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Research Paper

Examination of influential factors on shear strength of externally bonded FRP reinforcement in RC beams

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ABSTRACT

The fiber-reinforced polymer (FRP) retrofitting technique has been increasingly created to enhance the capacity of the existing concrete members. In this study, the shear contribution of the external FRP strengthening system in the reinforced concrete (RC) beams is estimated by the semi-empirical models available in the open literatures and guidelines. Number of beams monitored in the previous studies are first considered to assess the reliability of the models. Afterwards, the investigation of influential factors such as the beam configurations, the strengthening characteristics and the material properties are implemented. With high accuracy and low coefficient of variation, the model proposed in a previous study of the authors gains the mostly considerable estimation for the shear resisting strength of FRP strengthening system compared to the accessible data base from the experiments. In addition, the critical properties of the materials associating with the retrofitting systems for the strengthened beams are investigated to obtain the acquired shear performance.

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1 Introduction

Nowadays, the strengthening methods have been increased in the real applications for enhancement of the members' capacity and performance. The authors' group is carrying out a research project regarding to the structural intervention of the concrete beams in flexure and shear. The main purposes of the project are:(1) to provide a solution for repair of the corroded beams using steel fiber reinforced concrete through the experiment and analysis and (2) to investigate the shear strengthening performance of externally fiber-reinforced polymer (FRP) bonded reinforcement in the retrofitting beams. As a part, this

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study concentrates on the investigation of shear efficiency of concrete beams strengthened with externally bonded composites via the analytical model. Consideration of the shear failure of the reinforced concrete (RC) beams, the near surface mounting (NSM) technique, which has been adapted from the externally bonding (EB) method, has been indispensably created. In NSM method, the fiber-reinforced polymer (FRP) or steel composites are placed at the groove that previously prepared at the shear investigation zone of the RC beams (as Figure. 1). The prominent research regarding to the NSM method are carried out by Dias and Barros [1], Dias and Barros [2], Bui et al.[3]. Compared to externally FRP bonded method, the efficacy of the RC beams retrofitted by NSM elements was substantially improved through the good bond mechanism between NSM and concrete. However, the lack of design models for the members with NSM reinforcement has made the researchers and engineers paying attention on the guidelines and codes of the ordinary embedded reinforcement instead. Currently, the most common guidelines are the documentaries of the American Concrete Institute (ACI 440.1R-15 [4]) and the Japan Society of Civil Engineers (JSCE-97 [5]). Meanwhile, number of studies [3, 6] indicated the use of the mentioned guidelines for calculation of shear contribution of FRP retrofitting might result in the underestimation of prediction. One of previous studies [3] of the authors provided the modified effective strain equation in FRP incorporating with the truss analogy. Their improved model has drawn the considerable prediction of shear resisting forces of FRP strengthening systems. The current study deals with the assessment of the existing shear models in the prediction of the shear contribution of NSM retrofitting elements in the strengthened beams. The sensitive analysis of the shear model is also studied to highlight the prominent characteristics for the member design. In addition, the investigation of the influential factors on the shear resisting strength of the NSM retrofitting is offered to evaluate the potential of the shear model.

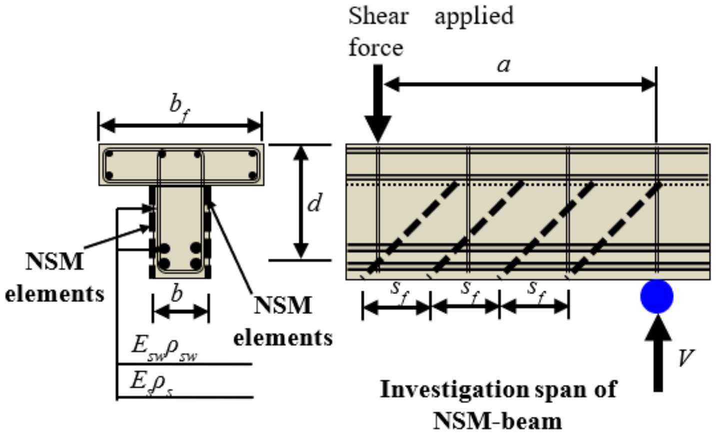


Fig. 1 – Illustration of NSM strengthening technique.

