Jurnal
Teknologi

Full Paper

FINITE ELEMENT MODELLING OF 2-SPAN CONTINUOUS RC BEAMS SHEAR STRENGTHENED AND SHEAR REPAIRED WITH CFRP STRIPS

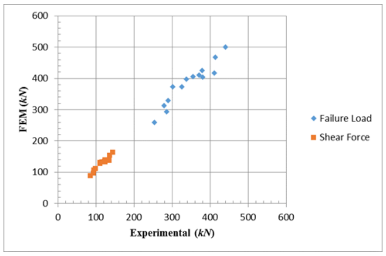
Abdul Aziz Abdul Samad[a,b], Noorwirdawati Ali[a], Noridah Mohamad[a,b], J. Jayaprakash[b], Tuan Duc Ngo[c], Priyan Mendis[c]

[a]Department of Structural and Materials Engineering, Faculty of Civil and Environmental Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Batu Pahat, Johor, Malaysia
[b]Department of Civil Engineering, The University of Nottingham Malaysia Campus, 43500 Semenyih, Selangor, MALAYSIA
[c]Department of Infrastructure Engineering, The University of Melbourne, Parkville, Victoria 3000, Australia

Article history
Received
5 August 2015
Received in revised form
17 December 2015
Accepted
13 March 2016

*Corresponding author
azizs@uthm.edu.my

Graphical abstract



Abstract

Strengthening of reinforced concrete (RC) continuous beams in shear have received very little attention among researchers even though most existing structures are in the form of continuous condition such as part of a floor-beam system. Therefore, in order to address the gap, a study on shear strengthening and shear repair of reinforced concrete continuous beam using Carbon Fibre Reinforced Polymer (CFRP) strips was conducted [15]. The validation of the experimental results was conducted with a simulation study using a finite element software ATENA v4 [16]. The research variables were number of layers of CFRP strips (one or two layers), wrapping schemes (four sides or three sides) and orientation of CFRP strips (0/90 or 45/135 degree's). From the analysis of the finite element results, ATENA shows it has successfully simulated the shear behaviour of strengthened and repaired of 2-span continuous RC beams externally bonded by CFRP strips.

Keywords: Finite Element Model, ATENA, Shear Strengthening and Shear Repair

Abstrak

Pengukuhan rasuk konkrit bertetulang (RC) berterusan dalam ricih telah mendapat perhatian yang rendah antara penyelidik, walaupun kebanyakan struktur yang sedia ada adalah dalam bentuk berterusan seperti sebahagian daripada sistem rasuk lantai. Oleh yang demikian, untuk mengatasi jurang tersebut, satu kajian mengenai pengukuhan ricih dan ricih pembaikan Konkrit Bertetulang rasuk berterusan menggunakan jalur Karbon Fiber Bertetulang Polimer (CFRP) telah dijalankan [15]. Proses pengesahan keputusan eksperimen telah dijalankan melalui kajian simulasi dengan menggunakan perisian unsur terhingga ATENA v4 [16]. Pembolehubah kajian adalah bilangan lapisan CFRP jalur (lapisan satu atau dua), skim balutan (empat sisi atau tiga sisi) dan orientasi jalur CFRP (0/90 atau 45/135 darjah).Dari analisa-analisa keputusan unsur terhingga, ATENA telah membuktikan bahawa ia telah berjaya menjalankan simulasi pengukuhan rasuk konrit bertetulang berterusan 2-span dalam ricih dengan jalur CFRP.

