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Strengthening of RC Beams with Large Openings in Shear by CFRP Laminates: 2D Nonlinear FE Analysis

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***Abstract*—**To date, theoretical studies concerning the Carbon Fiber Reinforced Polymer (CFRP) strengthening of RC beams with openings have been rather limited. In addition, various numerical analyses presented so far have effectively simulated the behaviour of solid beam strengthened by FRP material. In this paper, a two dimensional nonlinear finite element analysis is presented to validate against the laboratory test results of six RC beams. All beams had the same rectangular cross-section geometry and were loaded under four point bending. The crack pattern results of the finite element model show good agreement with the crack pattern of the experimental beams. The load midspan deflection curves of the finite element models exhibited a stiffer result compared to the experimental beams. The possible reason may be due to the perfect bond assumption used between the concrete and steel reinforcement.

***Keywords*—**CFRP, large opening, RC beam, strengthening

I. INTRODUCTION

OPENINGS are usually found in floors due to staircase, elevators, ducts and pipes. Openings are provided through the floor beams to facilitate the passage of utility pipes and service ducts. These service ducts are to accommodate essential services such as conduits, power supply, water and drainage pipes, ventilation system, air-conditioning and network system access or even for inspection purposes in beam structures. These arrangements of building services resulted in a significant reduction in headroom, minimize the storey height and results in major savings in material and construction cost especially in multi-storey buildings and tall building construction. [1].

However, the presence of opening in the web of a reinforced concrete beams resulted in many problems in the beam behavior including reduction in beam stiffness, excessive cracking and deflection and reduction in beam capacity. Furthermore, inclusion of openings leads to high stress concentration around the openings especially at the opening corners. The reduction of area in the total cross sectional dimension of a beam changes the simple beam behavior to a more complex one [2], [3].

Strengthening of beams with openings primarily depends on the condition of building services either pre-planned or post-planned. In the case of pre-planned, the sizes and locations of openings are known in advance during the design stage. Thus, sufficient strength and serviceability of beams with opening can be ensured before construction. Although no specific guidelines or standards are provided in any of the major codes, the design engineer can extract the necessary information and guidelines reported in the literatures [1]. To restore the original structural capacity of beam due to openings, the available literatures [4], [5] presented the role of diagonal bars as corner reinforcement and inclined reinforcement for strengthening around the opening [6]. Steel reinforcement provided at the upper and lower chords and diagonal reinforcement placed around the opening are considered as internal strengthening.

For the case of post-planned, it involves drilling of openings in an existing structure. Problems may arise during the laying process of utility pipes and ducts. During the process, M&E engineers request to provide or re-locate the position of opening to simplify the arrangement of pipes and ducts which is not considered in the design. If openings are to be provided in existing beams especially in the shear zone, sufficient treatment and attention is needed to ensure the safety and serviceability of the structure. In general, shear failure of concrete structures is catastrophic due to the brittle nature and the fact of no advance warning prior to failure. Thus, in an existing beam, strengthening externally around the opening is crucial with the use of external reinforcing material, such as steel plates or by fiber reinforced polymer (FRP) materials.

The application of FRP as external reinforcement to strengthen concrete beams has received much attention from the research community. The most common type of FRP in the concrete industry is made with carbon, aramid or glass fibers. The FRPs are usually in the form of sheets, strips, wraps or laminates. These materials were applied by bonding it to the external surfaces of the beams with various configurations and layouts. The use of FRPs to repair and rehabilitate damaged steel and concrete structures has become increasingly attractive due to its well-known good mechanical properties, particularly with its high strength to weight ratio and low weight. Numerous experimental studies have shown that externally bonded FRP laminates could significantly increase a member's stiffness and load carrying capacity, enhance flexural and shear capacities, providing confinement and ductility to compression structural members and also controls

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the propagation of cracks [7], [8]. Due to many advantages of using FRPs as external reinforcement for reinforced concrete members, various extensive experimental researches have been conducted in the area of FRP flexural and shear strengthening of solid beams without opening. On the contrary, the numerical studies to date for this application have been rather limited.

