGRAM

Four RC cantilever shear-deficient beams were casted as part of the experimental program conducted by Tanarslan (2011).[35] All RC beams have the same overall cross-sectional dimensions and internal reinforcement arrangements as presented in Fig. 1. The beams were 200 mm (7.9 in) wide, 350 mm (13.8 in) deep and 1600 mm (63 in) of clear span as shown in Figs. 1 and 2. Three 20 mm (0.78 in) diameter bars in the compression zone and three 20 mm (0.78 in) diameter bars in the tension zone were used as longitudinal reinforcements. The concrete clear cover was 30 mm (1.2 in) on all four sides of the beam specimens. The first beam was the unstrengthened control specimen (BEAM-2) and shown in Fig. 1. The other three RC beam specimens are shown in Fig. 2 and Fig. 3 were strengthened with NSM CFRP bars with different CFRP spacing and bar diameter. The strengthening process starts by cutting grooves with a size of one and a half times the diameter of CFRP reinforcement. Figure 4 shows the grooves that covers the beam's entire depth (350 mm; (13.8 in)). Afterwards, epoxy adhesives were poured covering half the length of the grooves. The CFRP rods were then inserted and pressed lightly to avoid the formation of openings between the rods and sides of the groove. Finally, more epoxy was added to fill the other half of the groove and the surface was leveled. Table 1 shows the specimens' designation and detailing. Further details of the experimental program can be found in Tanarslan (2011).[35]

The specimens were tested under cyclic loading applied incrementally at the free-end of the beam specimens as shown in Fig. 5. up to yielding of the flexural reinforcement or failure of the beam specimen.

DEVELOPMENT OF THE FE MODEL

Elements Description

The FE models were developed incorporating the same properties of the tested specimens described in the preceding section, and simulated using the commercial finite element software, ANSYS (2007).[36] Only one half of the tested beams were modeled, due to the symmetry in the transverse direction. Such decision reduced the overall computational time while maintained the same accuracy. The developed unstrengthened (BEAM-2) and strengthened (BEAM-3, BEAM-4, and BEAM-6) FE models are shown in Fig. 6.

The element used to model the concrete and adhesive was SOLID65 (ANSYS, 2007)[36] elements. SOLID65 element has 8-nodes, each node has three translational degrees of freedom in the x, y, and z directions and the element is capable of modeling the nonlinear behavior of materials and cracking in tension (ANSYS, 2007).[36] The steel and CFRP bars were modeled using LINK8 (ANSYS, 2007)[36] elements that has two nodes, each of which has 3 translational degrees of freedom and capable of elastic-plastic deformation and stress stiffening. The rigid concrete column support used in the experimental program didn't experienced any cracking during testing and thus was modeled using SOLID45 (ANSYS, 2007)[36] elements.

Bond-Slip and Cohesion Models

COMBIN14 (ANSYS, 2007)[36]elements were used to model the bond-slip between the longitudinal steel bars and concrete as well as the NSM CFRP bars and epoxy material. In addition, interface cohesion elements INTER205 (ANSYS, 2007)[36]are used herein to simulate the bond behavior between the epoxy and concrete surfaces.

The bond-slip behavior between the steel reinforcement and concrete, and NSM bar and concrete is based upon the first segment of the CEP-FIP (CEP-FIP, 1993)[37] model defined in Eq. 1. The stiffness (k) is presented in Eq. 1.

$$\tau = \tau_u \left(\frac{s}{s_u} \right)^{0.4} \qquad (1)$$

where τ is the bond stress at a given slip (s) in MPa (psi), τ_u is the ultimate bond stress in MPa (psi),and s_u is the ultimate slip in mm (in),corresponding to τ_u. The values of τ_u and s_u depend on the reinforcement bar type and surrounding material. The values of τ_u and s_u for the steel reinforcement embedded in concrete are $\sqrt{f'_c}$ MPa (psi), and 0.6 mm (0.02 in), respectively [36]. The values τ_u and s_u for NSM bars embedded in epoxy resin are 15.24 MPa (2210 psi) and 0.11 mm (0.004 in), respectively [20].

