Shear Strengthening of Reinforced Concrete (RC) beams using Fiber Reinforced Polymer

By

Osorio Mbuziavo Baltazar Nhanzilo

Dissertation submitted in partial fulfilment of
The requirements for the
Bachelor of Engineering (Hons)
(Civil Engineering)

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CERTIFICATION OF APPROVAL

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Approved by,

(Dr. Teo Wee)

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ABSTRACT

In the last 20 years or so, Fiber Reinforced Polymers (FRP) have been developed as cost effective materials that can be used in the construction field particularly in the reinforcement of structural elements in buildings and bridges. Some of the advantages that FRP composites bring include good corrosion resistance and due to their light weight FRP's provide ease in handling for site works.

This report is a summary of tasks done and relevant to a study made on 'Shear Strengthening of Reinforced Concrete (RC) Beams using Fiber Reinforced Polymers' by the author under the supervision of Dr. Teo Wee.

This report describes the outcomes obtained from experiments made to understand the shear contribution of externally bonded Carbon Fiber Reinforced Polymer on RC beams at 90, 45 and 25 degrees. Parameters such as shear span-to-depth ratio, CFRP orientation against the longitudinal axis particularly at shallower angles were the focus of this study. The analysis of this study is comprised of comparisons done from observing the shear behavior of externally strengthened and non-strengthened RC beams. In addition shear contribution predictions using ACI 440 formulas were also compared with data from the experiment. Tests results showed significant improvements in terms of ductility, superb cracking control particularly when CFRP plates are used at shallower angles. A few recommendations in terms of refining the parameters used for better results are also included in this study.

NOMENCLATURE

$Af = ntfwf,$	Area of FRP external reinforcement, (mm^2)
a/d	Shear span-to-depth ratio
Afv	Area of FRP shear reinforcement with spacing s, (mm^2)
Ag	Gross area of section, in.2 (mm2)
As	Area of nonprestressed steel reinforcement, (mm^2)
Ast	Total area of longitudinal reinforcement, in.2 (mm2)
b	Width of rectangular cross section, in. (mm)
bw	web width or diameter of circular section, in. (mm)
CE	environmental-reduction factor
d	distance from extreme compression fiber to the Neutral axis, in. (mm)
df	depth of FRP shear reinforcement as shown
Ec	modulus of elasticity of concrete, psi (MPa)
Ef	tensile modulus of elasticity of FRP, (MPa)
Es	modulus of elasticity of steel, (MPa)
fc	compressive stress in concrete, (MPa)
fc¢	specified compressive strength of concrete, (MPa)
ffe	effective stress in the FRP; stress level attained at section failure, (MPa)
ffu	ultimate tensile strength of the FRP material as reported by the manufacturer,(MPa)
fy	specified yield strength of nonprestressed steel reinforcement, psi (MPa)
$k =$	ratio of the depth of the neutral axis to the reinforcement depth measured on the same side of neutral axis
kf	stiffness per unit width per ply of the FRP reinforcement, (N/mm); $kf = Ef\,tf$
k_1	modification factor applied to kv to account for the concrete strength
k_2	modification factor applied to kv to account for the wrapping scheme
Le	active bond length of FRP laminate, in. (mm)
n	number of plies of FRP reinforcement

pfu *	ultimate tensile strength per unit width per play of the FRP reinforcement,.(N/mm); *pfu* * =*ffu*
sf	spacing FRP shear reinforcing as described in
tf	nominal thickness of one ply of the FRP reinforcement,(mm)
Vc	nominal shear strength provided by concrete with steel flexural reinforcement, (N)
Vn	nominal shear strength, lb (N)
Vs	nominal shear strength provided by steel stirrups, (N)
Vf	nominal shear strength provided by FRP stirrups, lb
wf	width of the FRP reinforcing plies, in. (mm)
a	Angle of inclination of stirrups or spirals, degrees
e*fe*	effective strain level in FRP reinforcement; strain level attained at section failure, (mm/mm)
e*fu*	design rupture strain of FRP reinforcement, in./in. (mm/mm)
e*fu* *	ultimate rupture strain of the FRP reinforcement (mm/mm)
k*m*	bond-dependent coefficient for flexure
k*v*	bond-dependent coefficient for shear
yf	additional FRP strength-reduction factor

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CHAPTER 1

INTRODUCTION

BACKGROUND OF STUDY

In the construction field, reinforced concrete structures are usually designed and built to last a given service life. During their designed service life many concrete structures go through a number of processes that end up inducing upon them higher loadings and stresses than those that they were designed for. After a number of years the wearing and tearing of the buildings becomes quite visible and the necessity for maintenance becomes more apparent. In addition there are cases whereby these structures are required to have a higher load carrying capacity due to either design code revision or the necessity to change the purpose of the building. Past practices to curb these needs included casting additional reinforced concrete, dowelling in additional reinforcement or externally post-tensioning the structure (Arya 2001).

