CERTIFICATION OF APPROVAL

SHEAR STRENGTHENING OF RC T-BEAMS USING CARBON FIBER REINFORCED POLYMER (CFRP)

By

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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ABSTRACT

This study is carried out to study the shear contribution of FRP in reinforced concrete (RC) T-beam section, Due to the lack of data regarding the behavior of T-beam with FRP. However, civil infrastructures are design for a particular period of life cycle and it deteriorates with time. Therefore, strengthening of the deteriorate structure would be appropriate to extend the life of the structure or to give it an extra capacity of load taking. Fiber reinforced polymer has been used widely in the recent years. Design guidelines gives different value of the predicted shear contribution therefore this study is focus in the deferent's of these values with the experimental data. Moreover, during this study ACI 440-2 and *fib* bulletin 14 were used to predict the shear contribution of FRP in T-beam and compared the results with the experimental results.

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INTRODUCTION

1.1. Background Study

Concrete is a construction material consisting of cement, fine aggregate, coarse aggregate and water. These materials are mixed in certain ratio to produce the concrete mix, the nominal ratio of coarse aggregate (size greater than 5mm): fine aggregates (size less than 5mm): cement is 4:2:1. A chemical process known as hydration is the process of concrete hardening and solidification after mixing with water. The water reacts with cement, which bonds the other constituents together, eventually creating a rock-like material.

Construction of different structural element; beams, columns, slabs, pavements and others etc; mainly using concrete due availability and cheap raw materials. However, concrete reinforced beams generally carrying vertical gravitational loads, though, beams area able to resist horizontal loads (i.e, earthquake and wind loading). As a result of the applied loads on a beam, it experience compression, tension and shear stress. Above the support, the beams experience a shear stress that usually would be resisted by the stirrup steel links.

However, concrete structures deteriorate with time a repairing and retrofitting of the existing structure become a necessity. Repairing and retrofitting are traditionally accomplished by using conventional material and construction techniques. The rehabilitation methods can be of two types: (1) repairing technique, when the purpose is to restore the load bearing capacity of the concrete element, and (2) strengthening techniques, when the purpose is to increase the load bearing capacity.

However, recent developments related to materials, methods and techniques for structural strengthening have been enormous. One of today's state-of-the-art techniques is the use of fiber reinforced polymer (FRP) composites, which are currently viewed by structural engineers as “new” and highly promising techniques in the construction industry. FRP are available today mainly in two forms stripes or sheets. Composites have been used as strengthening materials of reinforced concrete (RC) elements (such as beams, slabs, columns etc.) in thousands of applications worldwide, where conventional strengthening techniques may be problematic.

Composite materials (FRP) have been used to strengthen reinforced concrete (RC) beams in shear widely. Shear failure of RC beam strengthened with FRP is a complex and controversial subject, even for simply RC beams is still remains not fully understood. Over the years, many analytical and design equations have been developed for RC beams strengthened with FRP.

Since the development of external bonded (EBR) FPR materials, intensive research has been conducted to study the contribution of FRP to the shear capacity of the reinforced concrete (RC) member. In the early years, research assumed that FRP materials behave like internal stirrup. Over the years, researchers conducted theoretical studies based on the addition principal.

$$V_n = V_c + V_s + V_{frp} \qquad (1)$$

Where V_c, V_s and $V_{frp}$are the shear contribution from concrete, stirrup steel and FRP respectively. The concept of the additional principal is that the contribution of FRP added to the ones developed from the stirrups and concrete.

However, shear contribution depend on FRP configuration and distribution. FRP distribution could be applied either as continuous sheets or in a form of strips with a predetermined spacing, Figure 1.1 (a, b). Moreover, different configuration of FRP would yield different shear contribution of the FRP. Mainly there are three configuration of FRP: Full wrap, U-warp or 2-sides, Figure 1.1(c, d, and e respectively).