The stiffness of the COMBIN14 elements, *k* is given by Eq. 2 and is computed according to the CEP-FIB model [37] from the secant of Eq. 1. The derivation of the longitudinal stiffness (k) is reported by Nie et al. (2004)[38]

$$k = \frac{\pi}{s_u} p d_r N_r \tau_u \left(\frac{L_1 + L_2}{2} \right) \qquad (2)$$

where,
p is the horizontal distance between the bars, mm (in).
d_r is the diameter of reinforcements, mm (in).
N_r is the number of bars.
L_1 and L_2 are the lengths of two adjacent bar elements (LINK8), mm (in).

The bond between the epoxy material and concrete surfaces is modeled by placing interface INTER205 (ANSYS, 2007)[36] elements along the parameter of the axial vertical direction of the NSM groove as shown in Fig. 6. The employed interface element model (ANSYS, 2007)[36] is based on the cohesive zone model developed by Xu and Needleman (1994)[39]. The model requires the values of the maximum shear stress (τ_{max}) and its associated (s_u) to simulate the first increasing segment of the model. The model proceeds upon reaching τ_{max} with a softening response up to a maximum slip, assumed to be equal to $4s_u$.

Material Properties

The 28-day average cylindrical concrete compressive strengths was 25 MPa (3600 psi). For all specimens, standard deformed reinforcement steel bars with a measured characteristic strength of 414 MPa (60 ksi) and elastic modulus of 205 GPa were used for longitudinal reinforcement.

The tensile strength and modulus of elasticity of the CFRP and epoxy materials were, 2068 MPa (300 ksi), 30 MPa (4350 psi) and 124 GPa (17980 ksi), 3.8 GPa (551 ksi), respectively. The strengthening procedure includes the preparation of grooves, application of epoxy and bonding of CFRP reinforcements. A high viscosity epoxy, which avoids flowing away and dripping, was selected as an adhesive. Grooves were cut with the dimensions as function of reinforcement size (one and a half times the diameter of CFRP reinforcement).

The parabolic Hognestad model (Hognestad et al., 1955)[40] was used to model the concrete nonlinear behavior in compression. However, The William and Warnke (1975)[41] model implemented in the ANSYS (ANSYS, 2007)[36] concrete model is used to simulate concrete cracking. The cracking strength of concrete is taken as 3.1 MPa (450 psi). In modeling concrete cracking, the open and closed shear coefficient was taken as 0.2 based on finding from previous studies (Hawileh et al 2012, Hawileh et al. 2009)[42-43]. In addition, the cracking material model assumes a linear elastic behavior up to the tensile strength of the concrete material followed by a softening curve.

The flexural steel reinforcements are assumed to behave in an elastic-fully plastic pattern and failure of such reinforcement was defined using the Von-Misses failure criterion. However, the constitutive material model for the CFRP rods was modeled as a brittle elastic material. It should be noted that the concrete consecutive model is utilizing the isotropic hardening rule to degrade with the applied cyclic loading. The steel reinforcement material properties degrade using the kinematic hardening rule.

Failure Criteria

Yielding of the flexural steel reinforcement and debonding of the CFRP rod from the epoxy (CFRP bar pull-out) were considered as failure measures. Failure usually occurs once divergence in the FE solution is reached. The selected convergence criteria were based on force, displacement, and the tolerance limits of the ANSYS (ANSYS, 2007)[36] program. The force convergence criterion controls the solution of the analyzed models. It was found that convergence was difficult to achieve using the default tolerance value of 0.5% due to the nonlinear response and brittleness of the concrete elements with the associated large deflections. Thus, in order to obtain convergence of the equilibrium iterations, the force convergence tolerance limit was increased to 0.1 (typical range 0.05-0.25). The predicted load-carrying capacity along with its associated loading cycle is defined when the program diverges for a load increment of 10 N (2.24 lb) (Hawileh et al., 2010).[9] Upon divergence, the program presents an error message specifying that the model had a considerably large deflection, exceeding the displacement limitation of the ANSYS software (ANSYS, 2007)[36].