The use of CFRP to strengthen RC beams with openings has received much attention from researchers focusing on the experimental studies [9]-[12]. However, the numerical investigations of RC beam with openings are somewhat limited, particularly with the use of finite element method. Madkour [8] investigated on the non-linear behaviour of strengthened reinforced concrete beams with rectangular web openings with a new numerical implementation of damage–non linear elastic theory. The proposed theoretical approach analyzed the efficiency of applying CFRP laminates as an external strengthening technique in a three dimensional domain to determine the effective and economic strengthening configuration. Meanwhile, Pimanmas [13] studied the strengthening of reinforced concrete beams with circular and square opening by externally installed FRP rods. A numerical analysis was conducted using a finite element program and validated with the experimental results.

In this investigation, a non-linear finite element program, ATENA is used to validate the tested beams from the experiment [14]. Comparisons of the predicted results with the experimental data are presented.

II. EXPERIMENTAL PROGRAM

Experimental results were obtained from the experimental studies carried out [14]. Six reinforced concrete beams were loaded with a four point loading configuration with an effective length of 1800 mm, and distance between loads of 500 mm. All beams were 300 mm high, 120 mm wide and 2000 mm long. The effective depth, d to the main reinforcement was 280 mm. The longitudinal reinforcement consisted of two 12 mm ø bar for tension and two 10 mm ø bar for compression. Shear reinforcement was sufficiently provided and consisted of ø 6 mm c/c 300 mm, as seen in Fig. 1.

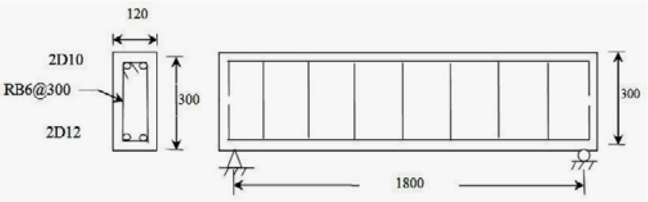


Fig. 1 Beam reinforcement details (Unit:mm)

Summary of the tested beams is listed in TABLE I. The RC beams consisted of two solid control beams, two un-strengthened beams with large square openings in shear region at distance 0.5d and d away from the support; and the remaining beams were similar to the un-strengthened beams, except that the large square openings in shear were strengthened by CFRP laminates. The size of the large square opening was 210 mm x 210 mm. The strengthening configuration with CFRP laminates was fully wrapped around the large square openings, as depicted in Fig. 2. The CFRP laminates with a thickness of 1.4 mm and width of 100 and 45 mm were used.

TABLE I
BEAM SPECIMENS

	Opening		
Beam	Shape	Location	Conditions
B1	Control	NA	-
B2	Control	NA	-
B3	Square	0.5d	Without Strengthening
B4	Square	d	Without Strengthening
B5	Square	0.5d	Strengthening
B6	Square	d	Strengthening

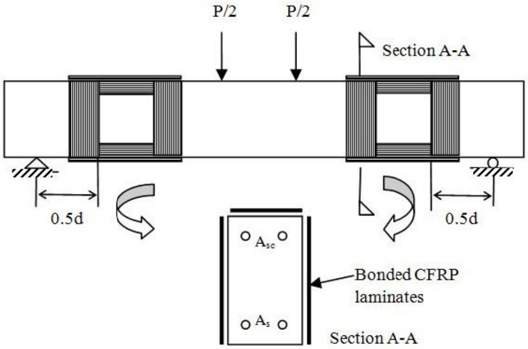


Fig. 2 CFRP strengthening configurations

III. NON-LINEAR FINITE ELEMENT ANALYSIS

In this study, a two dimensional model based on the finite element package, ATENA is adopted. The numerical predictions are compared to the test data.

A. Material Models for Concrete, Steel and FRP

For the concrete, the constitutive model of the finite element package ATENA [15] is used. In this approach, the elastic constants are derived from a stress-strain function known as equivalent uniaxial law which covers the complete range of the plane stress behaviour in tension and compression. For the stress-strain relationship of the concrete in compression, the formula recommended by CEB-FIP Model Code 90 has been adopted for the ascending branch. The elastic limit of the maximum concrete compressive strength is reached followed by a nonlinear behaviour until the maximum concrete strength is reached. The softening law in compression is linearly descending. In this case, the behaviour of concrete softens until the concrete crushing occurs. An ascending-descending behaviour for the concrete in tension is used. The slope of the ascending branch is equal to the concrete modulus of elasticity. In the descending branch of the stress-strain curve, a fictitious crack model based on a crack-opening law and fracture energy is applied, where the cracks occur when the principal stress exceeds the tensile strength. In this study, rotated crack model is adopted based on the smeared crack approach. Poisson's ratio for concrete was assumed to be 0.2. Fig. 3 shows the uniaxial stress strain law for concrete.

