SHEAR PERFORMANCE OF REINFORCED CONCRETE BEAMS STRENGTHENED WITH AN INNOVATIVE EMBEDDED THROUGH-SECTION SYSTEM

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ABSTRACT

Embedded through-section (ETS) technique is one of the modern strengthening techniques for enhancing shear performance of reinforced concrete (RC) structures. This study investigates the shear behavior of RC beams strengthened with glass fiber-reinforced polymer (GFRP) bars using an innovative ETS retrofit system. An experimental program including three ETS-strengthened beams and one reference beam was carried out. The crucial factors considering in the experiment consist of the presence of anchorage system and the two types of mechanical anchorages: steel and GFRP anchoring nuts. The shear strengths of the EST-strengthened beams calculated by the existing shear resisting models are validated against the shear strengths measured from the tests. The results obtained from the study demonstrate that the beam strengthened with ETS GFRP bars incorporating the GFRP anchoring nuts provide the great shear performance. To achieve the indispensable accuracy, the study indicates that the available shear strength models for prediction of shear contribution of the anchored ETS bars in the beams should be further developed.

Keywords: *Embedded through-section, Glass fiber-reinforced polymer, Shear strengthening, Reinforced concrete, Shear strength model*

1. INTRODUCTION

Reinforced concrete (RC) is commonly used in construction with a long history. However, under long term service and environmental factors, the RC structures are gradually deteriorated following by the reductions in their structural performances. Additionally, the shear failure in the RC members is usually occurred suddenly, resulting in the substantial damage in overall structures.

To avoid brittle mode of shear failure in the RC beams, many methods for retrofit and strengthening have been successfully introduced. The popular techniques are the Externally Bonded Reinforcement (EBR) and the Near Surface Mounted (NSM). As found in the previous research [1-3], the main drawback for both EBR and NSM techniques is the premature debonding of the retrofit elements to concrete. Recently, an innovative retrofit technique named Embedded Through-Section (ETS) has been proposed by several research groups. The ETS technique uses the steel or FRP bars that are embedded in the shear zone of the beams through the holes, which were predrilled crossing the beams' section [1, 4-6].

Chaallal et al. [1] and Barros and Dalfré [4] investigated the shear capacities amongst the three strengthening methods: EBR, NSM and ETS. Their findings indicated that the ETS technique could significantly enhance the shear capacity of the RC beams. For Barros and Dalfré [4], the obtained results showed that the average strengthening efficacy of ETS technique equal to 54%, but the other techniques gained the average results lower than 50%. As well as Chaallal et al. [1], they found the percentage for shear capacity of ETS method equal to 29% and 11% and 17% for EBR and NSM methods, respectively. Furthermore, the capacity of ETS method is 122% in specimens with unstrengthen by steel stirrups compared with 48% for EBR method and 61% for NSM method. Breveglieri et al. [5] also studied the efficiency of these techniques by applying their results to compare with the results from Dias and Barros [7], they observed that when the strengthening ratio increased, the strengthening capacity increased as well, which led to their conclusions that the performance of ETS technique is better than the others because the highest strengthening ratio of NSM and EBR techniques are almost the same strengthening capacity as the lowest strengthening ratio of ETS technique, around 25%. According to the previous studies, all of which can point out that the ETS technique is the most effective method that provide high shear capacity in RC members. The previous research investigated in many parameters such as the presence of transverse steels, stirrup or ETS strengthening ratios, and stirrup or ETS arrangements. However, there are insufficient literatures examining the beams strengthened with the ETS-GFRP retrofit system incorporating anchoring nuts.

This study aims to investigate shear behavior of RC beams strengthened by ETS-GFRP bars considering two following parameters. The first parameter is the effect of the anchorage presence in the ETS-GFRP strengthening system, and the second one is the influence of the two types of steel and GFRP anchoring nuts.

2. EXPERIMENTAL PROGRAM

The experimental program consists of four RC rectangular-cross section beams, in which one beam is without embedment ETS strengthening bars (reference beam R1). The remaining RC beams are designed with the ETS strengthening system.

2.1. EXPERIMENTAL DESIGN

Table 1 and Figure 2 show the experimental program and configuration of four beams: one reference beam (R1 (w/o ETS)), one ETS strengthened beam without anchorage (B1-0nut), one ETS strengthened beam with steel anchoring nuts (B2-2Snut), one ETS-strengthened beam with GFRP anchoring nuts (B3-2Gnut). The tested beams have 1800 mm length and the cross-section dimension of all specimens is 150×300 mm^2.