Kata kunci: Kaedah Unsur Terhingga, ATENA, Pengukuhan Ricih dan Pemulihan Ricih,

1.0 INTRODUCTION

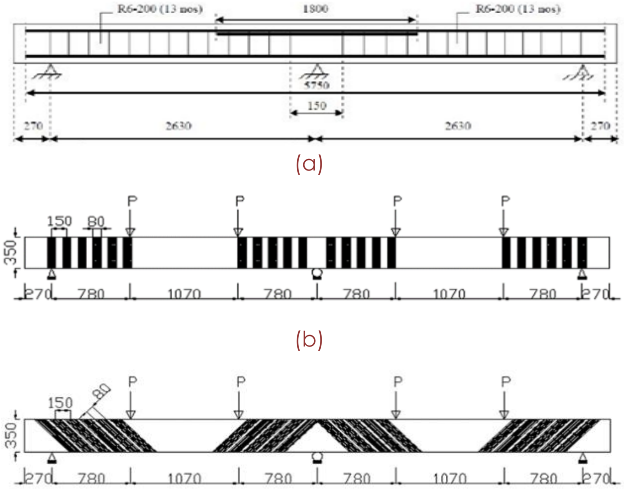
In order to strengthen or repair structures with shear defect, composite materials from Carbon Fiber Reinforced Polymer (CFRP) sheets [1] and externally bonded along the depth of the beam or perpendicular to the potential shear cracks have been commonly used. Studies have also shown that shear strengthening has improved the ductility of reinforced concrete (RC) beams because of the partial confining provided by the strengthening systems [2]. Generally, most investigations carried out experimentally by previous researchers focused on shear strengthening of RC beams that are simply supported. This was in fact acknowledged by ACI Committee 440 [3] which stated that existing studies and models have not been totally confirmed for shear strengthening in areas subjected to combine high flexural and shear stresses or in region of negative moment. This is true because most existing RC beams are cast monolithically and are usually part of a floor-beam system. For that reason, CFRP has been seen as a practical and flexible solution to overcome such problems and to potentially extend the service life of existing concrete structures. Studies have also shown that the shear strength capacity and ductility of RC beams strengthened or repaired by CFRP strips have been influenced by its wrapping schemes, the orientation angle, anchoring system, and its spacing of CFRP strips [4]-[14].

2.0 EXPERIMENTAL WORK

To fulfil this gap, a series of full scale testing of 2-span continuous RC beams subjected to four point bending test was conducted by [15]. The test focuses on the strengthening and repair of continuous beams wrapped with externally bonded CFRP strips within its shear span. Nine full scale 2-span continuous RC beams were fabricated and tested at the Heavy Structures Engineering Laboratory, Universiti Tun Hussein Onn Malaysia (UTHM). All beams have similar size of 150 mm width, 350mm depth and 5800mm of total span. The beams are classified into three; (1) Control Beam (Beam 1-0), (2) Group Beam 1 (Beam 1-1, Beam 1-2, Beam 1-3 and Beam 1-4) and (3) Group Beam 2 (Beam 2-1, Beam 2-2, Beam 2-3 and Beam 2-4). All beams are subjected to shear span to effective depth ratio, a_v/d, of 2.5. The strengthening and repair was conducted by applying CFRP strips of 80mm width at 150mm intervals. Beam specimens in Group Beam 1 are initially strengthened beams whilst Group Beam 2 were initially pre-loaded (upto 70-80% of the ultimate load) to generate pre-cracks and followed by repair with the CFRP strips. Table 1 illustrates the detail specification of all beam specimens. The beams have been design to fail in shear and are therefore typical reinforcement details as shown in Figure 1(a). The externally bonded CFRP strips are orientated in 0/90 and 45/135 degree as shown in Figure 1(b) and 1(c) respectively.

Table 1 Details of experimental beam specimens

Group Beams	Beam Specimens	a_v/d	Wrapping Schemes		
			CFRP Orientation (degree)	CFRP Wrap	No. of CFRP Layer
Control Beam	Beam 1-0	2.5	-	-	-
1	Beam 1-1	2.5	0/90	4-sides	1
	Beam 1-2		0/90	3-sides	1
	Beam 1-3		0/90	4-sides	2
	Beam 1-4		0/90	3-sides	2
2	Beam 2-1	2.5	0/90	4-sides	1
	Beam 2-2		0/90	3-sides	1
	Beam 2-3		45/135	4-sides	1
	Beam 2-4		45/135	3-sides	1



(a)

(b)

(c)

Figure 1 (a) Detail reinforcement and typical test set-up with a_v/d=2.5, CFRP orientation (b) 0/90 and (c) 45/135 degree

3.0 FINITE ELEMENT MODELLING

3.1 ATENA

A simulation study using ATENA [16], a commercially available software product for non-linear finite element (FEM) analysis of reinforced concrete structures, was conducted to validate the experimental work by [15]. The program has the capacity to simulate the real behaviour of concrete and reinforced concrete structures including concrete cracking, crushing and reinforcement yielding.