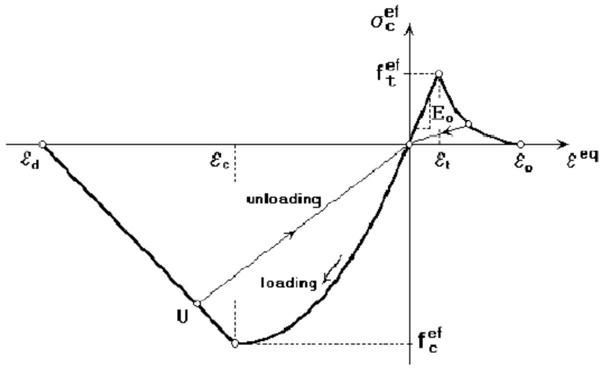


Fig. 3 Uniaxial stress strain law for concrete

The steel is represented by multi-linear law which consists of four lines as shown in Fig. 4. This law allows a linear modelling all four stages of steel behaviour: elastic state, yield plateau, hardening and fracture. The stress and strain of the steel reinforcement were measured in the experimental study. These values were used in the FEM model. A Poisson's ratio of 0.3 was used for steel reinforcement. The bond between steel reinforcement and concrete was assumed as a perfect bond. A linear elastic orthotropic constitutive relation is assumed for the FRP composites. A rupture point on the stress strain relationship for the fiber direction defines the ultimate stress and strain of the FRP.

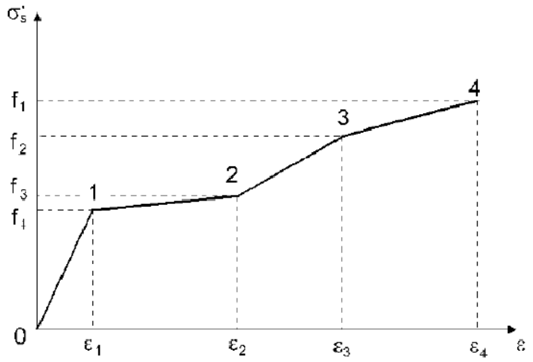


Fig. 4 Multi-linear stress strain law for reinforcement

B. FRP/Concrete Interface

A bond slip model developed by Lu et al. [16] shown in Fig. 5 is adopted. This bond slip model is considered as an accurate bond slip model that can be incorporated into finite element analysis [17]-[20]. The mechanical behaviour of the FRP/concrete interface is modeled as a relationship between the local shear stress, τ and relative displacement, s between the CFRP laminate and the concrete. The τ –s relationship is given by [17]

$$\tau = \tau_{max}\sqrt{s/s_o} \qquad \text{if } s \leq s_o \tag{1}$$

$$\tau = \tau_{max}\exp[-\alpha\,(s / s_o - 1)] \quad \text{if } s \geq s_o \tag{2}$$

The maximum bond strength τ_{max} and the corresponding slip s_o are governed by the tensile strength of the concrete f_t and a width ratio parameter β_w as follows:

$$\tau_{max} = \quad 1.5\beta_w f_t \tag{3}$$

$$s_o = 0.0195\beta_w f_t \tag{4}$$

The parameter β_w is defined in terms of the CFRP laminate width b_f and the width of the beam b_c as follows:

$$\beta_w = \sqrt{\frac{2.25 - b_f/b_c}{1.25 + b_f/b_c}} \tag{5}$$

The area under the τ –s curve indicates the interfacial fracture energy G_f which corresponds to the energy per unit bond area required for complete debonding; which is calculated as follows:

$$G_f = 0.308\beta^2_w\sqrt{f_t} \tag{6}$$

The difference in relative displacement between the concrete and CFRP laminate represents the slip at the interface. The interface elements are considered to act only in the directions parallel to the main fiber reinforcements.