Table 1 The experimental program of tested beams

Beam ID	d (mm)	f'_c (MPa)	d_b (mm)	Type of nut	No. of nut
R1 (w/o ETS)	250	35	-	-	-
B1-0nut	250	35	8	-	0
B2-2Snut	250	35	8	Steel	2
B3-2Gnut	250	35	8	GFRP	2

Notes: d is effective depth, f'_c is compressive strength of concrete, d_b is ETS diameter, and No. of nut is number of nuts at each end of ETS bars.

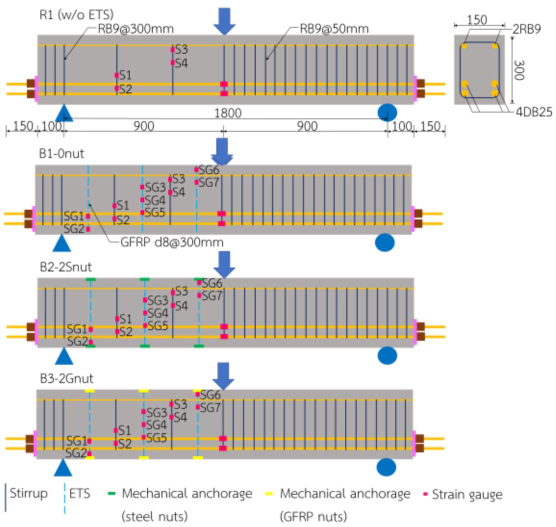

Figure 2 The experimental configuration of strengthened beams

Notes: R1 (w/o ETS) is the beam named R1 without ETS bars, B1-0nut is the beam named B1 without anchoring nuts, B2-2Snut and B3-2Gnut are the beams named B2 and B3 strengthened with two steel nuts and two GFRP nuts, respectively.

2.2. MATERIAL PROPERTIES

Table 2 presents the properties of materials used in the tests including the properties of steel reinforcement (RB9 and DB25), ETS-GFRP bars (8 mm diameter), and adhesive material.

Table 2 Properties of materials

Material	d_b (mm)	E_r (GPa)	f_y (MPa)	f_t (MPa)
GFRP	8	46*	-	862*
Steel (RB9)	9	200**	235**	385**
Steel (DB25)	25	200**	390**	620**
Epoxy	-	4.48*	-	24.8*

Notes: *Values from manufacturer, **Values from TIS 20-2543 [8] and TIS 24-2548 [9]. d_b is bar diameter, E_r is Young's modulus, f_y is yielding strength, and f_t is tensile strength.

2.3. PROCEDURE FOR ETS METHOD

Fig. 3 summarizes the three main steps for the procedure of the ETS strengthening method. First, holes with 1.5 times of the GFRP bar diameter were drilled in the desired location and were cleaned to eliminate tiny dust. Second, plastic sheets were glued at one end of holes to avoid the adhesive flow. Third, the adhesive was gradually injected into the cleaning holes. Then, the GFRP bars were inserted into the holes. During the procedure, it is apparent that the application of the ETS method is easier than that for the application of the other strengthening methods because it does not require the surface preparation for RC structures and does not require high performance for construction skills.

Figure 3 Procedure of ETS strengthening method

3. SHEAR STRENGTH MODELS

Generally, the nominal shear capacity (or total shear capacity, V_n) of reinforced concrete structures consists of two parts, the shear resistance provided by concrete (V_c) and the shear resistance provided by shear reinforcement (V_s). When the beam was reinforced by FRP system, the nominal shear capacity includes the shear strength form FRP system (V_f). Therefore, the total shear strength will become $V_n = V_c + V_s + V_f$. The common shear strength models available in the current codes or guidelines or the literatures are as follows:

3.1. ACI MODEL

The shear resistance of concrete [10] stipulates the following equations:

For $A_v \geq A_{v,min}$:

$$V_c = \left[0.17\lambda\sqrt{f_c'} + \frac{N_u}{6A_g}\right] b_w d \qquad (1)$$

$$V_c = \left[0.66\lambda(\rho_w)^{1/3}\sqrt{f_c'} + \frac{N_u}{6A_g}\right] b_w d \qquad (2)$$

For $A_v < A_{v,min}$:

$$V_c = \left[0.66\lambda_s\lambda(\rho_w)^{1/3}\sqrt{f_c'} + \frac{N_u}{6A_g}\right] b_w d \qquad (3)$$