RESULTS AND DISCUSSION

Figure 7 shows the predicted and measured load-deflection response envelopes to validate the accuracy of the developed FE models. The deflection results are measured at the free end of the beam specimens and the response curves are developed by connecting the data values at the peaks of the loading cycles. Response envelopes were developed by connecting peak deflection points at the end of each loading and unloading cycles. Table 2 presents a comparison between the measured and predicted deflection at failure. In addition, Figure 8 shows the predicted and measured load-deflection hysteresis loops of the modeled beam specimens. It is clear from Table 2 that the test results of the strengthened specimens indicate an increase in the load-carrying capacity and ductility over that of the unstrengthened specimen. A maximum increase in the load-carrying capacity 78.9% was achieved. In addition, the strength of the specimen (BEAM-4) with smaller spacing was about 13.9% more than that of specimen BEAM-3 with larger spacing. Similarly, the strength of specimen BEAM-6 was 10.4% more than that of specimen BEAM-3 with smaller CFRP rod diameter.

It can be seen from Figures 7 and 8 that there is a good agreement between the measured and predicted results at all stages of cyclic loading. Table 2 also shows that the highest deviation of the predicted failure load is 3% from the measured experimental values. In addition, it is clear from Table 2 that the developed FE models tend to slightly overestimate the extreme tip deflection at failure by a maximum deviation of 8.98%. Hence, it could be concluded that the presented FE models, developed in this study are capable of predicting the behavior of such strengthened structures with great accuracy.

FURTHER RESEARCH

For future research, the authors will investigate experimentally and numerically further shear deficient beams strengthened with different types and schemes of NSM FRP reinforcement. This is intended to provide further validation to the developed FE models.

SUMMARY & CONCLUSIONS

In this research, four FE models are developed to simulate the behavior of shear deficient RC beams strengthened with NSM-CFRP reinforcement. The finite element predicted results were compared with the experimentally measured values that are published in the open literature. It could be concluded that:

- The proposed NSM strengthening technique using CFRP rods showed an increase in the load-carrying capacity and ductility over that of the unstrengthened shear deficient beam specimen.
- The predicted and experimental results load-deflection results presented in the response envelop curves are in good agreement for the four beam specimens.
- The predicted load-deflection hysteresis loops match the experimentally obtained results.
- The highest deviation of the predicted failure load from the measured experimental data is 3%.
- The developed FE models slightly overestimate the deflection at the beams' free end at failure by a maximum deviation of 8.98%.
- The developed models are reliable in investigating RC beams strengthened in shear via NSM CFRP bars.

LIST OF NOTATIONS

f'_c is the concrete compressive strength, MPa (psi)

τ_u is the ultimate shear stress, MPa (psi)

τ is the shear stress, MPa (psi)

S is the slip at shear stress (τ), mm (in)

S_u is the slip at ultimate shear stress, mm (in)

S_f is the slip at failure, mm (in)

k is the longitudinal stiffness of the COMBIN14 elements

p is the horizontal distance between the bars, mm (in)

d_r *is t*he diameter of reinforcements, mm (in)

N_r is the number of reinforcement bars,

L_1 and L_2 are the lengths of two adjacent reinforcement elements (LINK8) , mm (in)

f_t is the concrete tensile strength, MPa (psi)

w_c is the width of concrete section, mm (in)

REFERENCES

1. Chajes, M., Januska, T., Mertz, D., Thomson, T., Finch, W., “Shear Strengthening of Reinforced Concrete Beams Using Externally Applied Composite Fabrics,” ACI Structural Journal, V. 92, no. 3, pp. 295-303.