2 Assessment of existing shear models

Based on the truss theory, there are many codes, standards, guidelines and studies proposing the shear resisting models for the FRP reinforcement internally embedded in the RC beams. According to the ACI 440.1R-15 [4] and JSCE-97 [5] guidelines, the equations to calculate the shear resisting forces of FRP shear reinforcement using modified truss analogy are expressed in the following Eqs. (1) and (2).

$$\mathrm{V}_f = A_v f_f \frac{d\left(\cot\theta + \cot\alpha\right)}{s}\sin\alpha \tag{1}$$

$$\mathrm{V}_s = A_v f_f \frac{z\left(\cot\theta + \cot\alpha\right)}{s}\sin\alpha = A_v f_f \frac{7d\left(\cot\theta + \cot\alpha\right)}{8s}\sin\alpha \tag{2}$$

The ACI guideline uses the formulation of f_f as displayed in Eq. (3).

$$f_f = \min\left(0.004E_f, f_{f,u}, f_{f,bend} = \left(\frac{0.05r_b}{d_b} + 0.30\right) f_{f,u}\right) \tag{3}$$

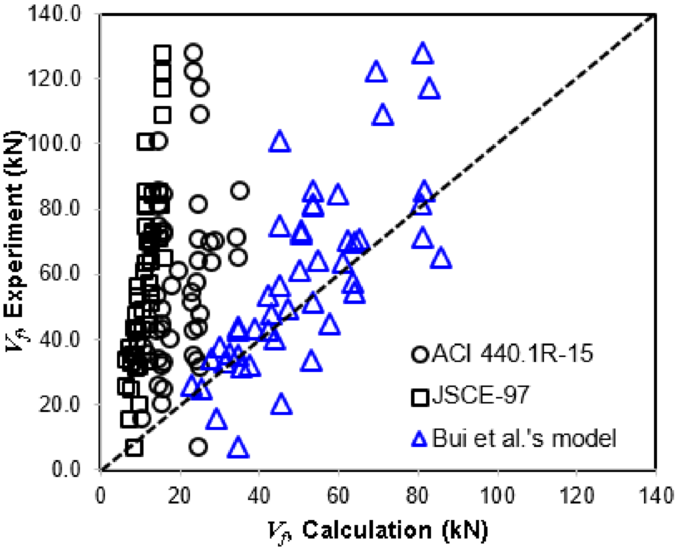
The JSCE guideline possesses the formulation of f_f as displayed in Eq. (4).

$$f_f = E_{fw}\sqrt{\left(\frac{h}{0.3}\right)^{-0.1} f_c^{'}\,\frac{\rho_s E_s}{\rho_{fw} E_{fw}}}\times 10^{-4} \qquad (4)$$

Bui et al. [3]'s model utilizes the equation for effective strain of the FRP strengthening system as Eq. (5). Then, the formulation of the effective strain is incorporated with the truss analogy in the ACI guideline to derive the shear resisting forces of the strengthening system.

$$\varepsilon_{fe} = -0.00127 + 0.0162\frac{\sqrt{f_c^{'}}}{\sqrt{a/d}+1}\,e^{\frac{-1000}{\rho_s E_s}-0.05\sqrt{\rho_{fw}E_{fw}+\rho_{sw}E_{sw}}} \qquad (5)$$

where z = section effective depth (mm); A_r = section area of FRP (mm^2); f_f = effective stress in FRP (MPa); ε_{fe} = effective strain in FRP, $f_{f,u}$= ultimate strength of FRP (MPa); $f_{f,bend}$= tensile strength of FRP bent element (MPa); r_b= bending radius of FRP (mm); d_b= the diameter of FRP in the bent portion (mm); f'_c = concrete compressive strength (MPa); a/d = shear span to depth ratio; $\rho_s/\rho_{fw}/\rho_{sw}$ = tension/FRP/stirrups reinforcement amount (%); $E_s/E_{fw}/E_{sw}$ = tension/FRP/stirrups reinforcement elastic modulus (GPa).



