Jurnal
Teknologi

Full Paper

THEORETICAL MODEL CONTRIBUTION OF CFRP LAMINATES ON SHEAR STRENGTHENING AND REPAIR OF RC BEAMS

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Article history
Received
13 July 2015
Received in revised form
11 October 2015
Accepted
5 November 2015

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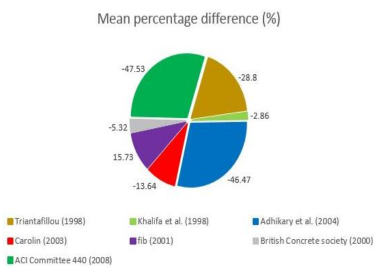
Graphical abstract



Abstract

The purpose of this case study is to review the effect and contribution of CFRP laminates on shear strengthening and repair of reinforced concrete beams. To date, the method is yet to become a mainstream application due to number of economical and design related issues. The current experimental work consists of one control beam and four beams wrapped with CFRP laminates [5]. The CFRP configuration are either fully wrapped or U shaped with orientation at 0°/90° and 45°/135°. This case study then identifies several theoretical model developed by Triantafillou [6]; Triantafillou and Antonopolous [7]; Khalifa and Nanni [8][9]; Adhikary *et al.* [10]; Carolin and Täljsten [11], and Täljsten [12] along with three design codes i.e. ACI 440 [2], BCS [3] and *fib* [4] towards predicing the shear contribution of CFRP laminate. The results for both experimental and theoretical value were then compared in term of mean percentage difference to select the best theoretical shear prediction value.

Keywords: CFRP, shear strengthening and repair, RC beam

Abstrak

Kajian kes ini bertujuan bagi mengulas mengenai kesan lapisan CFRP ke atas pengukuhan dan pemulihan rasuk konkrit bertetulang. Sehingga sekarang, kaedah ini masih lagi belum menjadi kaedah pembaikan dan pemulihan yang menjadi pilihan meluas industri Pembinaan disebabkan kos dan beberapa isu rekabentuk. Ujikaji makmal tersebut melibatkan satu rasuk kawalan dan empat rasuk yang diperkukuhkan dengan lapisan CFRP (N. Ali, 2014). Lapisan CFRP pula sama ada balutan penuh empat sisi ataupun bentuk-U dengan orientasinya sama ada 0°/90° dan 45°/135°. Seterusnya, kajian kes ini melibatkan pengenalpastian beberapa model teoritikal yang dibangunkan oleh Triantafillou [6]; Triantafillou dan Antonopolous [7]; Khalifa dan Nanni [8],[9]; Adhikary *et al.* [10]; Carolin dan Täljsten [11], dan Täljsten [12] bersama tiga kod rekabentuk iaitu ACI 440 [2], BCS [3] dan *fib* [4] bagi meramalkan nilai sumbangan daya ricih rasuk-rasuk yang telah diperkukuhkan dengan lapisan CFRP. Hasil daripada ujikaji makmal dan nilai teori seterusnya dibandingkan dengan mengambilkira perbezaan peratus purata bagi memilih model teori terbaik yang dapat memberikan nilai jangkaan kapasiti ricih rasuk.

Kata kunci: CFRP, pengukuhan dan pemulihan ricih, rasuk konkrit bertetulang

1.0 INTRODUCTION

Worldwide ageing infrastructures have arrested the interest of many researchers and organizations to find alternative materials and techniques to restore deteriorating and deficient structures. Recently, innovative composite materials known as carbon fiber reinforced polymer (FRP) have shown great promise in rehabilitation of existing reinforced concrete (RC) structures. Rehabilitation of these structures can be in the form of strengthening of structural members, repair of damaged structures, or retrofitting for seismic deficiencies. Many existing RC beams are deficient and in need of strengthening. Much focus and effort has been placed on understanding the behavior of FRP strengthened reinforced concrete structures especially beam. The question then is why advanced composites are suitable for civil engineering application? The shear failure of an RC beam is clearly different from its flexural failure. In shear, the beam fails suddenly without sufficient warning and diagonal shear cracks are considerably wider than the flexural cracks. In any case, composite materials are an excellent option to be used as external reinforcing because of their high tensile strength, light weight, resistance to corrosion, high durability and ease of installation.

2.0 LITERATURE RIVIEW

2.1 Type of de-bonding Failure

Based on previous study, a schematic representation of seven typical failure modes observed in tests is shown in Figure 1. For a full discussion of each of these failure modes, it is referred to Chen and Teng [1].