In recent times the technique of using steel plates as external reinforcement in concrete structures has been adopted, in order to effectively achieve this process adhesive and bolts have been used. Has an improvement of this practice Fiber Reinforced Polymers have been adopted as replacement for the steel plates and the most common practice employs the use of carbon fibers as FRP.

Due to their physical characteristics, CFRP of Carbon Fiber Reinforced Polymers has a number of advantages over steel. These can be used in situations where it would be impractical to use steel particularly in scenarios of limited headroom such as in bridges and tunnels. For plates of similar strength CFRP plates are lighter and thinner which prevents additional weight and dimension increments on the structure, and eliminates the need to temporarily support the plates until the adhesive gains strength (Arya 2001).

According to Darby (2010) there are numerous examples that clearly highlight and showcase the use of Fiber Reinforced Polymers; in countries that make up the United Kingdom where in order to fulfil a requirement to carry heavier commercial vehicles, a number of bridges had to undergo extensive assessments. To achieve this, bridge decks were strengthened by attaching FRP plates on soffits and top surfaces. Other reinforcement works involved, wrapping columns from the exterior in order to increase ductility and thus enhance seismic capacity of the bridge columns. When it comes to buildings, FRPs have been applied in strengthening floor slabs, wrapping main columns which in some cases resulted in addition of a few more floors. According to the source, all of the examples mentioned were achieved under minimal duration with very minimum increment in terms of the dimensions of the structure.

In the last decades the use of Fiber Reinforced Polymers in the construction field has been gaining growing popularity. Nowadays FRP composites can be considered to be somewhat construction materials, and as of late the engineering community has been preparing itself to conceive FRP composite materials as part of routine structural design alongside other usual construction materials (Bank 2006). The growing amount of extensive research work being done to this date is proof of the importance and recognition that FRP composites have gained. In addition, a number of textbooks and codes such as ACI 440.2R-02 and others further explain and give guidance on the limitations of its use in construction as internal reinforcement, and in depth information on their use as external reinforcement for RC members such as beams and columns.

FRP composites may come in three different types: glass-fiber-reinforced polymer (GFRP); carbon-fiber-reinforced polymer (CFRP); and last aramid-fiber-reinforced polymer (AFRP). All three types are based on the type of fiber used in their production mainly: carbon fibers, glass fibers and aramid fibers. For the purpose of conducting this project CFRP shall be used.

According to Teng (2002) all three types of FRP composites have been employed in RC strengthening for practical and research purposes and their mechanical properties are as follows:

Unidirectional advanced composite materials	Fiber content (% by weight)	Density (Kg/m^3)	Longitudinal tensile modulus (Gpa)	Tensile strength (Mpa)
GFRP	50-80	1600-2000	20-55	400-1800
CFRP	65-75	1600-1900	120-250	1200-2250
AFRP	60-70	1050-1250	40-125	1000-1800

Table 1 : Mechanical Properties of FRP Composites (Teng 2002)

It ought to be noted that the values displayed in the table above may be subject to change, and that the tensile strength may vary according to the defined thickness. Furthermore the mechanical properties of any type of FRP composite shall be followed according to recommendations from the manufacturer (Teng 2002).

An argument may arise as far as reinforcement is concerned when it comes to comparisons between steel bars or sheets and FRP composites. I such arguments it's important to understand the elastic behavior of which in order to estimate the extent in which one of these material is more suitable than the other. FRP composites, in terms of stress-strain behavior tend to have a linear elastic behavior until brittle failure occurs when subject to tension, whereas steel tends to have better ductile behavior (Teng 2002). Therefore, since FRP composites don't possess the ductility that steel does, they can't be used as direct replacements of steel during design. Having said so, it is important to understand that FRP composites can offer benefits in their use over steel.

FRP composites do not easily undergo corrosion which may lead to loss of strength like in the case of steel; they also provide ease of bonding with concrete members of any shape and surface irregularity (J. Jayaprakash, 2007) and high strength to weight ratio (Deniaud, Cheng 2001) which provides long lasting performance.

By following what was mentioned in the previous paragraph it can be stated that FRP sheets can be the primary choice over steel sheets when it comes to external reinforcement of RC structures on buildings and bridges. After long years of existence a structure may lose its original strength or ductility; this loss may be due to fatigue or corrosion of steel reinforcement as a result of environmental effects.