Note: V_c should not be taken less than zero but greater than $0.42\lambda\sqrt{f_c'}b_w d$.

where, A_g is the gross area of concrete member section (mm^2), A_s is the area of longitudinal reinforcement (mm^2), A_v is the area of shear reinforcement within spacing s (mm^2), $A_{v,min}$ is the minimum area of shear reinforcement within spacing s (mm^2), b_w is the web width or diameter of circular section (mm), d is the effective depth in the members' section (mm), f'_c is the compressive strength of concrete (MPa), N_u is the axial force which taken as positive for compression and negative for tension (N), λ is the modification factor for effect of lightweight concrete, λ_s is the modification factor for size effect, and ρ_w is the ratio of longitudinal reinforcement.

The shear resistance of steel shear reinforcement [10] stipulates the following equations:

$$V_s = \frac{A_v f_{yt}(\sin\alpha + \cos\alpha)d}{s} \qquad (4)$$

where, f_{yt} is yield strength of transverse reinforcement (MPa), s is center-to-center of reinforcements measured parallel to longitudinal bars (mm), and α is angle between inclined stirrups or spirals and longitudinal axis (°).

The shear resistance of FRP shear reinforcement [11] stipulates the following equations:

$$V_f = \frac{A_f f_{fv} d}{s}(\sin\alpha + \cos\alpha) \quad (5)$$

$$f_{fv} = \min\left(0.004E_f, f_{fu}, f_{fb} = \left(\frac{0.05r_b}{d_b} + 0.30\right) f_{fu}\right) \quad (6)$$

where, A_f is the area of FRP shear reinforcement (mm^2), f_{fv} is the effective tensile strength of FRP system (MPa), f_{fu} is ultimate tensile strength (MPa), f_{fb} is strength of bent portion of FRP stirrups (MPa), d_b is diameter of bent portion of FRP bar (mm), E_f is modulus of elasticity of FRP bar (MPa), and r_b is bending radius of FRP bar (mm).

3.2. EQUATIONS OF JSCE MODEL

The shear equations proposed by JSCE [12-13] is as follows:

$$V_c = 0.2\sqrt[3]{f_c'}\sqrt[4]{\frac{1000}{d}}\sqrt[3]{100\rho_w}b_w d \quad (7)$$

$$V_s = \frac{7A_v f_{yt} d}{8s}(\sin\alpha + \cos\alpha) \quad (8)$$

$$V_f = \frac{7A_f f_{fv} d}{8s}(\sin\alpha + \cos\alpha) \quad (9)$$

$$f_{fv} = E_f\sqrt{\left(\frac{h}{0.3}\right)^{-0.1} f_c' \frac{\rho_w E_w}{\rho_f E_f}} \times 10^{-4} \quad (10)$$

where, E_w is modulus of tension reinforcement (MPa), h is member depth (mm), and ρ_f is ratio of FRP shear reinforcement in interval s.

3.3. EQUATION OF BUI ET AL.

Bui et al. [6] proposed a new equation to estimate the effective strain in the FRP strengthening system as follows:

$$\varepsilon_{fe} = -0.00127 + 0.0162\frac{\sqrt{f_c'}}{\sqrt{a/d}+1}e^{\frac{-1000}{\rho_w E_w} - 0.05\sqrt{\rho_f E_f + \rho_v E_v}} \quad (11)$$

where, ε_{fe} is effective strain of shear strengthening system, a is shear span of beam (mm), E_v is modulus of transverse steel (MPa), and ρ_v is ratio of steel stirrups.

4. RESULTS AND DISCUSSION

4.1. LOAD-DEFLECTION RELATIONSHIP

The load-deflection curves at the loading point of the test beams are shown in Fig. 4. It is obvious that the investigated factors affect substantially the load-deflection responses of the specimens. The beams strengthened with ETS bars provide the greater stiffness and the load-carrying capacity than those of the reference beam due to the use of high shear reinforcement percentages of the strengthened specimens. When the diagonal cracks formed, the stiffness of beams was decreased to transfer the carrying load from the concrete to the steel reinforcement and ETS bars. At the high load level, the ETS bars in the strengthened were significantly triggered until the failure by the concrete fracture in shear zone.

