COMPARATIVE STUDY ON THEORETICAL MODELS AND DESIGN CODES FOR THE SHEAR CONTRIBUTION OF NSM FRP BARS IN RC BEAMS

Abdul Aziz Abdul Samad*, Noridah Mohamad, Josef Hadipramana, Mohamad Razi Ashaari Amiruddin

Department of Structural and Materials Engineering, Faculty of Civil and Environmental Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Batu Pahat, Johor, Malaysia

*Corresponding author
azizs@uthm.edu.my

Graphical abstract

Rizzo and De Lorenzis [8]

Cisneros D. *et al* [9]
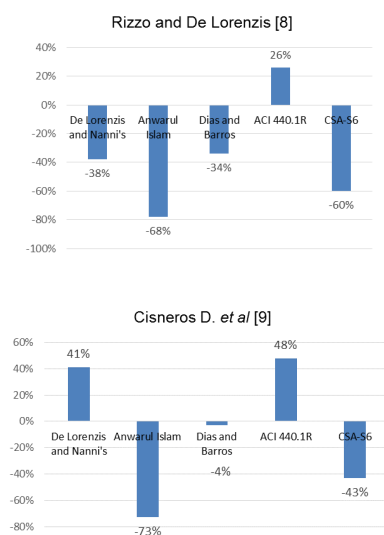
Abstract

This paper presents a comparative study on various theoretical models and design codes for the shear contribution of Near-Surface Mounted (NSM) using Fibre Reinforced Polymer bars to reinforced concrete (RC) beams. Theoretical models from De Lorenzis and A. Nanni, Anwarul Islam and Diaz and Barros, and ACI440.1R-06 and CSA-S806 design codes were selected. All the equations were compared by integrating experimental parameters from Rizzo and De Lorenzis, and Cisneros D. *et al*. From analysis, it was observed that the theoretical models shows substantial differences by underestimating the experimental findings of Rizzo and De Lorenzis from -68% to -38%. Similarly with Cisneros experimental work, the three theoretical models also produces large differences ranging from -73% to +41%. The analysis from the two design codes from ACI440.1R-06 and CSA-S806 also resulted with both design codes having significant differences ranging from -60% to +48%. However, from close observation, Dias and Barros theoretical model showed more accuracy by having a difference of just -4% with ACI440.1R-06 design code giving a much higher but acceptable difference of +26% compared to CSA-S806 at -60%.

Keywords: Shear Strengthening, Near-Surface Mounted (NSM), Fiber Reinforced Polymers (FRP), Theoretical Models, Design Codes

Abstrak

Kajian ini bertujuan untuk membandingan pelbagai teori dan kod reka bentuk terhadap sumbangan teknik pemasanagn berhampran permukaan dengan bar polimer tetulang fiber terhadap daya ricih rasuk konkrit bertetulang. Model teori yang terpilih terdiri dari De Lorenzis dan Nanni, Anwarul Islam, Diaz dan Barros, bersama kod reka bentuk ACI440.1R-06 serta CSA-S806. Kesemua teori dan kod reka bentuk telah digandingkan dengan data eksperimen dari Rizzo dan De Lorenzis, serta Cisneros D. *et al*. Perbezaan peratusan yang ketara telah diperolehi dari semua pengiraan. Dari data eksperimen Rizzo dan De Lorenzis, teori dan kod reka bentuk telah menghasilkan nilai peratusan perbandingan yang rendah antara -68% hinga -38%. Data eksperimen Cisneros juga telah menghasilkan peratusan perbandingan yang ketara julatnya antara -73% sehingga +41% untuk teori dan -60% hingga +48% untuk kod rekabentuk. Secara terperinci, teori dari Dias dan Barros telah berjaya menghasilkan keputusan peratusan terendah sebanyak -4% sahaja, manakala kod reka bentuk ACI440.1R-06 telah memberi peratusan yang boleh diterima sebanyak +26% berbanding kod CSA-S806 yang menghasilkan peratusan jauh lebih besar sebanyak -60%.