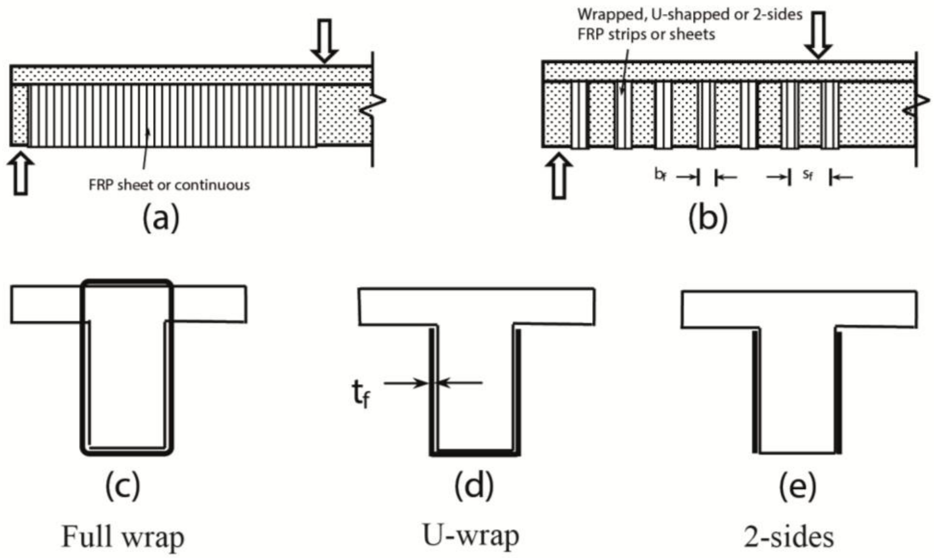

Figure 1.1 : Distribution and configuration schemes of FRP *(source fib 2001)*

Most of the studies at that time did not take any consideration of the strain fields nor interaction with steel stirrups. Chaalla model considered being one of the first models that predict the FRP contribution to strengthen shear. The model was based on the assumption that FRP materials and stirrups behave similarly. Moreover, the model assumes that the tensile strength of FRP is reached when it intersect by shear failure crack, if sufficient bond length is available. Malek and Saadatmanesh introduced the anisotropic behavior of the FRP considering the fiber orientation. Triantafillou derived a model supported by experimental data, using the strut-and-tie theory based on the calculation of the effective FRP strain. Khalifa developed Triantafillou'smodel by proposing a strain limitation due to the shear crack opening and extensive loss of aggregate interlocks. However, considering more tests assessed the model. Deniaud and Cheng carried out the tests and conclude that the FRP strain among the FRP crossing the crack are uniform. A design model was derived combining the strip method and the shear friction approach, based on the failure mechanism observed on the tested specimens.

Nevertheless, Chen and Teng proposed a refined model in 2004. The analysis of shear failure of reinforced concrete (RC) beams strengthened with FRP and concludes that the strain distribution in the FRP along the crack is non-uniform. The proposed model was based on the fiber rupture and debonding. Bond length coefficient and strip width coefficient was set as stress limitation. Based on the works of Chen and Teng, new design proposals have been formulated using reduction factors for the ultimate tensile strength and for the spacing between FRP strips. Zhang and Hsu proposed shear bond model following two approaches: model calibration by curve fitting and bond mechanism. Any of the two methods yield the smallest reduction factor for the effective strain was recommended to be used. Ye developed a shear debonding strength model based on Chen and Teng's model. Model was developed following the truss approach and describes the concrete, steel and FRP contribution to the shear capacity of RC beams based on the experimental observations made was carried by Pellegrino and Modena, taking lateral concrete peeling failure, under shear loading, of FRP into consideration. Monti and Liotta introduced a debonding model for the FRP-based shear strengthening of RC beams. The models take into consideration three elements: generalized constitutive law for the FRP-concrete bond, boundary limitations and shear crack opening provisions. Two cases for failure criterion of FRP strips/sheets are considered: straight strip/sheet and strip/sheet wrapped around a corner. The design proposal described in this model is used currently in the Italian design code CNR.

However, contribution of the FRP to strengthen RC depending on several parameter including stiffness of the FRP sheets, epoxy resin quality, concrete grade, wrapping scheme, number of layer of FRP and fiber orientation angle.