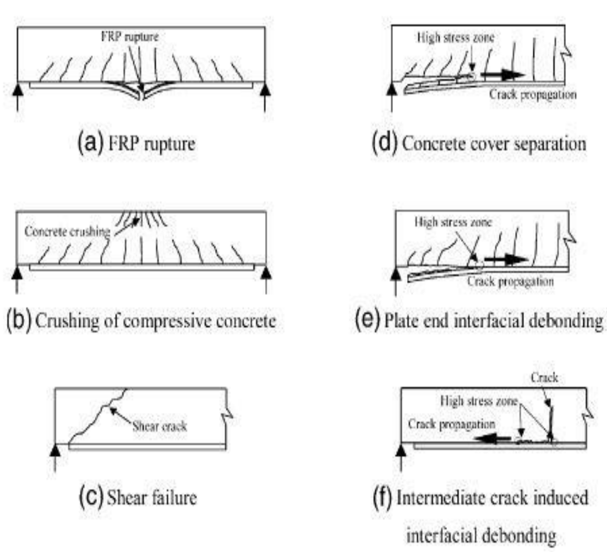


Figure 1 Failure modes of RC beam strengthened with CFRP [1]

2.2 Shear Strength of CFRP Strengthened RC Beams

The nominal shear strength of an RC beam may be computed by the basic design equation presented in most national codes [2], [3], [4]:

$$V_d = V_c + V_s \tag{1}$$

In this equation the design shear strength, V_d is the sum of the shear strength of the concrete, V_c and the contribution from the steel stirrups, V_s. Here, it is assumed that the law of superposition yields. If this also can be assumed to yield for CFRP strengthened beams, the shear strength can be expressed as:

$$V_d = V_c + V_s + V_{frp} \tag{2}$$

Based from the Eq. (2), it contain the contribution from the composites, V_{frp}. The problem now is to find an expression for V_{frp}. The value of V_{frp} is determined from the various strength model equation in shear failure.

3.0 METHOD AND MATERIALS

In this section, an interpretation of the available test data and a discussion of the current experimental approaches is presented. An interpretation of the available test data helps identify the parameters that have a certain impact on the shear contribution of CFRP.

3.1 Assessment of Current Experimental Works for CFRP Shear Contribution

A total of five beams were fabricated and tested at the Heavy Structures Engineering Laboratory, Universiti Tun Hussein Onn Malaysia (UTHM). The experiments involves a full-scale reinforced concrete continuous beams with a size of 150 mm width, 350mm depth and 5800mm effective length of each span. The values of beam shear span to effective depth ratio, a_v/d are 2.5. All the reinforcement details is shown in Figure 2 while CFRP strips orientation is in Figure 3. The experimental work was conducted by N. Ali [5].

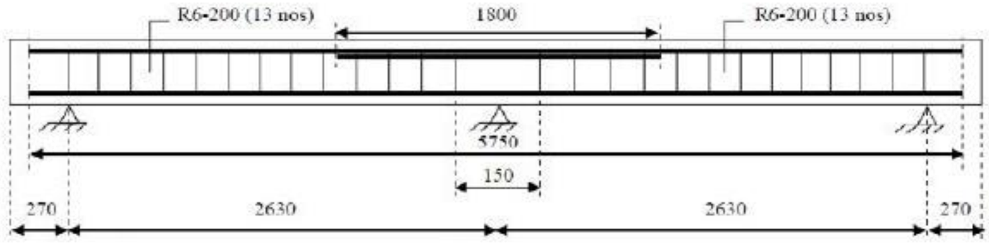


Figure 2 Reinforcement details [5]