Kata kunci: Pengukuhan Ricih, Pemasanagan Berhampiran Permukaan (NSM), Polimer Tetulang Fiber (FRP), Model Teori dan Kod reka bentuk

1.0 INTRODUCTION

The Near-Surface Mounted (NSM) technique using FRP bar is an alternative method for enhancing shear and flexural strength of deficient Reinforced Concrete (RC) members [1]. Hence, by applying the NSM FRP techniques, an increase in its durability and service life of the structure is expected. It has been recorded that the NSM FRP bar technique does not require extensive surface preparation work as compared to applying FRP lamintaes. This technique requires minimal installation time by cutting grooves along the side or soffit of the beam and inserting FRP bars to these grooves with epoxy. NSM FRP bar technique is an interesting method where it is applicable to various types of structures. Previous and ongoing research have been conducted to study the characteristic behaviour on the strengthening of reinforced concrete structures using NSM FRP bars. These study eventually produces various theretical models. However, it has been observed that available data and models on the shear strengthening of RC beams with NSM FRP bars is relatively limited. It is known that the failure mechanism for strengthened beams are accounted for by the conventional reinforced concrete theory [2]. This approach also applies to beams strengthened with NSM FRP bars [3]. Hence, the aim of this paper is to conduct a comparative study on available theoretical models for the shear strengthening of RC beams using NSM FRP bar technique [4]. To complement the study, an American Standard and Canadian Standard have been selected for further comparison.

2.0 SHEAR FAILURE

Factually, shear failure or diagonal tension failure is difficult to predict accurately. Shear failure will cause buildings or structures to collapse due to the inability of the structural damage system to bear the load.
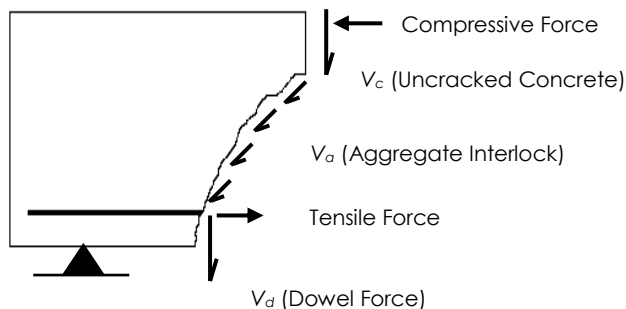

Figure 1 Typical shear crack mechanism acting at reinforced concrete beam without stirrups [5]

A typical shear crack mechanism for a reinforced cocnrete beam is shown in Figure 1. This mechanism was highlighted by Wang *et al.* [5] describing the shear failure in reinforced concrete without steel stirrups by a combination of the following mechanisms:

i) Shear resistance of the uncracked concrete, V_c
ii) Aggregate interlock force, V_a (tangentially along the crack line)
iii) Dowel action, V_d (the resistance of the longitudinal reinforcement to a transverse force

Previous research have revealed that shear failures can be strengthend or repaired by applying the NSM FRP bar technique [6]. As shown above, the shear capacity of any RC beams is equal to the summation of the shear strength provided by the concrete and steel stirrups (when included). By applying this method, the shear parameter (V_f) generated from NSM FRP bars will be considered as part of the overall shear capacity of the RC beam. Hence, this paper discusses three previous research highlighting theoretical models for predicting V_f.

3.0 THEORETICAL MODEL AND DESIGN CODES

3.1 De Lorenzis and Nanni [1]

According to De Lorenzis and Nanni [1], its theoretical model was proposed based on an experimental test, which was carried out on eight T beams considering parameters, such as strengthening configuration, anchorage and spacing of NSM reinforcement bars as well as percentage of existing steel stirrups. Basically, the equation (V_f) computes the shear contribution of this technique assuming debonding of NSM bars as the governing mode of failure in the strengthened beams. In fact, this equation was built up based on three main assumptions. Firstly, the shear cracks have a constant angle of inclination equal to 45 degree. Secondly, at ultimate, there is an even distribution of bond stress over the effective length of the strengthening bars. The third assumption is that in all the NSM reinforcement bars intersected by shear cracks, the bond stress is taken as the ultimate stress. This model is shown below as Equation (1).

$$V_f = 2. \sum Ai \, fi = 2\pi d_b \tau_b L_{totmin} \qquad (1)$$

Where *Ai* is the nominal cross-sectional area of the FRP rods, *fi* is the tensile stress in the FRP rod at the crack location, and summation is extended to all the rods intersected by a 45° crack. τ_b is the average bond strength of the FRP reinforcements. L_{totmin} is the sum of the effective lengths of all the FRP reinforcements crossed by the crack.