Two aspects which external reinforcement usually addresses are flexural and shear strengthening. Over the years a number of methods have been developed to address flexural failure, whereas previous research done to predict shear failure has not been conclusive enough in predicting shear strength of strengthened reinforced concrete members (Gyuseon, Jongsung, Hongseob, 2007). This is due to factors such as shear span-to-depth ratio, FRP-concrete bond-slip relationship, and orientation of the FRP sheets; which have proven to be quite complex in nature.

Shear failure is of most concern as concrete failure may occur without prior notice or warning. In this project the aim is to look further into previous theoretical work done in the field of FRP and to extensively study shear strengthening in concrete beams using Carbon Fiber Reinforced Polymer sheets aligned at angles of 90, 45 and 25 degrees.

1.2 PROBLEM STATEMENT

In RC beams shear and flexural failure are of concern, and RC beams are normally designed to have flexural failure as the strength-governing failure mode since flexural strength is ductile. Ductility in reinforced concrete beams allows stress redistribution which gives out a warning of possible failure to users of a certain structure. Shear failure in reinforced concrete is a major concern because it may occur without prior warning. If an RC beam has less shear capacity than flexural capacity, after flexural strengthening has been done shear strengthening must be done (Teng 2002).

Shear stresses in concrete are known to create diagonal cracking, as measure to not only contain such cracking but to also increase shear capacity FRP composites have been used. However, most research work done has only addressed the effectiveness of FRP at either vertical, horizontal or 45 degree inclination. The study of the effectiveness of FRP has not been shown to focus on angles lower than 45 degrees.

The significance of conducting studies on FRP external reinforcement with sheets aligned at angles shallower than 90 degrees lies on the principle that perpendicular arrangement of the FRP sheets tackles diagonal cracking better. Furthermore, Teng (2002) explains that the positioning of fibers at all directions with the exception of those that are parallel to shear cracking, do help in limiting the shear crack with.

1.3 OBJECTIVES

- To understand the effectiveness of using CFRP sheets at vertical, 45 and 25 degree angles in terms of shear strengthening contribution on reinforced concrete elements such as beams given a shear span-to-depth ratio $a/d = 3.7$
- To study the performance of CFRP in terms controlling diagonal cracking of RC beams.
- To relate and conduct analysis of data gathered from theoretical predictions of shear contribution of CFRP against experimental data.

1.4 SCOPE OF STUDY

Due to the amount of time allocated and the magnitude of final year projects, this project focuses only on aspects related to shear strength and shear strengthening contributions of CFRP on RC beams. Within the scope of shear failure the study looks into analyzing the failure of an externally reinforced beam given a span to depth ratio of a/d = 3.7, CFRP inclination and spacing. Flexural failure shall not be covered here, as a number of researches have been done to study its effects on RC beams.

A total of four (4) rectangular beams of size 100 x 200 mm^2 were used for testing; the beams are of 2 meter length, for flexural reinforcement 4 steel bars of 12 mm diameters each were used with no stirrups. The beams were casted using concrete batch that was supplied by a private source. It is common practice from previous studies conducted not use stirrups which have the purpose of providing shear reinforcement. Another reason behind this decision is to limit the amount of factors to be analyzed in the understanding of CFRP shear contribution on RC beams.

CFRP sheets shall be used for shear reinforcement, and the specimens shall be subjected to 2 point loads that will induce deformation. A number of laboratory tests will be conducted to assess the shear contribution of FRP sheets placed at shallow angles, on concrete beams.

All the procedures performed to come out with the test specimen including the attachment process of CFRP on the beams were based on instructions from codes as well as product use recommendations from the manufacturers of CFRP.

1.5 PROJECT FEASIBILITY

Based on the objectives set, and the clear understanding of the scope of the project, it could be stated that the amount of time allocated to conduct this research was just enough to obtain results in order to perform the required analysis. The process that leads to the testing date is quite extensive by itself; the reinforced concrete beam specimens need to observe a 28 day curing, and the process to obtain the CFRP plates that fit the dimensions needed can take approximately 2 weeks to prepare. In addition the period to set up the beam and to prepare the required adhesive combined with the period of CFRP attachment all the way to having a dry bond, can take another week per beam. In short, most of the period given to conduct this research was spent doing planning and setting up the test specimens, and in the end 4 beams was tested successfully.

If not for time constraints the number of tests done could have been doubled as enough test specimens were available and other arrangements of CFRP external reinforcement could have been tested. In the end it can be stated that the schedule does fit in terms of achieving the goals of this research.