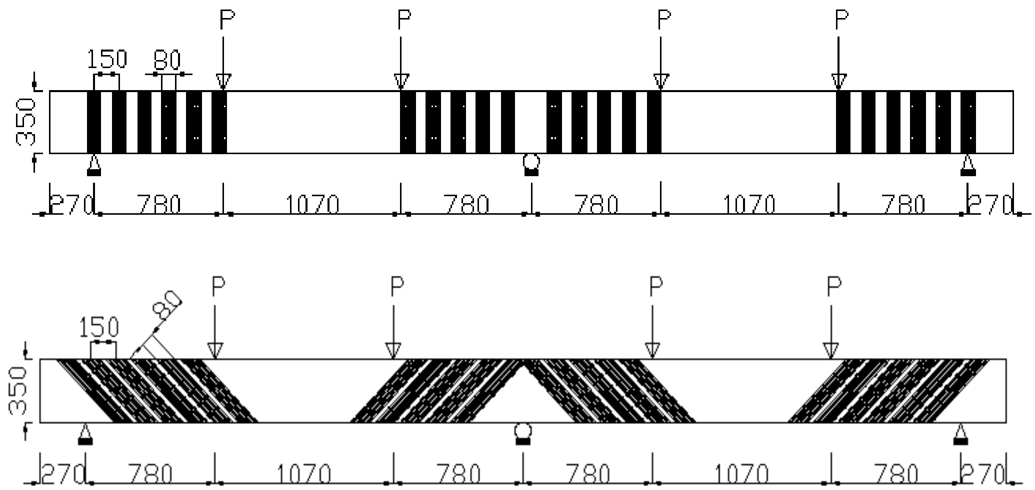


Figure 3 CFRP strips with different orientation [5]

Between the five beams tested, one of the beam were selected as a control beam (unwrapped) to compare between unstrengthen beam and strengthened beam with CFRP and named as (Beam 1-0). The second beam were fully wrapped with CFRP with 0/90 degrees of CFRP strips orientation and named as (Beam 2-1). The third beam has same CFRP strips configuration but different in wrapped scheme that is in U-shaped and named as (Beam 2-2). For the fourth beam, it is fully wrapped with 45/135 degrees of CFRP strips and named as (Beam 2-3). The last is the fifth beam that wrapped in U-shaped and the degrees of CFRP strips configuration is 45/135 [5].

All specimens of reinforced concrete continuous beams were designed in accordance to the British Standard, BS 8110: Part 1: 1997. Structural Use of Concrete: Code of Practice for Design and Construction with identical size of 150x350x5800mm. All the perimeter databases from the experimental work were summarize as Table 1 below.

Table 1 Parameter database (experimental work) [5]

Beam	CFRP properties								Experimental Data	
	d_f (mm)	E_{FRP} (GPa)	$\varepsilon_{FRPP,u}$ (%)	$f_{FRP,u}$ (MPa)	t_{FRP} (mm)	w_{FRP} (mm)	s_{FRP} (mm)	θ (°)	Contribution of CFRP, $V_{f,exp}$ (kN)	Modes of Failure
Beam 1-0	309	-	-	-	-	-	-	-	-	Shear
Beam 2-1	309	230	0.015	3800	0.165	80	150	27.6	87.60	Shear and CFRP rupture
Beam 2-2	309	230	0.015	3800	0.165	80	150	40.3	51.98	Shear, CFRP rupture and de-bonding
Beam 2-3	309	230	0.015	3800	0.165	80	150	41.9	125.15	Shear and CFRP rupture
Beam 2-4	309	230	0.015	3800	0.165	80	150	35.1	94.64	Shear, CFRP rupture and de-bonding

Notes: θ – experimental shear crack angle

3.2 Assessment of Existing Theoretical Models for Estimating CFRP Shear Contribution

This subsection summarizes seven existing theoretical model that is four in shear capacity model and three from design code. All models have been developed to evaluate shear contribution of externally bonded Carbon Fiber Reinforced Polymer (CFRP).

3.2.1 Triantafillou and Antonopoulos (1998,2000) Prediction Model [6][7]

$$V_f = 0.9\left(\frac{\varepsilon_{FRP,e}}{\gamma_{FRP}}\right) E_{FRP}\rho_{FRP} b_w d(1+\cot\beta)\sin\beta \qquad (3)$$

3.2.2 Khalifa and Nanni (2000,2002) Prediction Model [8][9]

According to Khalifa and Nanni [8], [9] the expression used to compute shear contribution of CFRP reinforcement is similar to that shear contribution of steel stirrups and it is expressed as:

$$V_f = \frac{A_{FRP} f_{FRP,e}(\sin\beta + \cos\beta) d_{FRP}}{s_{FRP}}$$

3.2.3 Adhikary et al. (2004) Prediction Model [10]

To compute the shear contribution provided by FRP bonded sheets, Adhikary *et al.* [10] proposed:

$$V_f = \rho_{FRP} E_{FRP} \varepsilon_{FRP,e} d_{FRP} b_w (\sin\beta + \cos\beta) \qquad (5)$$

3.2.4 Carolin and Täljsten (2005) [11] and Täljsten (2003) [12] Prediction Model

The proposed design model by Carolin and Täljsten [11], and Täljsten [12] is given by:

$$V_f = \eta\, \varepsilon_{cr} E_{FRP}\, t_{FRP}\, r_{FRP}\, z \frac{\sin(\theta + \beta)}{\sin\theta} \qquad (6)$$