2. Norris, T., Saadatmanesh, H., Ehsani, M., “Shear and Flexural Strengthening of R/C Beams with Carbon Fiber Sheets”. J. of Structural Engineering, Vol. 123, no. 7, 1997, pp. 903-911.

3. Khalifa, A., and Nanni, A. “Rehabilitation of Rectangular Simply Supported RC Beams with Shear Deficiencies Using CFRP Composites,” Construction and Building Materials, Vol. 16, 2002, pp. 135-146.

4. Alzoubi, F., and Zhengliang, L., “Overview shear strengthening of RC Beams with Externally Bonded FRP Composites,” J. of Applied Sciences, Vol. 7, No. 8, 2007, pp. 1093-1106.

5. Lee, H., Ha, S., Afzal, M., “Finite element analysis of shear-deficient RC beams strengthened with CFRP strips/sheets,” Structural Engineering and Mechanics, Vol. 30, No. 2, 2008, pp. 247-261.

6. Tanarslan, M., Ertutar, Y., Altin, S., “The Effects of CFRP Strips for Improving Shear Capacity of RC Beams,” Journal of Reinforced Plastics and Composites, Vol. 27, No. 12, 2008, pp. 1287-1308.

7. Hawileh, R., Abdalla, J., Tanarslan, M., Naser, M., “Modeling of Nonlinear Cyclic Response of Shear-Deficient RC T-beams strengthened with Side Bonded CFRP Fabric Strips,” Computers and Concrete, An Int'l Journal, V. 8, No. 2, 2010, pp. 193-206.

8. Zhao, X., Al-Mahaidi, R., Rizkalla, S., “Bond characteristics between CFRP and steel plates in double strap joints,” The International Journal of Advanced Steel Construction, V. 1, No. 2, pp. 17-27.

9. Consenza, G., Manfredi, Realfonzo, R., “Behavior and modeling of bond of FRP bars to concrete,” ASCE, J Compos Constr., V. 2, 1997, pp. 40–51.

10. Riadh Al-Mahaidi, Kuan Lee, and Geoff Taplin, (2001) “Behavior and Analysis of RC T-Beams Partially Damaged in Shear and Repaired with CFRP Laminates “ASCE Structures: A Structural Engineering Odyssey, Proceedings of Structures Congress 2001.

11. Sabrina, A., Xiao-Ling, Z., Al-Mahaidi R., “Bond–slip models for double strap joints strengthened by CFRP,” Composite Structures, V. 92, 2010, pp. 2137–2145.

12. Al-Tamimi, K., Hawileh, R., Abdalla, J., Rasheed, H., “Effects of Ratio of CFRP Plate Length to Shear Span and End Anchorage on Flexural Behavior of SCC R/C Beams,” J. Compos. for Constr., ASCE, 2011, In Press.

13. Naser, M., Hawileh, R., Abdalla, J., and Al-Tamimi, A., "Bond Behavior of CFRP Cured Laminates: Experimental and Numerical Investigation." In Press, ASME Journal of Engineering Materials and Technology, 2010.

14. Ombres, L., “Prediction of intermediate crack debonding failure in FRP strengthened reinforced concrete beams,” Compos Struct., V. 92, No. 92, 2010, pp. 322–9.

15. Lu, F., and Ayoub, A.S., “Effect of bond properties on the behavior of FRP-strengthened RC girders subjected to monotonic and cyclic loads”, accepted for publication, ACI Special Publication SP-253, (2008).

16. You YM, Ayoub A, Belarabi A. Non-linear finite element analysis of PC girders strengthened in shear with FRP composites. In: Fiber reinforced polymer reinforcement for concrete structures. Proceedings of the 9th international symposium, University of Adelaide, Sydney, Australia; 2009.

17. De Lorenzis, L., and Teng, J., "Near-surface mounted FRP reinforcement: an emerging technique for strengthening structures.," J Compos, Part B, V. 38, 2007,pp. 119–43.