3.2 Anwarul Islam [7]

Anwarul Islam [7] tested four beams having some percentage of steel stirrups and strengthened in shear by using vertical NSM carbon rods. Basically, the results of the experiment were then used to establish a theoretical formula to compute the shear contribution of Near Surface Mounted technique in RC beams. It was actually found that the effective strain in the carbon rods at the shear failure stage in those beams was equal to about 30% from the ultimate strain of the carbon bars. In addition, in this experiment, no shear failures such as debonding or fracture of NSM bars were obtained. Therefore, it was assumed that the shear contribution of NSM technique (V_f) when NSM reinforcement bars are used in RC beams can be calculated using Equation (2):

$$V_f = \frac{1 A_d f_{yf}\, d}{3s}(\sin\theta + \cos\theta) \tag{2}$$

Where f_{yf} is the tensile yield strength of FRP bars, θ is the inclination of the FRP reinforcement. d is the distance from the external compression fiber to centroid of longitudinal tension reinforcement (mm), A_d is the area of FRP reinforcement in shear (mm^2) and s is the spacing of the FRP reinforcement (mm).

3.3 Dias and Barros [8]

According to Dias and Barros [8], an analytical model was established to calculate the shear contribution of NSM technique in RC beams, see Equation 3. Fundamentally, this model calculates the shear contribution of NSM technique bases on a similar concept to that of calculating the shear strength provided by steel stirrups. Nevertheless, the concept of using FRP effective strain is adopted instead of using the yield strain of steel stirrups. It is worth to mention this model was developed using the results of 40 tested RC beams taking into account parameters, such as the strength of concrete, the percentage of both steel stirrups and composite material, and the orientation of the NSM reinforcements.

$$\varepsilon_{fe} = \frac{V_f}{h_w \times \frac{A_{fv}}{s_f} \times E_f \times (\cot\theta_a + \cot\theta_f) \times \sin\theta_f} \tag{3}$$

Where ε_e is the effective strain of FRP bar. V_f is the shear contribution of NSM technique in RC beams. E_f is the elastic modules of FRP reinforcements. h_w is the web depth of the beam. A_{fv} is the cross sectional area of FRP bars or laminates. θ_a and θ_f are the orientation of both shear failure cracks and FRP bars or laminates. S_f is the spacing of FRP reinforcements.

3.4 Design Codes

The two selected design codes related to shear strengthening using FRP is tabulated in Table 1.

Table 1 Design Codes

Design Code	Design Equations	Year
ACI440.1R-06 [10]	$V_f = \dfrac{A_{fv} f_{fe}(\sin\alpha + \cos\alpha) d_{fv}}{s_f}$	2008
CSA-S806 [11]	$V_f = \dfrac{A_f E_f \varepsilon_{fe} d_f (\cot\theta + \cot\alpha)\sin\alpha}{s_f}$	2006

Further details on the above design equations are available in their respective references and design codes.

4.0 EXPERIMENTAL WORK

NSM FRP technique are essentially inserting FRP round bars, either vertically or inclined, and placed at a grooved-filled epoxy within the shear zone of the beams. Numerous researchers have been conducting experimental work on this technique and their findings have been published elsewhere. To compliment this study, two established research work have been identified and selected, and their experimental parameters are briefly presented in Table 2 and Table 3 below.

Table 2 Experimental parameters by Rizzo, A. and De Lorenzis, L. [8]

Beam	FRP Type	FRP θ	Spacing mm	Ult. load kN	Ult. Shear kN	V_f kN
NB90-73	Bars	90	73	352.8	176.4	54.2

Table 3 Experimental parameters by Cisneros D. *et al.* [9]

Beam	FRP Type	FRP θ	Spacing mm	No. of bars	f_{cm} MPa	V_f kN
B90-6	Bars	90	115	6	26.69	56.55

When data on material strength are not available, these data will be assumed based on manufacturing guidelines.