3.2 Concrete Model

The material model for concrete used in ATENA [16] is SBETA model. SBETA is a fracture-plastic constitutive material model available in ATENA and it is suitable for brittle material such as concrete. The material model SBETA includes the behaviour of concrete on non-linear behaviour in compression, fracture of concrete in tension (based on the non-linear fracture mechanics), biaxial strength failure criterion, and reduction of compressive strength after cracking, tension stiffening effect and reduction of the shear stiffness after cracking. In this model, two crack models were used; fixed crack direction and rotated crack direction.

In the basic assumptions of the strain, stress and material stiffness, the formulation of constitutive relations is considered in the plane stress state. The material properties such as cracks or distributed reinforcement uses a smeared approach where material properties defined for a material point are valid within the entire finite element. The constitutive model is based on the stiffness and is described by the equation of equilibrium in a material point:

$$s = De,\ \ s = \{\sigma_x, \sigma_y, \tau_{xy}\}',\ \ e = \{\varepsilon_x, \varepsilon_y, \gamma_{xy}\}'$$

Where s, D and e are stress vector, material stiffness matrix and strain vector respectively. The strains are common for all materials. The stress vector, s, is related to the total cross section area. The matrix D has a form of the Hooke's law of either isotropic or orthotropic material. For isotropic material (un-cracked concrete), the principal directions of the stress and strains are identical whilst for anisotropic material (cracked concrete), they can be different. For the bond between concrete and reinforcement, perfect bond is assumed within the smeared concept. No bond slip can be directly modelled except for the one included inherently in the tension stiffening.

In order to simulate cracking of the concrete, Rankine failure criterion, exponential softening and rotated or fixed crack model based on the smeared crack concept was adopted. In this model, the strains for the smeared model are calculated for each element separately followed by the application of the crack-opening law. The material model is based on elastic, plastic and fracturing strain components. The compressive behaviour of concrete for crushing is modelled using a plasticity-based model. The stress-strain and failure laws governed by the model are shown in Figure 2.

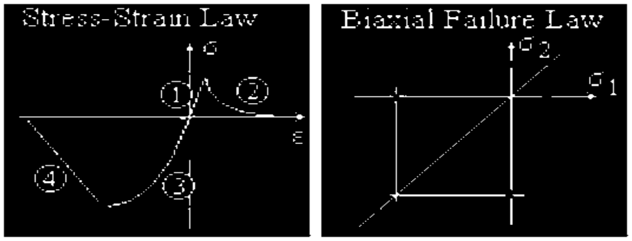
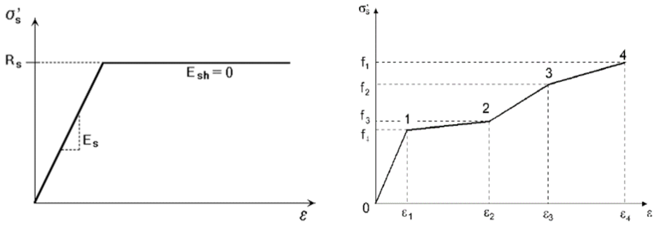


Figure 2 Stress-strain and biaxial failure law [16]

3.2 Reinforcement

Reinforcement can be modelled in two forms: discrete and smeared. Discrete reinforcement is in form of reinforcing bars and is modelled by truss element. The smeared reinforcement is a component of composite material and can be considered either by a single material in the element under consideration or as one of the more such constituents. The bi-linear law, elastic-perfectly plastic, is assumed as shown in Figure 3(a) where E_s is the elastic modulus of steel and E_{sh} is hardening modulus. However, for the multi-linear law, it consists of four lines as shown in Figure 3(b). This law allows modeling all four stages of steel behaviour which are elastic stage, yield plateau, hardening and fracture. The multi-line is defined by four points which can be specified by user. Both bi-linear and multi-linear law can be used for discrete or smeared reinforcement. The main reinforcement and stirrups adopted the discrete reinforcement which in the form of reinforcing bars and modelled using truss element. In this study, smeared reinforcement was used to model the CFRP materials because the material was at the vertical part of the model and a non-circular section. For smeared reinforcement, two additional parameters are required; reinforcement ratio and the direction angle, β. Bilinear with hardening was used as the material properties because the other options in ATENA do not feature any strain limit. The bond between CFRP and concrete was taken as perfect connection.