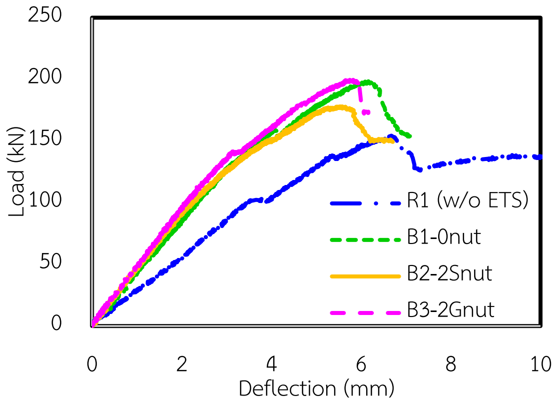

Figure 4 Load-deflection relationship of the tested beams

In Fig. 4, the reference beam without retrofitting ETS bars (R1 (w/o ETS)) offers the lowest load carrying capacity by 154.38 kN and the deflection at peak load 6.68 mm. However, for the strengthened beams without anchorage (B1-0nut) and with steel/GFRP anchorage (B2-2Snut, B3-2Gnut), the maximum load capacities are 198.42 kN, 178.10 kN, and 200.36 kN and the displacements at peak load are 6.16, 5.54, and 5.75 mm for the beams B1, B2, and B3, respectively. The aforementioned findings indicate that the performance of the ETS-strengthened beams depend on the presence of the anchorage system and the properties of the anchoring nuts. Indeed, the ETS-GFRP-strengthened beam with GFRP anchoring nuts illustrates a considerable efficiency in the load and deflection characteristics compare to the ETS-strengthened beam inserted steel anchoring nuts. It is because the equivalent stiffness of an anchoring-GFRP ETS-GFRP system is lower than that of an anchoring-steel ETS-GFRP system. This may mitigate the premature fracture phenomenon in concrete due to the impact of anchorage to concrete beams, where the anchoring nuts were placed. In addition, the detailing of anchorage may also affect the effectiveness of the ETS-strengthening system in the RC beams.

4.2. LOAD-STRAIN RELATIONSHIP

As observed in the test results, the strains in ETS bars depend on the distance between the shear cracks and the strain gauges. The strain values are high as the strain gauges are closed to the cracks. Figure 5 shows the load-strain response for strain at the same position of the glued strain gauges in ETS-GFRP bars for the strengthened beams. The retrofit beams start to carry the load in the range of 120-140 kN. The strain values in ETS bars at strain gauge SG1 for the beams B1, B2, and B3 at maximum load are 584.8, 3406.3, and 3224.7 $\mu\varepsilon$, respectively. In addition, the strain results indicate that the strengthened beams with steel and GFRP nuts offer higher strains in ETS bars than those of the unanchored beam due to the influence of mechanical anchorage. In particular, the beam B3 with the ETS bars anchored with GFRP nuts resulted in highest strain response since the equivalent stiffness of combined ETS-GFRP anchorage. These findings apparently demonstrate the efficiency of the anchorage system to activate effectively the capability of the ETS bars.

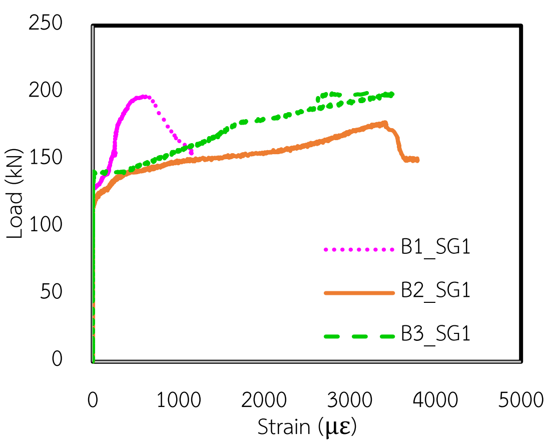

Figure 5 Strains in ETS-GFRP bars for the retrofitted beams

4.3. FAILURE MODE

The cracking failures of the reference beam and strengthened beams are displayed in Fig. 6. All test beams failed due to the shear failure mode, resulting in the main diagonal cracks that are wide and propagated from the supporting to the loading. For beam R1 without ETS-strengthening bars, the shear cracks are wider than those for the beams with ETS-GFRP. The main reason is because the reference beam reinforced by only transverse steels to carry the shear resisting force. Whereas the ETS-strengthened beams demonstrate the small cracks because the shear resisting mechanism was carried by both stirrups and ETS system after forming first cracks in concrete. Additionally, the specimens B2 and B3 with ETS and anchorage system offer more cracks than the specimen B1 with ETS and without anchorage. This implies that the anchorage triggered the shear resisting transfer of the ETS bars along with the bonding efficiency.