1.2. Problem Statement

Civil infrastructures are design for a particular period of life cycle and it deteriorates with time. Therefore, maintenance or strengthening of the deteriorate structure would be appropriate to extend the life of the structure or to give it an extra capacity of load taking. Fiber reinforced polymer has been used widely in the recent years. Therefore, different design guidelines has been published and practiced worldwide. However, different formulation in each design guide such as ACI 440, *fib* Bulletin 14 and CNR-DT 200/2004 for defining the shear contribution of FRP in different configuration. Moreover, most of the studies were conducted to study the use the FRP strengthening for rectangular beams, which create a lack of data for T-beam sections.

1.3. Objective and Scope of Work

The purpose of this study is to:

1. Study the shear contribution of FRP in RC T-beam.
2. Compare the experimental results with the predicted results using the ACI 440, *fib* and CNR-DT 200/2004.

CHAPTER 2

LITERATURE REVIEW

In recent years, an outstanding research effort has been undertaken with a view to understand the behavior of externally bonded (EB) fiber reinforced polymer (FRP) used for strengthening and retrofitting concrete structures. As a result, numerous aspects of the subject have been addressed, and many codes and design guidelines (hereafter called "the guidelines")for concrete structures strengthened with EB FRP have been published worldwide [e.g., American Concrete Institute (ACI)2008; CNR-DT 200/2004, 2006; fib 2001]. The use of FRP reinforcement for strengthening RC beams and slabs in flexure and for confinement of columns is well established. However, because of its complexity, the shear strengthening of RC members with EB FRP is still a research problem and requires further investigation to be completely solved (Bousselham and Chaallal 2004). Between 1992 and 2008, numerous research studies on the shear strengthening of RC beams with EB FRP composites were carried out [e.g., Chaallal et al. 1998; Triantafillou 1998; Khalifa et al. 1998; Pellegrino and Modena 2002; Chen and Teng 2003; Monti and Liotta 2006; Bousselham and Chaallal 2008].

The results of these studies led to several design equations and analytical models that were implemented in a code format to predict the shear contribution of EB FRP. However, recent findings have highlighted major influencing parameters related to shear strengthening with EB FRP that have still not been captured by existing theoretical predictive tools, including the codes and guidelines (Bousselham and Chaallal 2008). Although experimentally observed and quantified, these parameters remain insufficiently documented, and many questions about them remain unanswered.

The present section is intended to give a review of the most well-knowndesign guides for the prediction of the EBR FRP contribution for the shear strengthening of RC beams.

2.1. ACI 440.2R (2008)

The American Concrete Institute (ACI) (2008) is based on the Khalifa [9, 10] model, which is based on Triantafillou model [7], recommended a modified effective strain, both for fiber rupture and debonding failure. The FRP shear contribution to the total capacity of thebeam is given by:

$$V_{frp} = \frac{A_{frp} f_{frp} (\sin\beta + \cos\beta) d_{frp}}{s_{frp}} \quad (2)$$

The effective strain is different for the full-wrap FRP scheme, U-wrap and side-bonded FRP scheme. However, FRP-to-concrete bond mechanism is used to calculate the effective strain for U-wrap and side-bonded FRP scheme as follow:

$$\varepsilon_{fe} = k_v \varepsilon_{fu} \leq 0.004 \quad (3)$$

$$k_v = \frac{k_1 k_2 L_e}{11{,}900 \varepsilon_{fu}} \leq 0.75 \, ; L_e = \frac{23{,}300}{(n_f t_f E_f)^{0.58}} \quad (4)$$

$$k_1 = \left(\frac{f_{cm}}{27}\right)^{2/3} \; ; k_2 = \begin{cases} \frac{d_f - L_e}{d_f} \; (U - wrap) \\ \frac{d_f - 2L_e}{d_f} \; (Side - bonding) \end{cases} \quad (5)$$

2.2. *fib* (2001)

The regression of the experimental results preformed by Triantafillou and Antonopoulos (2000) was the bases of the *fib* (2001) provision on shear strengthening of RC beams. The shear contribution of the FRP shear reinforcement in the *fib* (2001) model is given by:

$$V_{frp} = \rho_f E_{fu} \varepsilon_{fd,e} b_w d (cot\theta + \cot\alpha) \sin\alpha \quad (6)$$

Where

$\varepsilon_{fd,e}$ = design value of effective FRP strain

b_w = minimum width of cross section over the effective depth

d = effective depth of cross section

ρ_f = FRP reinforcement ratio equal to $2t_f \sin\alpha / b_w$ for continuously bonded shearreinforcement of thickness t_f (b_w = minimum width of the concrete crosssectionover the effective depth), or $(2t_f/b_w)(b_f/s_f)$ for FRP reinforcement in the form ofstrips or sheets of width bf at a spacing s_f(Figure ….)