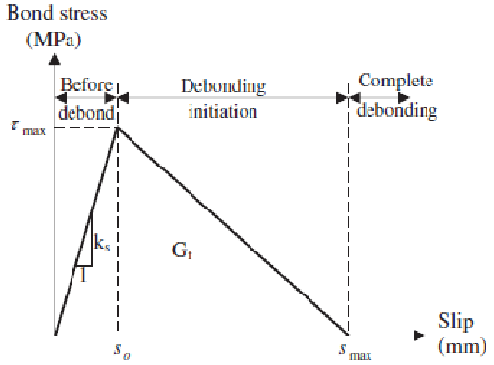


Fig. 5 Bond slip model

C. Geometrical Modeling

To represent the concrete, SBETA material model for two dimensional plane stress elements was used. The tensile behaviour of concrete is modelled by nonlinear fracture mechanics combined with the crack band method, in which the smeared crack concept is adopted. The steel reinforcement, stirrups and CFRP laminates were modelled by a single straight line in a discrete manner by bar reinforcement elements. Full bond is assumed between the steel reinforcement and the surrounding concrete. The bond slip relation of CFRP and concrete was defined in bond for reinforcement material and assigned in the properties of discrete reinforcement bar of CFRP.

D. Nonlinear Solution

In this study, a displacement-controlled incremental loading method was adopted with an iterative solution procedure based on the Newton-Raphson method was employed.

IV. NUMERICAL RESULTS AND DISCUSSION

The results presented in the following sections are given in terms of load versus mid-span deflection curve relationships and crack patterns.

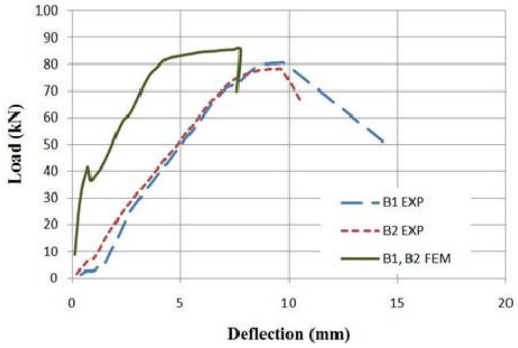
A. Load Deflection Curves

The load deflection curves obtained for control beams, un-strengthened and strengthened beams with large square openings in shear region are illustrated in Fig. 6.

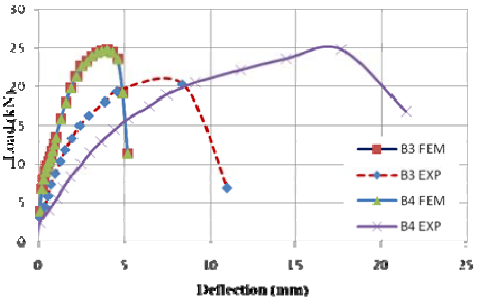
Fig. 6a depicts the load deflection curves of control beams, B1 and B2 from experiments and FEM analysis. The control beams were solid beams without any openings. Similar trend of load deflection curves was observed between FEM and experimental results for the control beam. The FEM analysis predicts the beam to be stiffer and stronger. The possible cause for the difference in stiffness between the control beam in the experiment and the finite element analysis is due to the assumed perfect bond between concrete and steel reinforcement.

For the un-strengthened beams with large square openings in shear region at distance 0.5d and d away from the support, B3 and B4 which are shown in Fig. 6b, the results of both FEM models are close to identical, both demonstrated a stiffer trend than the experimental results. After the cracks started to appear, the perfect bond models increasingly overestimate the stiffness of the beam. Similar as in the control beams, the possible reason may be due to the assumed perfect bond condition between concrete and steel reinforcement.

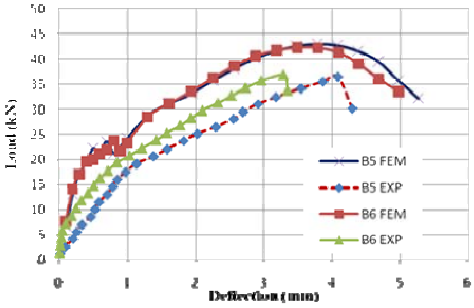
The load deflection curves of the strengthened beams with CFRP fully wrapped around the large square openings in shear region at distance 0.5d and d away from the support, B5 and B6 are illustrated in Fig. 6c. After incorporating the bond slip model which defined in the discrete reinforcement properties of CFRP, almost similar trend was obtained between both FEM models compared to their respective experimental results. At early stage before initial crack, it was observed that the stiffness of beam B6 in finite element model are closely matching to the stiffness of experimental beam. Likewise, the second point of cracking at 1 mm deflection, a slight drop was observed in all FEM and experimental curves. In the range of yielding of reinforcement to failure, the load deflection curves of both FEM models were comparable with the load deflection curves of both experimental results.