Models	ACI 440.1R-15	JSCE-97	Bui et al.'s model
Mean	0.456	0.227	1.029
COV (%)	107.7	71.9	65.7

Fig. 2 – Comparison between calculation and experiment considering three models.

To validate the shear resisting models, the entire test programs and results in the study of Dias and Barros [1] are used. The details of the experimental data could be found in their study with close consideration of the design parameters and NSM-FRP shear contributions. Figure. 2 presents the validation of the calculation made by the models to the accessible data base determined from the tests. Owing to the underestimation of the effective stress equations provided by the JSCE and ACI guidelines, the shear contribution of NSM-FRP reinforcement produced by those models gives the conservative estimation against the test results. The results calculated by the JSCE model show the most underestimation in comparison to the other models although that model considered various parameters in the equation of the effective stress. The means of the average of the ratio of the computed shear contributions to the monitored ones are 0.456 and 0.227 for the models in the ACI and JSCE, respectively. In addition, the values of the coefficient of variation (COV) of the means for the ACI and JSCE models are 107.7% and 71.9% respectively. Regarding to mentioned results, the model offered in the JSCE guideline could be adopted to predict the shear resisting forces of external NSM-FRP shear reinforcement in the strengthened beams for a proper design with consideration of the safety format.

It is also seen in figure. 2 that the shear contribution of NSM-FRP in the strengthened beams made by the model of Bui et al. [3] incorporating with the truss analogy depicts the good estimation against the experimental data. In fact, the mean of the average of the ratio between the shear contributions made by the model and the test is 1.029 and the COV of the mean is 65.7%. This indicates that the model proposed by Bui et al. [3] could avoid the underestimation of the models provided by the guidelines. In addition, with the mentioned statistical values, the accuracy of the shear strength model by Bui et al. [3] is acceptable in predicting of the shear contribution of the externally bonded FRP reinforcement. Meanwhile, there exists the deviation between the model validations due to the complicated failure modes of the strengthened specimens, which might result in the premature debonding failure. Indeed, for the NSM technique, the NSM-FRP was placed at the outer surface in the shear region of the beams, thereby the earlier debonding was possibly occurred due to the insufficient bond mechanism at increasing of the subjected load.

To consider the influences of the NSM-concrete bond behavior and the sensitization of the shear model, the expression for the effective strain in NSM-FRP in Bui et al. [3]'s model can be simply modified as Eq. (6).

$$\varepsilon_{fe} = k \times \left(-0.00127 + 0.0162 \frac{\sqrt{f_c^{'}}}{\sqrt{a/d}+1} e^{\frac{-1000}{\rho_s E_s} - 0.05\sqrt{\rho_{fw}E_{fw}+\rho_{sw}E_{sw}}} \right) \tag{6}$$

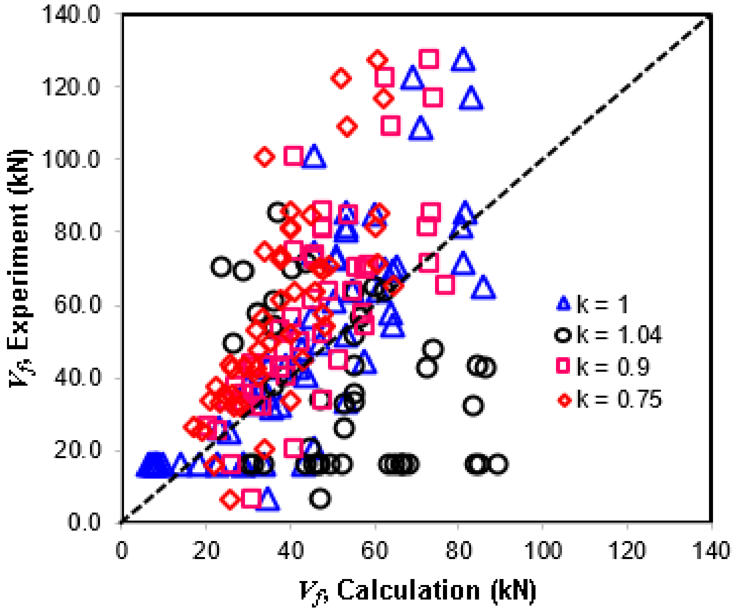


Fig. 3 – Sensitive analysis on shear contribution prediction of NSM-FRP.