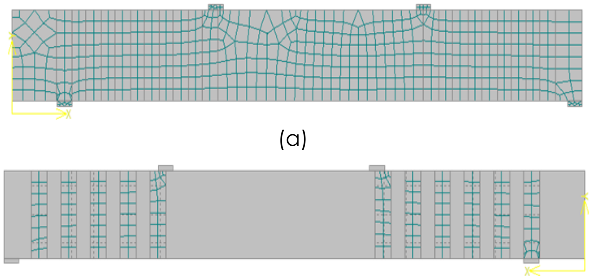


(a) (b)

Figure 3 (a) The bilinear stress-strain law for reinforcement (b) The multi-linear stress-strain law for reinforcement [16]

3.2 Mesh and Boundary Conditions

For this study, all beams were modelled as a half beam in two-dimension (2D). The concrete and steel plate element (longitudinal reinforcement and stirrups) was modelled using four node quadrilateral element as shown in Figure 4(a). CFRP strips were modelled using smeared reinforcement which was placed onto the concrete element with two layers representing the bi-directional type of the CFRP sheet (0/90 degree and 45/135 degree), see Figure 4(b). The size of the mesh was selected at 0.05m. This size was selected after a series of trial test on various mesh sizes from 0.02m to 0.08m was conducted. Appropriate boundary conditions were then used to simulate the restraint as shown in Figure 4(a) and 4(b).



(a)

(b)

Figure 4 (a) Concrete and steel mesh (b) CFRP mesh

4.0 COMPARISON BETWEEN EXPERIMENTAL AND FEM RESULTS

4.1 Failure Loads and Deflections

Table 2 shows the experimental failure load $P_{u,exp}$, shear force V_{exp} and deflection Δ_{exp} and its comparison with the FEM results ($P_{u,FEM}$, V_{FEM} , Δ_{FEM}). Generally, the FEM results gave good agreement but had overestimated its prediction by up to +18%. In Group Beam 1, the $P_{u,FEM}$ results shows differences from +11.88% to +13.93%. Beam 1-1 and Beam 1-2 are beams with one layer of CFRP strips, orientated at 0/90 degree and wrapped at 4 sides and 3 sides respctively. The $P_{u,FEM}$ results gave values of 424.80kN and 405.20kN for Beam 1-1 and Beam 1-2. This illustrates differences of +11.88% and +13.93% to their respective experimental results at 379.68kN and 355.65kN. Beam 1-3 and Beam 1-4 are beams with two layers of CFRP strips. Again, the FEM results gave similar trends as above at differences of +13.58% and +12.82%. The finding confirms that no signifiicant differences exists between one or two layers of CFRP strips. In Group Beam 2, the FEM overestimated its failure prediction values, $P_{u,FEM}$, but with wider variation ranging from as low as +1.35% to as high as +17.74%. Surprisingly, the $P_{u,FEM}$ for Beam 2-3 and Beam 2-4 with CFRP orientation of 45/135 degree gave close agreement at +1.35% and +6.21% compared to Beam 2-1 and Beam 2-2 of 0/90 degree CFRP orientation at 9.82% and 17.74% respectively. Figure 5 below shows the graphical distribution of experimental and FEM failure load and shear force of the shear strenghtened and shear repair of 2-span continuous RC beams with CFRP strips. The graph shows good and consistent distribition between experimental and FEM results.