E_{fu} = elastic modulus of FRP in the principal fiber orientation

Θ = angle of diagonal crack with respect to the member axis, assumed equal to 45^o

α = angle between principal fibre orientation and longitudinal axis of member

In the fib guide, strengthening configuration and FRP type are controlling the effective strain. According to *fib* report the effective strain for side-bonded or U-wrap schemes can be calculated using a function of the axial rigidity of FRP (E_f, ρ_f) and the compressive strength of concrete as follow:

$$\varepsilon_{fe} = min\left[0.65\left(\frac{f_{cm}{}^{2/3}}{E_f\rho_f}\right)^{0.56} \times 10^{-3};\ \ 0.17\left(\frac{f_{cm}{}^{2/3}}{E_f\rho_f}\right)^{0.30} \varepsilon_{fu}\right] \qquad (7)$$

Where E_f is in Gpa and f_{cm}= cylindrical compressive strength of concrete in Mpa.

2.3. CNR-DT200 (2004)

The study by Monti et al [] was the base of the Italian CBR (2004) design guidelines for shear contribution of FRP. However, the CNR presented an equation for each type of FRP configuration as follow:

1- For U-warp FRP configuration

$$V_{fd} = \frac{1}{\gamma_{rd}}.0.9df_{fed}.2t_f.(cot\theta + cot\beta).\frac{w_f}{s_f} \qquad (8)$$

$$f_{fed} = f_{fdd} . \left[1 - \frac{1}{3} . \frac{L_e sin\beta}{min\{0.9; \hbar_w\}}\right] \quad (9)$$

2- For side-bonded configuration

$$V_{fd} = \frac{1}{\gamma_{rd}} . min\{0.9; \hbar_w\} . f_{fed} . 2t_f . \frac{sin\beta}{sin\theta} . \frac{w_f}{s_f} \quad (10)$$

$$f_{fed} = f_{fdd} . \frac{Z_{red,eq}}{min\{0.9d; \hbar_w\}} . \left[1 - 0.6 . \sqrt{\frac{L_{eq}}{Z_{red,eq}}}\right]^2 \quad (11)$$

Where

$$Z_{red.eq} = Z_{red} + L_{eq} , Z_{red} = min\{0.9d; \hbar_w\} - L_e sin\beta , L_{eq} = \frac{s_{uf}}{f_{fdd}/E_f} . sin\beta \quad (12)$$

Where:

γ_{rd} = Partial factor assumed to be 1.20 for side-bonded

f_{fed} = Effective FRP design strength

β = Angle of fiber angle with respect of member longitudinal axis

w_f , s_f = FRP width and spacing respectively.

f_{fdd} = Ultimate design strength.

L_{eq} = Effective bond length

s_{uf} = Ultimate debonding slip assumed to be equal to 0.2 mm.

E_f = FRP Young modulus of elasticity

CHAPTER 3

METHODOLOGY

3.1. Introduction

Ten T-beams section specimens were prepared for this research, each beamhas a length of 2 meters long, 300 mm flange width and 200 mm depth (As shown in figure 3.1). However, a formwork is made to cast the concrete beams. The beams are set to have concrete design strength of +/- 30Mpa. The following steps are to be done before the beams can be cast:

1. The formwork (non-permeable material) for the beam is constructed according to the planned dimensions.
2. Reinforcement bars to be bent and installed as per design.
3. Ordering concrete mix G30 from the batching plant (Ready-mix Concrete)
4. The design mix is batched to make the test beams.
5. Casting the test beams (10Nos).