3.2.5 Fib (2001) Design Codes [4]

The shear capacity of a strengthened element may be computed as:

$$V_f = 0.9\varepsilon_{FRP,e} E_{FRP}\rho_{FRP} b_w d(\cot\theta + \cot\beta)\sin\beta \qquad (7)$$

3.2.6 British Concrete Society (2000) Design Codes [3]

The FRP shear contribution can be calculated using the same analogy as web steel reinforcement. Shear resistance of the FRP sheets is given by:

$$V_f = \left(\frac{1}{\gamma_{FRP}}\right) A_f E_{FRP}\varepsilon_{FRP,e} \sin\beta(1+\cot\theta)\left(\frac{d_{FRP}}{s_{FRP}}\right) \qquad (8)$$

3.2.7 ACI Committee 440 (2008) Design Codes [2]

The shear contribution of the FRP shear reinforcement is given by (4) the equation:

$$V_f = \frac{A_{FRP} f_{FRP,e}(\sin\beta + \cos\beta) d_{FRP}}{s_{FRP}} \qquad (9)$$

4.0 RESULTS AND DISCUSSION

Table 2 below shows the result from calculation of theoretical model verified with several design codes. The data perimeter is obtained from current experimental work done by N. Ali [5] at UTHM.

Table 2 Theoretical results

Beam specimen	$V_{f,theory}$ (kN)							$V_{f,exp}$ (kN)
	Triantafillou [6] & Triantafillou and Antonopoulos [7]	Khalifa and Nanni [8][9]	Adhikary et al. [10]	Carolin and Täljsten [11] Täljsten [12]	fib [4]	British Concrete Society [3]	ACI Committee 440 [2]	Experimental works at UTHM
Beam 2-1	70.02	82.66	50.43	96.3	160.72	191.28	50.03	87.60
Beam 2-2	45.24	59.93	50.43	59.36	64.01	69.51	50.03	51.98
Beam 2-3	98.73	116.90	71.11	75.27	125.63	98.19	70.76	125.15
Beam 2-4	63.79	84.76	71.11	86.25	93.01	54.65	70.76	94.64

Figure 4 below shows the mean percentage difference in predicting shear capacity between theoretical models and experimental works.

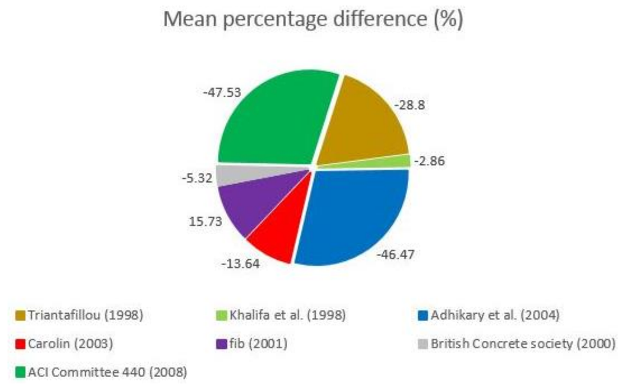


Figure 4 Mean percentage difference between theoretical and experimental

4.0 CONCLUSION AND RECOMMENDATIONS

In this case study, the shear performance of continuous RC beam has been investigated by N. Ali [5] at Universiti Tun Hussein Onn Malaysia (UTHM). Experimental database including results of shear contribution from CFRP from the experimental work were selected and compared from seven theoretical models selected for this study. The selected theoretical models are Triantafillou [6]; Triantafillou and Antonopolous [7]; Khalifa and Nanni [8], [9]; Adhikary *et al.* [10]; Carolin and Täljsten [11], and Täljsten [12] , followed by selected established design codes *fib* [4], British Concrete Society [3] and ACI Committee 440 [2] Hence, from the analysis conducted, it can be concluded that Khalifa *et al.* [8] model and British Concrete Society [3] design code model shows the most suitable equation in predicting the shear capacity for RC beams wrapped with CFRP laminates. Based on this studies, several recommendation suggested for future research are as follows:

1) To optimize the shear capacity prediction more beam data needs to be obtained with different value of CFRP thickness.
2) Effect of existing transverse steel reinforcement, shear span-to-effective depth ratio, a_v/d and FRP orientation in 0° on the shear contribution of CFRP needs to be considered in the proposed design.
3) The study on effective bond length should further be investigated as two opposite concept was applied by different available code.

Acknowledgement

The authors would like to thank the support provided by staff and students of the Department of Structural and Materials Engineering, Faculty of Civil and Environmental Engineering, Universiti Tun Hussein Onn Malaysia in successfully conducting this study.

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