For the deflection behaviour, Δ_{FEM} in Group Beam 1 gave values in the range of 12.74mm to 14.53mm. These deflection values were higher when compared to the experimental deflection, Δ_{exp}, at 8.71mm to 13.19mm. The higher FEM deflection values indicate that ATENA has underestimated the stiffness values of the initially strengthened beams with CFRP strips oreintated at 0/90 degree. By observing Group Beam 2, the Δ_{FEM} for Beam 2-1 and Beam 2-2 were observed at 12.71mm and 12.60mm and was higher compared to Δ_{exp} at 10.85mm and 10.08mm. Again, ATENA shows lower beam stiffness values for the pre-cracked /repaired beams. For Beam 2-3 and Beam 2-4 with CFRP orientation at 45/135 degree, the Δ_{FEM} and Δ_{exp} was measued at 9.86mm and 9.20mm compared to 13.14mm and 11.29mm respectuively. The results observed that ATENA gave better and more reliable deflection predictions when CFRP strips were oreintated at 45/135 degree compared to orientation at 0/90 degree.

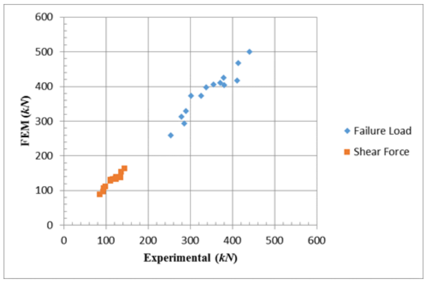


Figure 5 Experimental and FEM failure load and shear force distribution results

4.2 Crack Patterns and Failure Modes

Figure 6 below shows the FEM crack patterns and failure modes from ATENA for Beam 1-0 (Control Beam), Beam 1-2 (Group Beam 1) with CFRP orientation of 0/90 degree and Beam 2-3 (Group Beam 2) with CFRP orientation of 45/135 degree. All FEM beams shows

(a) Beam 1-0 (Control Beam)

(b) Beam 1-2 (Group Beam 1) 0/90 degree

(c) Beam 2-3 (Group Beam 2)45/135 degree

Figure 6 Crack Patterns and Failure Modes for Beam 1-0, Beam 1-2 and Beam 2-3 from ATENA

All the above figures shows the expected behaviour of beams where vertical cracks are observed at mid-span followed by the development of diagonal cracks within the critical shear zone at the inner shear span of the beam. Prior to failure, the propagation of both vertical cracks at mid-span and the diagonal cracks at the shear span area has appeared to enlarge.

Table 2 Comparison between Experimental and FEM Results

Beam Specimens	Experimental Results			FEM Results			% Diff. Failure Load, Pu
	Failure Load, $P_{u,exp}$ (kN)	Shear Force, V_{exp} (kN)	Deflection, Δ_{exp} (mm)	Failure Load, $P_{u,FEM}$ (kN)	Shear Force, V_{FEM} (kN)	Deflection, Δ_{FEM} (mm)	
Beam 1-0	286.10	93.70	10.87	293.71	96.19	7.44	+2.66
Beam 1-1	379.68	124.35	12.28	424.80	139.12	12.74	+11.88
Beam 1-2	355.65	116.48	8.71	405.20	132.70	13.38	+13.93
Beam 1-3	439.86	144.05	13.19	499.60	163.62	14.53	+13.58
Beam 1-4	414.48	135.74	11.00	467.60	153.14	13.18	+12.82
Beam 2-1	373.70	122.39	10.85	410.41	134.41	12.71	+9.82
Beam 2-2	338.08	110.72	10.08	398.05	130.36	12.60	+17.74
Beam 2-3	411.25	134.68	13.14	416.79	136.50	9.68	+1.35
Beam 2-4	380.74	124.69	11.29	404.40	132.44	9.20	+6.21

5.0 CONCLUSIONS AND RECOMMENDATIONS

An experimental work on the shear strengthening and shear repair of 2-span continuous RC beams with CFRP strips was conducted by N. Ali [5] at Universiti Tun Hussein Onn Malaysia (UTHM). The 2-span continuous RC beams were subjected to a four point bending test until failure. A simulation study using ATENA software on the above experimental work was conducted for comparison and validation. From the analysis of the FEM results, the following observations and conclusions were achieved:

1. ATENA has successfully simulated the shear behaviour of strengthened and repaired beams externally bonded with CFRP strips under various parameters such as 4 sides or 3 sides wrapped, different orientation at 0/90 or 45/135 degree and one or two CFRP layers.
2. ATENA has successfully predicted the failure load of the strenghtened or repaired 2-span continuous RC beams but overestimated its results by up to 18%.
3. ATENA software has successfully predicted the deflection values of the beam at failure. However, ATENA has underestimated the deflection values for beams with CFRP orientation of 0/90 degree but overestimated its deflection with CFRP orientation of 45/135 degree.
4. ATENA has successfully predict the crack patterns and failure modes of the strengthened and repaired beams.