The first step in specimens' preparation is the formwork, which was done using plywood in a T-section shape. Next, strain gauges are placed in a predetermined location on the rebar. After that, the rebar was placed in the formwork. However, rebar positions, location and spacing of the links, tying of links, dimension of rebar and link as well as concrete cover spacing to be maintained throughout. By completing this step the formwork is ready to be greased before pouring the concrete. Concrete was casted using 3 layer of concrete. Poker vibrator was used to ensure air is not entrapped and to avoid honeycomb in the concrete. However, the vibrator should not been used for too long to avoid bleeding and segregation problem in the concrete beams. Curing of concrete was carried out after finishing casting to avoid cracking in the beam due to the rapid loss of heat. Curing is done by spraying water on the concrete beams for twice a day for 14 days. After 3 days, the formwork is removed. The beams left for 28 days to reach full curing as per standard instructed. Next, the beams had been grinded to get a smooth surface for the FRP to be applied. After that, beams are reinforced by the FRP sheets and strips. Lastly, the beams are tested for the shear loss and the results will be compared to the control beams and the predicted results that were obtained using the calculation method according to design guidelines.

3.2. Reinforcement Arrangement:

The T-beam sections has been design to have two bars of 16 mm diameter for transverse steel and four bars of 10 mm diameter for top steel in the flange as shown in Figure 3.1(a) Two sets(A) and (B) of beams where prepared each set consist of 5 beams. Set (A) was prepared without shear links steel except for three links at each end as shown in Figure 3.1 (b) at spacing of 63 mm. Set (B) is provided with shear links steel at 150 mm spacing in each beam as shown in Figure 3.1 (c)

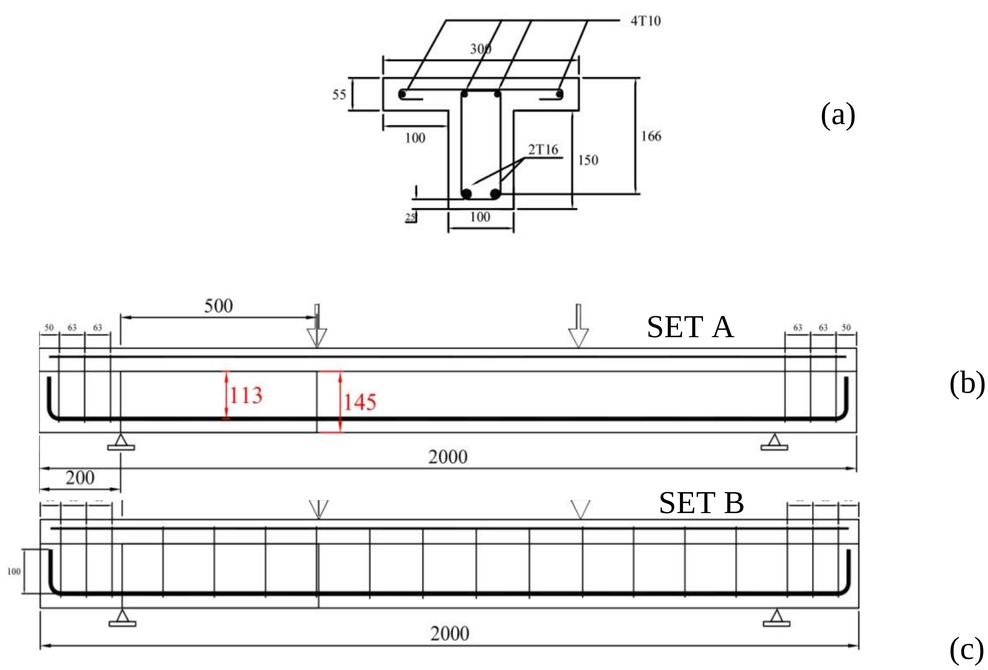

Figure 3.1 : Reinforcement steel arrangement

Figure 3.2 : Completed steel reinforcement bars

The above figure shows one of the beams after finishing tightening the steel bars using steel string to hold the bars in place.