18. De Lorenzis, and L., Nanni, A., "Bond between near-surface mounted FRP rods and concrete in structural strengthening," ACI Struct J. V. 99, No. 2,2002, pp. 123–133.

19. Kotynia, R., "Bond between FRP and concrete in reinforced concrete beams strengthened with near surface mounted and externally bonded reinforcement," Constr Build Mater., In Press.

20. Anwarul, "Effective methods of using CFRP bars in shear strengthening of concrete girders," Eng Struct., V. 31, No. 3, 2009, pp. 709–14.

21. Al-Mahmoud, F., Castel, A., François, R., Tourneur, C., "Effect of surface preconditioning on bond of carbon fibre reinforced polymer rods to concrete," Cem Concr Compos., v. 2, No. 9, 2007, pp. 677–89.

22. Hassan, T., and Rizkalla, S., "Bond mechanism of near-surface-mounted fiber reinforced polymer bars for flexural strengthening of concrete structures," ACI Sturct J., V. 101, No. 6, 2004, pp. 830–9.

23. Rasheed, H., Harrison, R., Peterman, R., Alkhrdaji, T., "Ductile strengthening using externally bonded and near surface mounted composite systems," Compos Struct., V. 92, No. 10, 2010, pp. 2379–90.

24. Hawileh, R., "Nonlinear finite element modeling of RC beams strengthened with NSM FRP rods," Construction and Building Materials., V. 27, No. 9, 2011, pp. 461–471.

25. Taljsten, B., Carolin, A., Nordin, H., "Concrete structures strengthened with near surface mounted reinforcement of CFRP," Adv Struct Eng., V. 6, No. 3, 2003, pp. 201–13.

26. El-Hacha, R., and Rizkalla, S. H., "Near-surface-mounted fiber-reinforced polymer reinforcements for flexural strengthening of concrete structures," ACI Struct J., v. 105, No. 5, 2004; pp. 717–26.

27. Al-Mahmoud, F., Castel, A., François, R., Tourneur, C., "Strengthening of RC members with near-surface mounted CFRP rods," Compos Struct, V. 91, 2009, pp. 138–47.

28. Badawi, M., and Soudki, K.., "Flexural strengthening of RC beams with prestressed NSM CFRP rods – experimental and analytical investigation," Constr Build Mater. V. 23, No. 10, 2009, pp. 3292–300.

29. De Lorenzis, and L., Nanni, A., "Strengthening of reinforced concrete beams with NSM fiber-reinforced polymer rods," ACI Struct J, V. 91, No. 1, 2001, pp.60–8.

30. De Lorenzis and L, Nanni A. Characterization of FRP rods as near-surface mounted reinforcement. J Compos Constr 2001;5(2):114–21.

31. Dias, J., and Barros, J., "Performance of reinforced concrete T beams strengthened in shear with NSM CFRP laminates," Eng Struct., V. 32, No. 2, pp. 373–84.

32. Rizzo, A., and De Lorenzis, L., "Modeling of debonding failure for RC beams strengthened in shear with NSM FRP reinforcement," Constr Build Mater., V. 23, No. 4, pp. 1568–77.

33. Capozucca, R., "Static and dynamic response of damaged RC beams strengthened with NSM CFRP rods," Compos Struct., V. 91, No. 3, pp. 237–48.

34. Oudah, F., and El-Hacha, R., "Performance of RC Beams Strengthened Using Prestressed NSM-CFRP Strips Subjected to Fatigue Loading," J. Compos. for Constr. ASCE, 2012, InPress.

35. Tanarslan, H., "The effects of NSM CFRP reinforcements for improving the shear capacity of RC beams," Constr Build Mater., V. 25, No. 5, 2011pp. 2663–73.

36. ANSYS. Finite Element Computer Code. Version 11. ANSYS, Inc. Canonsburg, PA, 2007.

37. Comite Euro-International du Beton (CEB-FIP). CEB-FIP model code 1990. Bulletin D'Information No. 213/214 (Concrete Structures), Lausanne, Switzerland; 1993.