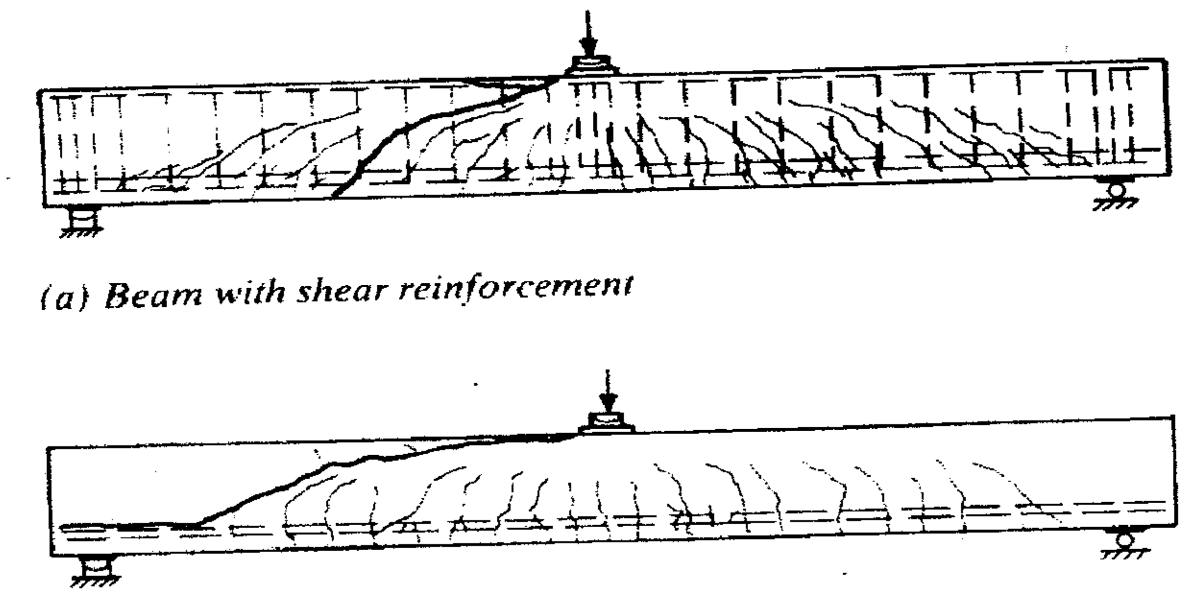
CHAPTER 2

LITERATURE REVIEW

2.1 SHEAR FAILURE IN CONCRETE BEAMS

Since one of the main objectives of this project is to study the contribution of CFRP towards shear strengthening of concrete beams, before conducting furthers studies, the topic of shear failure in concrete beams must be addressed and understood.

If diagonal failure can be considered as a signal of failure in reinforced concrete member, then according to a paper written by Michael D. Kotsovos, diagonal failure occurs when the 'shear capacity' of a critical section of the member in question is exceeded. He also claims that diagonal failure will have different type of occurrences depending on the existence of shear reinforcement on the beam or not. The prediction can be seen in the figure bellow whereby with shear reinforcement the diagonal failure occurs closer to the applied load, and without it occurs closer to the support.



(a) Beam with shear reinforcement

(b) Beam without shear reinforcement

Figure 1 : Effect of Shear Reinforcement upon Diagonal failure of beams (Michael D. Kotsovos)

Source: Kotsovos, 1983, *Mechanisms of 'shear failure'*

Besides the presence of shear reinforcement, other factors that contribute to the mode of diagonal failure are: shear span to depth ratio (a_v/d), amount of longitudinal reinforcement which factors into the load that causes a certain mode of failure. Further support for the claim that shear failure in a concrete beam without stirrups is directly related to shear span to depth ratio (a_v/d) can be found in 'Kani's shear valley' see figure 2 (Kani 1967, Valerio 2009).