3.3. Strain Gages:

A waterproofing strain gages has been placed on the bottom steel bars for set(A) beams, which is shear steel links is not provided and another two gages were installed on a shear links in both sides for set (B) beams, which shear links steel is provided. The process of installing the strain gages were installed with careful avoiding strain gages being spoiled. First, the bonding surface of the steel was polished and flatten using grinder and smoothen the surface using sandpaper of 300, then clean the surface with acetone. Next, is bonding the strain gages to the steel surface, the bonding process carried as follow:

1. A generous amount of CC33A being place on the back of the gage backing to form a coating.
2. The gage been set in place, covered it's surface with the polyethylene film, and with the tip of a finger, applying pressure to the gage installation from the film, thereby ensuring close adhesion of the gage.
3. Keeping the pressure for about 30 to 60 seconds, film been removed, then curing the gage installation at room temperature for about 4 hours.

4. A rubber coating, a mix of resin and hardener as well as silicon, around the strain gage is provided to avoid the damage of the gage during casting the specimen and the usage of vibrator.

Figure 3.3 : Strain gage place at the bottom reinforcement

3.4. Casting Preparation:

The formwork was greased with oil to avoid wood being hardened against the concrete surface. After the installation of the strain gages the steel frames was installed and placed in the wood form-work to be cast using ready-mix concrete as shown in Figure 3.4. A minimum cover assurance cube (Figure 3.5) was attached to the steel frames to insure that the minimum cover of concrete to be 25 mm.

Figure 3.4 : Rebars are placed and positioned in the form-work

Figure 3.5 : Minimum cover assurance cube

Then, grade 30 ready-mix concrete was delivered to cast the specimen. The casting of each beam was performed in three layers to ensure proper compacting of concrete and. An auto vibrator was used to avoid honeycomb in concrete. Three days later, the form-work was disassembled and beam was cured by spraying water for a week.

Figure 3.6 : Pouring concrete, vibrate and finishing surfaces

3.5. FRP Layering

The surface of the beams was grinded to remove cement laitance, loose and friablematerial to achieve a profiled open textured surface. All dust; loose and friable material was completely removed from all surfacesbefore application of the Sikadur®-330 by brush and industrial vacuum cleaner. Weak concretehad to be removed and surface defects such ashoneycombed areas, blowholes and voids ware fully exposed.

Sikadur®-330, a 2-part epoxy impregnation resin was used in preparation of the FRP layering. The ratio of the hardener to resin is 4:1 by weight; it was mixed until a grey color was developed according to the manufacturer instruction. A 1.00 mm layer thick was spread over the grinded surface using brush.

SikaWrap®-231 (C), Carbon fiber fabric for structural strengtheningwas used to strengthen the specimens. The CFRP was installed and rolled on top of the resin layer using a roller as been shown in Figure 3.7.

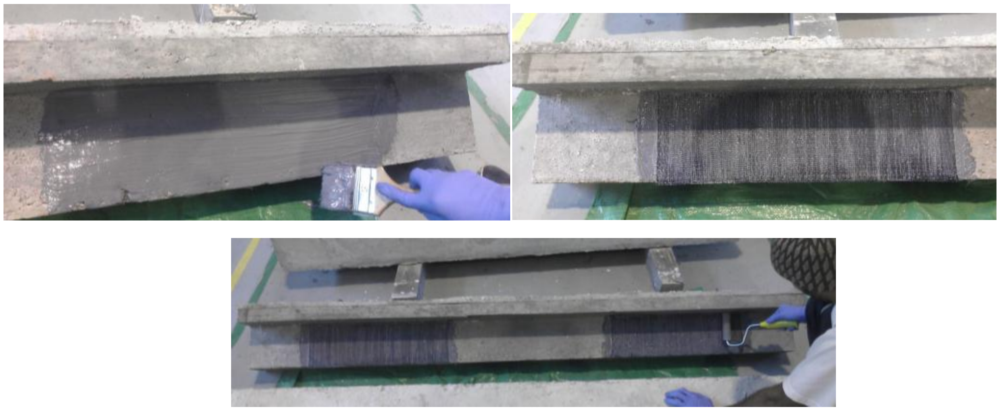

Figure 3.7 : Applying Epoxy and rolling FRP on designated positioned

After the installation of the CFRP layer the specimen would be cured for 24 hours in a room temperature, to insure a proper curing of the resin and the CFRP layer. Figure 3.8 shows diagram of all T-beams FRP layouts with dimensions and spacing of FRP.