Figure. 3 illustrates the sensitive characteristics of the model validation considering the calibrated coefficient in the shear model of Bui et al. [3]. Clearly, the calibrated coefficient (*k*) affects substantially the calculation results of the shear resisting forces of NSM-FRP elements. The slight increase of *k* results in the significant overestimation and scatter of the calculated shear strengths to the experimental shear strengths due to the high elastic modulus of FRP materials. While the sharp decrease of *k* exhibits the slight decrease and the insignificant dispersion of the predicted shear contributions to the corresponding test results. To assure the properly safety requirement, the coefficient *k* = 0.75 should be used to predict reasonably the shear contribution of the NSM-FRP strengthening system.

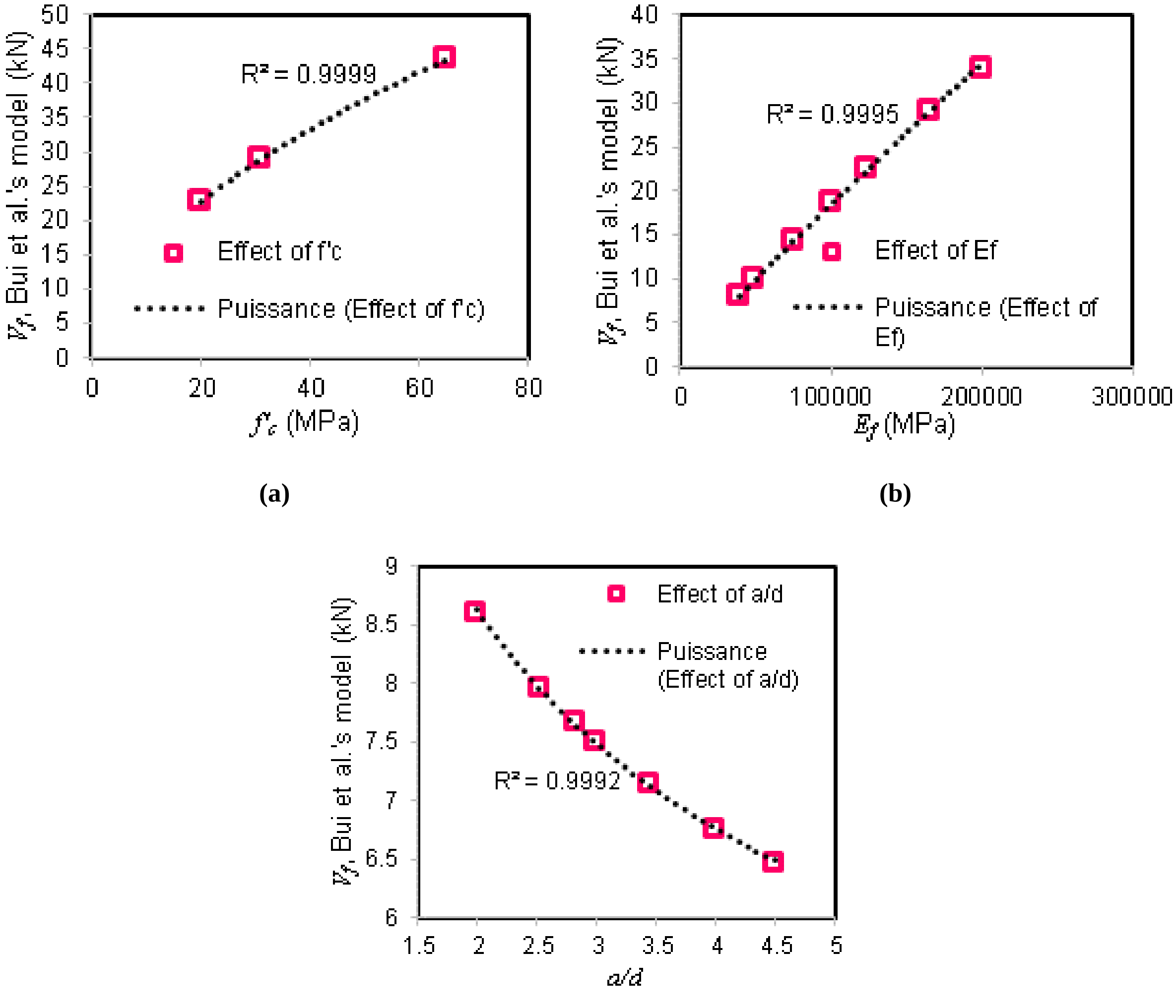
3 Analysis of influential factors on shear strength of NSM-FRP