(a) Control beams



(b) Un-strengthened beams

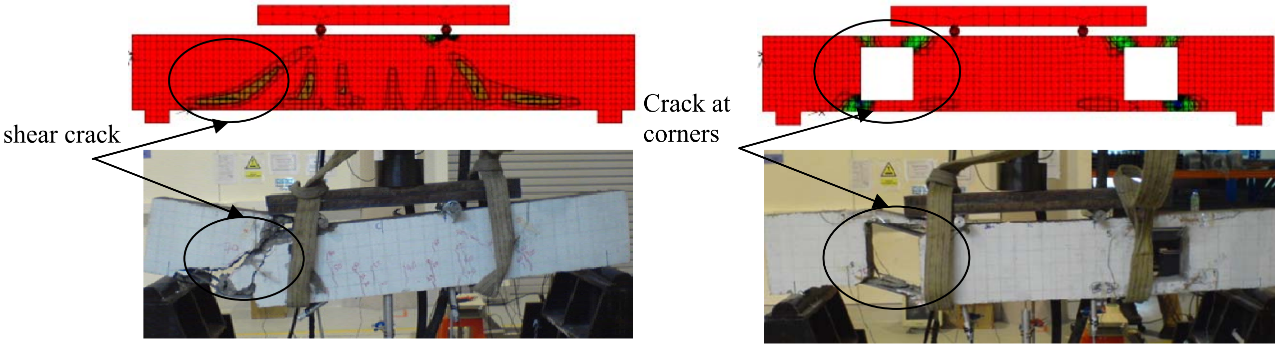


(c) Strengthened beams

Fig. 6 Load deflection curves of beams, obtained by experiment and finite element method

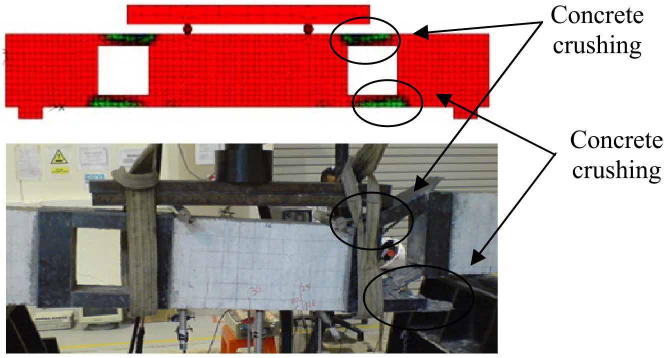
B. Crack Patterns

Fig. 7 shows a comparison between principal strain obtained from the finite element analysis and crack patterns obtained from the experiments for the control beam B1; un-strengthened beam with large square openings in shear region at distance d from the support, B4 and strengthened beam with CFRP fully wrapped around the large square openings in shear region at distance d from the support, B6. The cracks obtained in the experiments and in the simulations are similar. This indicates that the model can predict the mechanisms of fracture in the beams.



(a) Control beam

(b) B4



(c) B6

Fig. 7 Comparison between principal strain from FEM analysis and crack pattern from experiments

V. CONCLUSION

In this study, a two dimensional nonlinear finite element analysis was conducted to validate the results of the experimental beams. It is shown that the simulation is capable of predicting the crack pattern and load deflection relationship of beams. The predicted crack pattern in FEM shows good agreement with the crack pattern of the experimental beams. Meanwhile, the load midspan deflection curves of the finite element models exhibited a stiffer result compared to the experimental beams. The possible reason may be due to the perfect bond assumption used between the concrete and steel reinforcement.

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REFERENCES

[1] M.A. Mansur and K.H. Tan, Concrete Beams with Openings: Analysis and Design, CRC Press, 1999.

[2] Mansur M.A., "Design of Reinforced Concrete Beams with Web Openings," Proceedings of the 6th Asia-Pacific Structural Engineering and Construction Conference (ASPEC 2006), 5-6 September 2006, Kuala Lumpur, Malaysia., 2006, pp. 104-120.