5.0 RESULTS AND DISCUSSIONS

Figure 2 shows the shear strength contribution of NSM FRP technique obtained from Rizzo and De Lorenzis [8] experimental work and its comparison with the calculated values from the theoretical models and design codes. Figure 3 designates the percentage difference between experimental result and the calculated theoretical models and design codes. As clearly shown in Figure 2 and Figure 3, the shear strength contribution from Rizzo and De Lorenzis experimental work was measured at 54.20kN. However, it was obvious that all three theoretical models gave an underestimated shear strength values of 33.6kN (De Lorenzis and Nanni), 17.28kN (Anwarul Islam) and 35.67kN (Dias and Barros), which is a reduction of -38%, -68% and -34% respectively. From design codes, a shear strength of 68.08kN for ACI440.1R-06 was measured indicating an increase of +26%, however for CSA-S806 the shear contribution was calculated at 21.44kN indicating a drop of -60%.
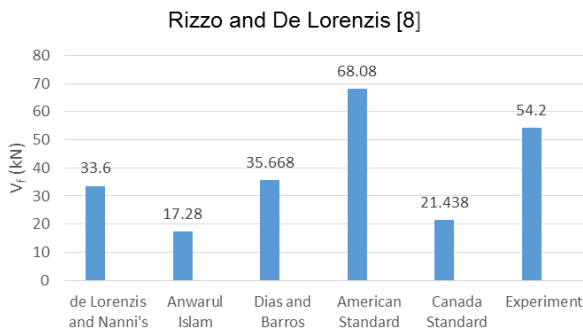

Figure 2 Shear strength contribution (V_f) compared to Rizzo and De Lorenzis [8] experimental work
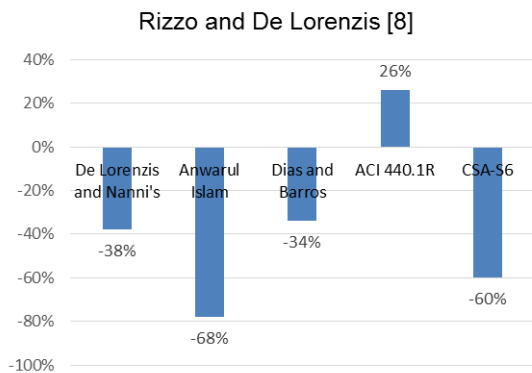

Figure 3 Percentage difference of shear strength contribution from Rizzo and De Lorenzis [8]

Figure 4 compares the experimental work from Cisneros D. *et al.* [9] to the shear strength contribution of NSM FRP technique from the calculated theoretical models and design codes. Figure 5 further highlights the percentage differences achieved between theoretical and design codes to the experimental value (56.55kN). From the figures

presented above, it was obvious that from the three theoretical model and two design codes, De Lorenzis and Nanni's model and ACI440.1R-06 design code gave an overestimated shear strength values of 79.77 kN (+41%) and 83.55kN (+48%). However, the other two theoretical model gave an understimated shear strength value of 15.3kN (Anwarul Islam) and 54.18kN (Dias and Barros), which is a drop of -73% and -4% respectively. From CSA-S806 design code, a shear strength of 32.55kN was measured, hence resulting in a reduction of -43%.
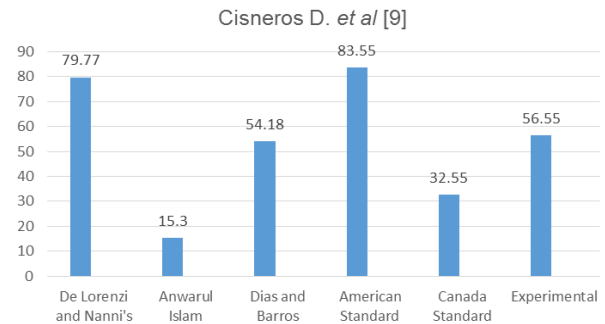

Figure 4 Shear strength contribution (V_f) compared to Cisneros D. *et al.* [9] experimental work
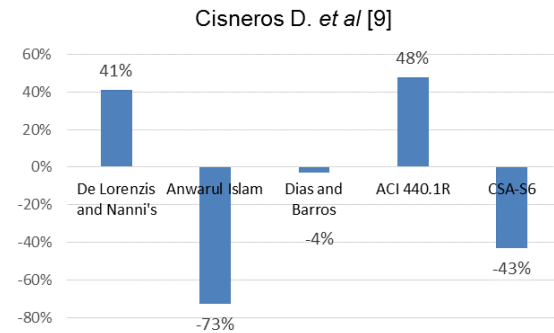

Figure 5 Percentage difference of shear strength contribution to Cisneros D. *et al.* [9]

6.0 CONCLUSION

A comparative study on three theoretical models and two design codes for the shear strengthening of RC beams using NSM FRP technique were conducted in this paper. De Lorenzis and Nanni [1], Anwarul Islam [6] and Dias and Barros [7] theoretical model with ACI440.1R-06 [10] and CSA-S806 [11] have been selected for the purpose of this study. All models and design codes were integrated with experimental parameters from Rizzo and De Lorenzis [8] and Cisneros, *et al*. [9]. Comparison between experimental and calculated theoretical models and design codes were conducted. From the results and analysis made, the following conclusions were acheived:

(i) The three theoretical models and two design codes have different characteristics. These characteristics were observed as follows:

    a. De Lorenzis and Nanni's model is dependent on the bond strength of the FRP bars with limitation of fixed shear crack direction at 45°.

    b. However, Anwarul Islam's model focuses more on the tensile strength of FRP bar with orientation of FRP and actual shear crack direction.

    c. It was also obvious that Dias and Barros's model has some similarity with Anwarul Islam's model but uses values of strain of FRP bars, its orientaion of FRP bars and actual crack direction as the core of its equation.

    d. From observation, there were similarity in approaches between ACI440.1R-06 design code with Anwarul Islam's theoretical model and, between CSA-S806 design code with Dias and Barros model. Both design codes have undergone modification to suit different conditions and requirements.

(ii) From the calculations made, De Lorenzis and Nanni's model with Dias and Barros model had underestimated Rizzo and De Lorenzis experimental work by -38% and -34% respectively. Unlike Anwarul Islam's model which calculated an even bigger (underestimate) difference of -68%.

(iii) ACI440.1R-06 design code gave a reasonably acceptable (but overestimated) shear contribution difference at +26% from Rizzo and De Lorenzis experimental work, unlike design code CSA-S806 which gave an underestimated value of -60%.

(iv) From Cisneros's experimental parameters, a lack of inconsistency in the calculated theoretical models was in evidence when all three models gave unpredictable differences ranging from De Lorenzis and Nanni at +41%, followed by Anwarul Islam's underestimated value at -73% difference and Dias and Barros of only -4% difference.

(v) The design codes from Cisneros experimental parameters gave ACI440.1R-06 an overestimated difference of +48% with CSA-S806 underestimated by -43%.

(vi) From close observation and comparison made, Dias and Barros theoretical model and design code ACI440.1R-06 gave close and acceptable differences (with the selected experimental work) in determining the shear contribution of NSM FRP bars on a RC beam.

(vii) However, further study on the accuracy and reliability of the model from ACI440.1R-06 design code may be required.

Aknowledgement

References

[1] Lorenzis, L. D., and Nanni, A. 2002. Bond Between Near-Surface Mounted Fiber-Reinforced Polymer Rods And Concrete In Structural Strengthening. *ACI Structural Journal.* 99(2).

[2] Rahal, K. N. and Rumaih, H. A. 2011. Tests On Reinforced Concrete Beams Strengthened In Shear Using Near Surface Mounted CFRP And Steel Bars. *Engineering Structures.* 33(1): 53-62.

[3] Dias, S. J. E., Barros, J. A. O., and. Lima, J. L. T. 2007. Efficacy of CFRP-based Techniques For Flexural And Shear Strengthening Of Concrete Beams. *Cement and Concrete Composites.* 29: 203-217.

[4] Wang, C. K., Salmon, C. G. and Pincheira, J. A. 2007. *Reinforced Concrete Design.* 7th ed. New Jersey, USA, John Wiley.

[5] Dias, S. J. E and Barros, J. A. O 2006. Near Surface Mounted CFRP Laminates for Shear Strengthening of Concrete Beams. *Cement and Concrete Composites.* 28: 276-292.

[6] Anwarul Islam, K. M. 2009. Effects of NSM CFRP Bars in Shear Strengthening of Concrete Members, In Structures Congress - Don't Mess with Structural Engineers: Expanding Our Role. *ASCE.* 1-14.

[7] Dias, S. J. E. and Barros, J. A. O. 2008. Shear strengthening of T-Cross Section Reinforced Concrete Beams by Near-Surface Mounted Technique. *Journal of Composites for Construction.* 12(3): 300-311.

[8] Rizzo, A. and De Lorenzis, L. 2009. Modeling of Debonding Failure for RC Beams Strengthened In Shear With NSM FRP Reinforcement. *Construction and Building Materials.* 23(4): 1568-1577.

[9] Cisneros, D., Artega, A., Diego, A. D., Alzate A., and Perera, R. 2012. Experimental Study on NSM FRP Shear Retrofitting of RC Beams. In *6th International Conference on Fiber Reinforced Polymer (FRP) Composites in Civil Engineering (CICE2012), Rome, Italy.* 13-15.

[10] ACI440.1R-06. 2006. Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars, American Concrete Institute.

[11] CSA-S806. 2006. Design, and Construction of Building Components with FRP, Canadian Standard Association. 218.