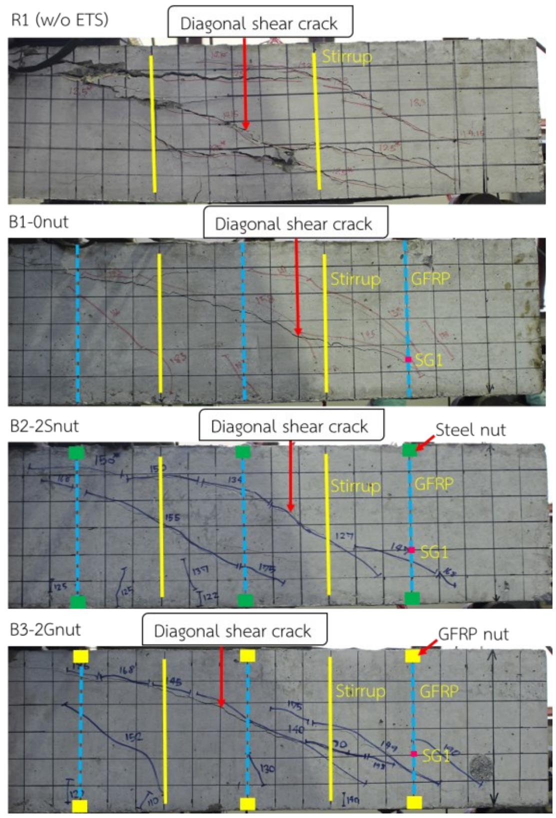

Figure 6 Crack pattern of reference beam and strengthened beams with location of SGs

4.4. VERIFICATION OF SHEAR STRENGTH MODELS

Table 3 shows a comparison between the test results and the predictable models in terms of shear nominal strengths of the beams. In the calculation made by the models, the modified effective strain proposed by Bui et al. [6] is utilized instead of the original ones.

Table 3 Shear strength of test beams derived from experiment, ACI and JSCE models

Beam ID	$F_{Exp.}$ (kN)	$V_{Exp.}$ (kN)	$V_{n\ ACI}$ (kN)	$V_{n\ JSCE}$ (kN)	$V_{n\ ACI}/V_{Exp.}$	$V_{n\ JSCE}/V_{Exp.}$
R1 (w/o ETS)	154.4	77.2	58.0	77.1	0.75	1.00
B1-0nut	198.4	99.2	70.3	87.8	0.71	0.89
B2-2Snut	178.1	89.1	70.3	87.8	0.79	0.99
B3-2Gnut	200.4	100.2	70.3	87.8	0.70	0.88
Mean	-	-	-	-	0.74	0.94
COV	-	-	-	-	0.055	0.069

Note: Subscript Exp. is data from the experimentation.

As shown in Table 3, the total shear strength calculated from the JSCE model incorporating with the modified effective strain offers the closer results to the actual shear resisting force than that made by the ACI code. The means of the ratios of the measure values to the calculated values are 0.94 and 0.74 for the computations with the JSCE and ACI guidelines, respectively. It is implied that the experimental shear strengths were slightly larger than the analytical shear strengths. Therefore, the JSCE and ACI models combining with a modified effective strain formula can be safely utilized to estimate the load carrying capacity of the concrete beams strengthened in shear with anchored-ETS bars and unanchored-ETS bars.

5. CONCLUSIONS

Based on the obtained results, the main conclusions can be pointed out as follows:

(1) The performance of inserting the ETS-GFRP bars without anchorage in RC beam was found by the increase of shear carrying capacity of 29% comparing with the reference beam. In addition, the beam retrofitted by ETS bars with two anchoring GFRP nuts offered 30% higher load carrying capacing of the reference beam. Whilst, the shear resistance in the ETS-strengthened beam with two anchoring steel nuts increased only by 15% compared to the load capacity of the unstrengthened beam.

(2) From the tested results, the anchorage presence and anchorage properties play an crucial role in the structural intervention efficiency of the ETS strengthening method for the RC beams.

(3) The beams strengthened with ETS bars provided more crack amount and less crack width than those in the reference beam. In addition, the ACI and JSCE models incorporating with the modified effective strain greatly predict the shear nominal strength of the beams. The accuracy of the model in the JSCE guideline is higher than that in the ACI guideline. Both the ACI and JSCE models associating with the modified strain equation can be used to estimate the shear resisting forces of the strengthened beams for a safety requirement.

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