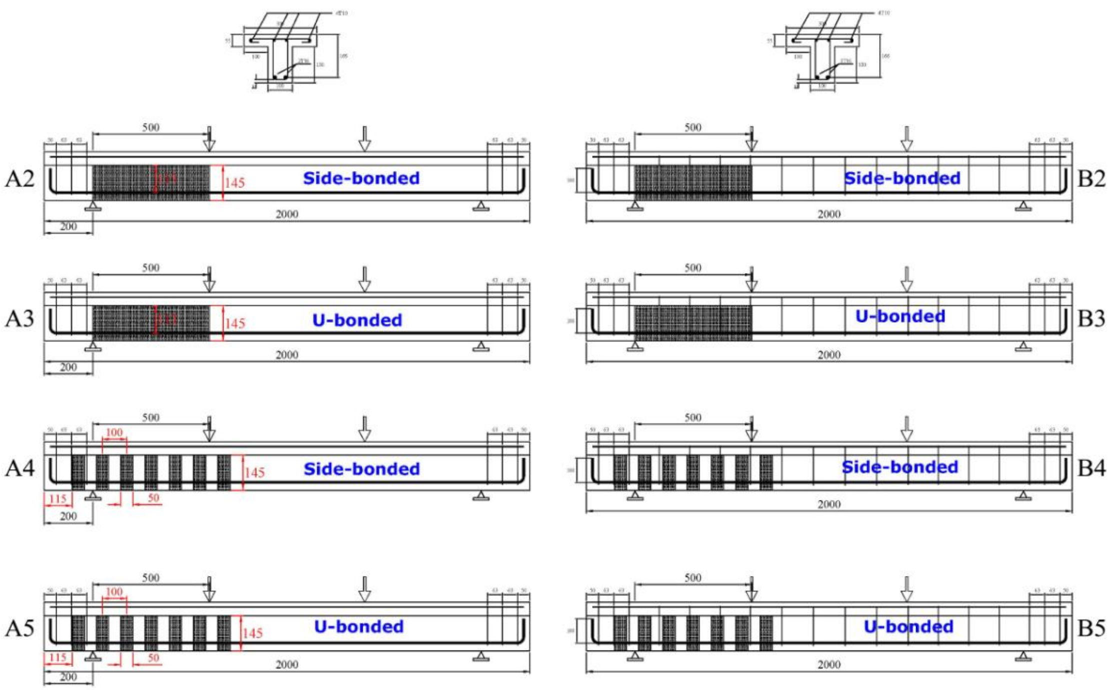

Figure 3.8 : FRP layout for both sets of specimens

TABLE 1: Beams specification summary

Set	Beams No	Length (mm)	Depth (mm)	Flange width (mm)	Web width (mm)	Flange depth (mm)	Shear Links (mm)	CFRP Distribution	FRP Config.
	A1							-	-
	A2							Continuous	2-sides
A	A3	2000	200	300	100	50	NO	Continuous	U-wrap
	A4							Strips	2-sides
	A5							Strips	U-wrap
	B1							-	-
	B2							Continuous	2-sides
B	B3	2000	200	300	100	50	YES	Continuous	U-wrap
	B4							Strips	2-sides
	B5							Strips	U-wrap

3.6. Testing Device

A steel column was fabricated in order to test the specimens in static loading testing. Figure 3.9 shows the diagram of the steel column. Beside the column a manual hydraulic jack was used for applying incremental loads.