Acknowledgements

The authors would like to acknowledge the research funds received from the Ministry of Higher Education Malaysia. The authors are also in-debt to staff and students of the Department of Structural and Materials Engineering, Faculty of Civil and Environmental Engineering, Universiti Tun Hussein Onn Malaysia for their contribution in the success of this research work.

References

[1] Sika. 2007. Manufacturer's Product Data Sheet, Switzerland, Sika Wrap®- 160 BI-C/15. Woven carbon fiber fabric for structural strengthening. Edition 11/09/2007.

[2] Balaguru, P., Nanni, A. & Giancaspro. J. 2009. *FRP Composites for Reinforced and Prestress Concrete Structures*. USA: Taylor & Francis Group.

[3] ACI Committee 2008. Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures.

[4] Dong, J., Wang, Q., and Guan, Z. 2013. Structural Behaviour of RC Beams with External Flexural and Flexural-Shear Strengthening by FRP Sheets. *Composites: Part B*. 44: 604-612.

[5] Dias, S. J. E and Barros, J. A. O. 2011. Shear Strengthening of RC T-section Beams with Low Strength Concrete using NSM CFRP Laminates. *Cement and Concrete Composites*. 33: 334-345.

[6] El-Ghandour, A. A. 2011. Experimental and Analytical Investigations of CFRP Flexural and Shear Strengthening Efficiencies of RC Beams. *Construction and Building Materials*. 25: 1419-1429.

[7] Li, L. J., Guo, Y. C., Liu, F. & Bungey, J. H. 2006. An Experimental and Numerical Study of the Effect of Thickness and Length of CFRP on Performance of Repaired Reinforced Concrete Beams. *Construction and Building Materials*. 20: 901-909.

[8] Carolin, A., and Täljsten, B. 2005. Theoretical Study Of Strengthening For Increased Shear Bearing Capacity. *J. Compos. Constr*. 9(6): 497-506.

[9] Adhikary, B. B., Mutsuyoshi, H., and Asyraf, M. 2004. Shear Strengthening of Reinforced Concrete Beams using Fiber Reinforced Polymer Sheets with Bonded Anchorage. *ACI Structural Journal*. 660-668.

[10] J. F. Chen & J. G. Teng. 2003. Shear Capacity of FRP-Strengthened RC Beams: FRP de-bonding. *Construction and Building Materials*. 17: 27-41.

[11] Täljsten, B. 2003. Strengthening Concrete Beams for Shear with CFRP Sheets. *Construction and Building Materials*. 17: 15-16

[12] Khalifa, A. and Nanni, A. 2002. Rehabilitation of Rectangular Simply Supported RC Beams with Shear Deficiencies using CFRP Composites. *Construction and Building Materials*. 16: 135-146.

[13] Li. A, Diagana, C. & Delmas, Y. 2002. Shear Strengthening Effect by Bonded Composite Fabrics on RC Beams. *Composites: Part B*. 33: 225-239.

[14] Khalifa, A. and Nanni, A. 2000. Improving Shear Capacity of Existing RC T-Section Beams using CFRP Composites. *Cement and Concrete Composites*. 22: 165-174

[15] Ali, N. 2014. Shear Strengthening Of Pre-Cracked And Non Pre-Cracked Reinforced Concrete Continuous Beams Using Bi-Directional Cfrp Strips. PhD Thesis, Universiti Tun Hussein Onn Malaysia. 289.

[16] Cervenka, V., Jendele, L. & Cervenka, J. 2001. ATENA Program Documentation Part 1: Theory. Prague, Czech Republic: Cervenka Consulting Ltd.