[3] M.A. Mansur, L.M. Huang, K.H. Tan, and S.L. Lee, "Deflections of reinforced concrete beams with web openings," ACI Struct. J., vol. 89, no. 4, pp. 391-397, Jul-Aug. 1992.

[4] M.A. Mansur, K.H. Tan, and S.L. Lee, "Design method for reinforced concrete beams with large openings," ACI Struct. J., vol. 82, no.4, pp. 517-524, Jul-Aug. 1985.

[5] K.H. Tan, M.A. Mansur, and W. Wei, "Design of reinforced concrete beams with circular openings," ACI Struct. J., vol. 98, no. 3, pp. 407-415, May-June, 2001

[6] K.H. Yang and A.F. Ashour, "Inclined reinforcement around web opening in concrete beams," Proceedings of the ICE-Structures and Buildings, vol. 160, no. 3, 2007, pp. 173-182.

[7] E. Ferrier, S. Avril, P. Hamelin, and A. Vautrin, "Mechanical behavior of RC beams reinforced by externally bonded CFRP sheets," Materials and Structures, vol. 36, no.8, pp. 522-529, Oct. 2003.

[8] H. Madkour, "Non-linear analysis of strengthened RC beams with web openings," Proceedings of the ICE-Structures and Buildings, vol. 162, no.2, 2009, pp. 115-128.

[9] M.A. Mansur, K.H. Tan, and W. Wei, "Effects of creating an opening in existing beams," ACI Struct. J., vol. 96, no.6, pp. 899-906, Nov-Dec 1999.

[10] H. A. Abdalla, A. M. Torkey, H.A., Haggag, and A.F. Abu-Amira, "Design against cracking at openings in reinforced concrete beams

strengthened with composite sheets". J Compos Struct., vol. 60, no. 2, pp. 197-204, May 2003.

[11] S.M. Allam, "Strengthening of rc beams with large openings in the shear zone". J Engr, Alexandria, vol. 44, no. 1, pp. 59-78. 2005

[12] T. El Maaddawy and S. Sherif, "FRP composites for shear strengthening of reinforced concrete deep beams with openings". J Compos Struct., vol. 89, no. 1, pp. 60-69, Jun 2009.

[13] A. Pimanmas, "Strengthening R/C beams with opening by externally installed FRP rods: behavior and analysis," J Compos. Struct., vol. 92, no. 8, pp. 1957-1976, Jul. 2010.

[14] S.C. Chin, N. Shafiq and M.F. Nuruddin, "Strengthening of RC beams with large openings in shear by CFRP laminates: Test results," International Conference on Civil, Offshore and Environmental Engineering, 12-14th June, Kuala Lumpur, Malaysia, 2012, (Submitted).

[15] V. Cervenka, L. Jendele, and J. Cervenka, "ATENA Program Documentation Part 1 Theory," Cervenka Consulting Ltd, Prague. 2010.

[16] X.Z. Lu, J.G. Teng, L.P. Ye, and J.J. Jiang, "Bond – slip models for FRP sheets / plates bonded to concrete," Engineering Structures, vol. 27, no. 6, pp. 920-937, Apr. 2005.

[17] R. Kotynia, H.A. Baky, K.W. Neale, M. Asce, and U.A. Ebead, "Flexural strengthening of rc beams with externally bonded CFRP systems :test results and 3d nonlinear FE analysis," J. Compos. Constr.,vol. 12, no.2, pp. 190-201, Mac-Apr. 2008.

[18] Y.T. Obaidat, S. Heyden and O. Dahlblom, "The effect of CFRP and CFRP/concrete interface models when modelling retrofitted RC beams with FEM", J Compos. Struct. vol. 92, no. 6, pp. 1391-1398, May 2010.

[19] A., P. Godat, Labossière, and K. W. Neale., "Numerical investigation of the parameters influencing the behaviour of FRP shear-strengthened beams". Constr. and Build. Mat.,2011. In Press

[20] A. Godat, K.W. Neale, and P. Labossière, "Towards modelling FRP shear-strengthened reinforced concrete beams," Proceedings of the 8th International Symposium on Fiber Reinforced Polymer Reinforcement for Concrete Structures", University of Patras, Patras, 2007.