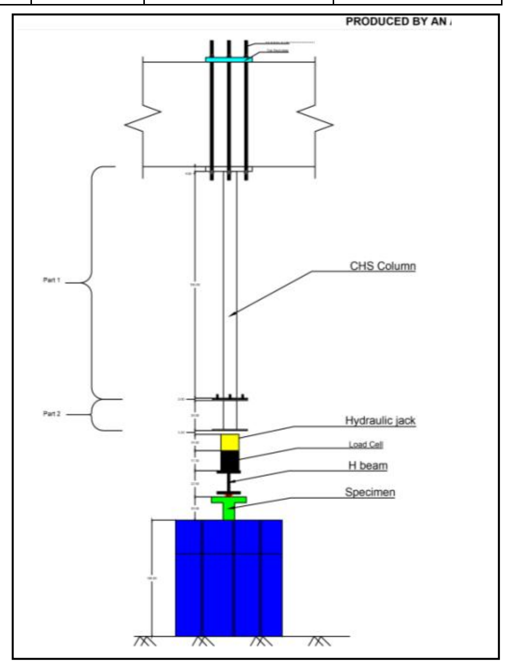

Figure 3.9 : Testing Scheme

CHAPTER 4

RESULT AND DISCUSSION

This research has been carried to study the shear contribution of FRP in RC T-beam using CFRP; therefore the following data was studied:

1. Compressive strength of the concrete using Portal Cement (OPC) for the beams.
2. The shear capacity of the beams with and without shear links steels.
3. The shear contribution of CFRP in different configuration (i) continuous U-warp, 2-sides and (ii) strips U-wrap and 2-sides bounding.

Casting of 10 no's of concrete T-beams, ready-mix concrete was used to maintain homogeneous concrete and to standardize the concrete batching. Ready-mix concrete was used due to the large volume of concrete (0.72 m^3) needed to cast the 10 no's of T-beams, since the mixer machine in concrete lab is not sufficient to prepare the one batch for all the T-beams.

4.1 Compression Test

The compression test was carried out for 12 cubes (100mm x 100mm) were tested. The results of the compression test are as in table below: (Using Ready-Mix concrete G30)

Day	Cube	Compressive Strength (N/mm^2)	Average Stress (N/mm$^{2)}$
	1		
	2		
	3		
	4		
	5		
	6		
	7		
	8		
	9		
	10		
	11		
	12		

Table 2: Compression test results

4.2 Predicted Results

Shear contribution of FRP (V_f) changes as the FRP configuration changes. Hence, the predicted result of the different configuration of FRP is shown in table 3. The results obtained are according to ACI 440-2 and *fib* Bulletin 14 (2001).

Beams No	FRP Distribution	FRP Configuration	ACI 440-2 (kN)	*fib* Bulletin 14 (2001) (kN)
A2, B2	Strips	U-Wrap	27.64	37.27
A3, B3	Strips	2-sides	22.58	37.27
A4, B4	Continuous	U-wrap	55.30	50.67
A5, B5	Continuous	2-sides	54.078	50.67

Table 3: Summary of predicted result

CHAPTER 5

CONCLUSION

Based on the result and discussion the difference between the ACI 440 and fib prediction indicate that there is variance in formulation and this results should be compared with the experimental data, which would be obtained via static loading testing.

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NOTATION LIST

γ_{frp}	partial safety factor for the tensile strength of FRP
b_w	minimum width of CS over the effective depth
d	effective depth of the CS
β	fibre angle direction with respect to the longitudinal axis of the beam
$\varepsilon_{frp,e}$	effective FRP strain at failure
t_{frp}	thickness of the FRP
E_{frp}	the elastic modulus of FRP
f_c	Concrete compressive strength
w_{frp}	width of the FRP
θ	crack angle direction with respect to the longitudinal axis of the beam
d_{frp}	effective depth of FRP over the height of the beam
$f_{frp,e}$	effective tensile stress in FRP
$h_{frp,e}$	the effective height of the FRP bonded on the web
h	height of the beam
d_t	is the distance from the compression face to the top edge of the FRP
d_c	the distance from the compression face to the lower edge of the FRP
$f_{frp,u}$	Ultimate tensile strength of FRP
γ_b	the partial safety factor for bond strength equals 1.25
$\varepsilon_{frp,u}$	ultimate tensile strain of FRP
ε_{cr}	is the critical strain
τ_{max}	is the maximum shear stress of concrete
$\gamma_{frp,d}$	is a partial safety factor depending on application quality
s_{frp}	is the distance between the FRP strips/sheets
w	is the width measured orthogonally to β
l_e	is the effective bond length
$f_{frp,dd}$	is the debonding strength
α	is the crack opening angle
$f_{frp,ed}$	is the effective debonding strength
h_w	Is the height of the web of a T beam
η	equals to 0.6 is the strain reduction factor