This section carries out the investigation of influential factors, such as f'_c, FRP types and *a/d*, on shear contribution of NSM-FRP system in the strengthened beams via the validated shear resisting model. The concrete compressive strength (f'_c)

is varying in range from 20 MPa to 60 MPa for group 1, and the Young's modulus (E_f) of NSM strengthening is in range from 40000 MPa (FRP case) to 200000 MPa (steel case) for group 2. Besides, for the group 3, the shear span to effective depth ratios are diversative amongst 2–4.5 to induce various types of failures such as the diagonal tension failure, shear failure and flexural failure.

Table 1 - **Beams' groups for parametric study**.

Beam groups	**f'_c (MPa)**	**E_f (MPa)**	***a/d***
G1	Varying 20–60	166000	2.52
G2	31.1	Varying 40000–200000	2.52
G3	31.1	166000	Varying 2–4.5



(a) **(b)**

(c)

Fig. 4 – Shear contribution of NSM strengthening system via model under effects: (a) f'_c; (b) E_f; (c) a/d.

Figure. 4(a) provides the effect of f'_c on the shear contribution of NSM-FRP in the retrofitted beams. The shear resisting forces of NSM-FRP increased as the concrete strength increased. This is because the high concrete strength resulted in the high capacity, which offered the great capacity of NSM-FRP. In addition, the high concrete strength may improve the interfacial profile between NSM systems and concrete in the intervened members. This causes for the bond-mechanic efficiency that could trigger the resistance of NSM-FRP optimally. Figure. 4(b) reveals the influence of the NSM types on the shear strength of NSM-FRP. It is obvious that the increase in the NSM elastic modulus increased linearly the shear contribution of the NSM system in the RC strengthened beams. The use of the NSM steel bars induced the largest shear strength due to the high tensile force capacity of steel at rupturing strain (note that in Bui et al. [3] model, the post-yield response was considered in calculation). On the other hand, in Figure. 4(c), the increasing of the *a/d* ratios reduced the contribution in shear of NSM-FRP. Indeed, the low *a/d* ratio produces the diagonal tension failure, which made the high strength in the shear zone, therefore the NSM-FRP was substantially activated. However, with the high *a/d* ratio, the failure of the strengthened beams is governed by the flexure, meaning that the shear carrying forces responsible by NSM-FRP was small. Thereby, the shear resistance of NSM-FRP decreased as the *a/d* ratios increased. The aforementioned findings were also reported in the study by Dias and Barros [2].

4 Conclusion

The primary conclusions of this study can be drawn as follows:

The shear strength prediction made by the ACI and JSCE guidelines is used for a conservative design format through the model underestimation. In particular, the model expressed by the JSCE guideline should be employed for the cases with safety requirement.

The estimation of shear contribution of NSM-FRP produced by Bui et al. [3]'s model fits well the test results rather than the guideline models.

The calibration coefficient $k = 0.75$ for the effective strain equation should be accounted to calculate reasonably the shear carrying forces of the NSM-FRP retrofitting systems in the RC beams for dealing with the safety requirement.

The influential factors f'_c, E_f, *a/d* affect substantially the shear performance of the NSM strengthening system in the beams. In practical use, the optimum parameters of the materials and elements for the NSM-strengthened beams could be initially selected from the results in figure. 4 to assure the design shear strength.

In future study, the proposed shear model will be utilized to assess the shear mechanism and strength of the corroded beams repaired in the tension zone by the steel fiber reinforced concrete.

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