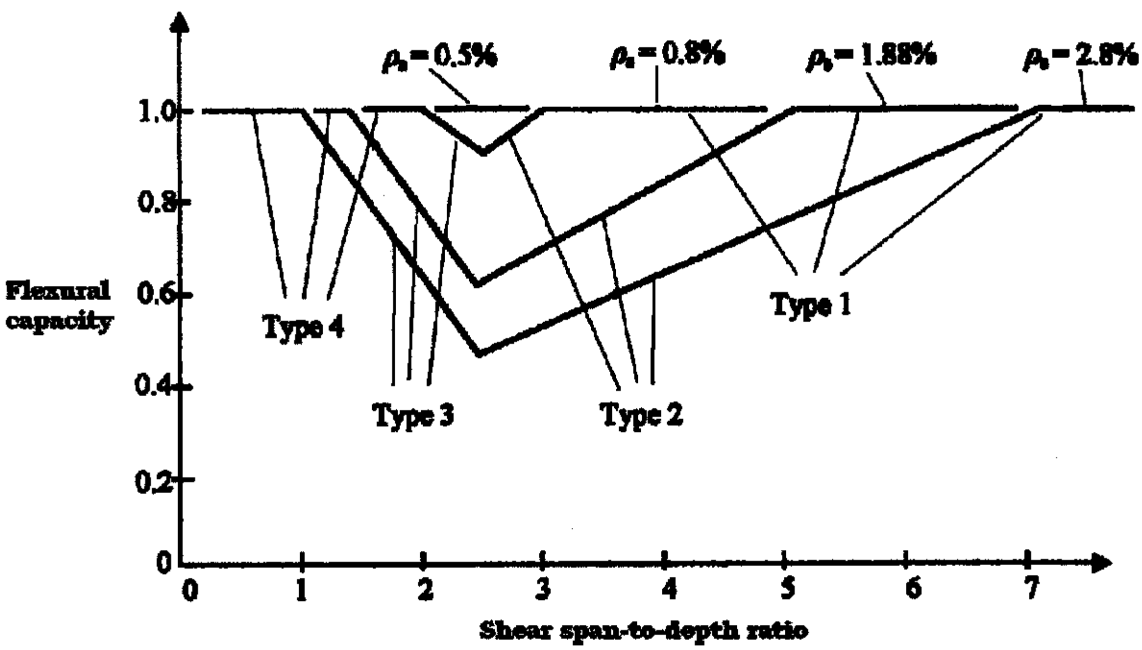


Figure 2 : Kani's 'shear valley' diagram
Source: Kotsovos, 1983, *Mechanisms of 'shear failure'*

According to Kani the figure can be interpreted as such: Type 1 stands for flexural failure, Type 2 for diagonal tension failure, Type 3 shear-compression failure and web-crushing failure as Type 4. Furthermore he depicts that slender beams will fail in diagonal tension, but the use of stirrups may invert shear failure in beams to flexural failure as concrete members with the right amount of stirrups will endure flexural failure or shear-compression in the compressive zone. Having said that, shear span to depth ratio (a_v/d) remains the primary factor that governs shear failure.

Another great piece of research that although is of some age is a very fundamental piece of work written by Kani (1964) explains how shear force was the main reason behind diagonal cracking in beams. Based on the paper by analyzing failure in concrete beams due to point loads, cracks began to appear outside of the central section where bending moment prevailed. The only forces acting outside the central section were shear force, thus it was concluded that only shear forces were the reason behind cracking and the name shear failure surfaced. Reasons such as failure of bond between concrete and steel have also been considered to contribute to shear failure even thou they can only be considered as third party.

2.2 FIBER REINFORCED POLYMER

In order to undertake this project a number of research papers in the field of FRP use were looked into to understand the depth of work that has been done.

Deniaud and Cheng (2000) came out with a study that analysis and compares design methods to be used in shear design of reinforced concrete beams to be externally strengthened with fiber reinforced polymers. They used eight T beams with FRP as tests specimens and the results revealed that FRP strengthening was dependant on the amount of reinforcement used. If beams were heavily reinforced with internal shear reinforcement the FRP sheets would be less effective, and that the external use of FRP could decrease the beam shear capacity by changing the critical path which would lead to an even more sudden shear failure. It should also be noted that in this test they used FRP sheets at an orientation angle of 90° (ninety degrees). In this study they included the following equations and analytical models:

- Triantafillou 1998;
- Malek and Saadatmanesh 1988;
- Khalifa et al. 1998;
- Chaallal et al. 1988;
- CSA-S806 2000;
- Modified shear Friction Method; and
- Strut-and-tie model.

The above models were used to compare theoretical and experimental results that the specimens produced. Based on the analysis of the results the Modified Shear Friction method proved to be the most reliable as it predicted accurately concrete crack angles and gave a description of shear failure modes. Models such as strut-and-tie proved to give only conservative results for the study.

Further studies made to compare different forms of orientations and inclination of FRP sheets were made by Zhang, Cheng-Tsu and Thomas Hsu (2010). In their analysis they used eleven rectangular (152.4 x 228.6 mm2) RC beams, where five of them were 1.22 meters long and the rest 1.83 m long. To be noted that 6 beam bars were reinforced against flexural failure and proper anchorage was provided. In terms of external reinforcement Carbon Fiber Polymers were used.

Out of all the orientations used two CFRP orientations stood out in terms of tests results, which are of relevance to our studies. One of the beams used CFRP inclined at an angle of 45° (forty five degrees) and the other at 90° (ninety degrees). Three types of tests were used to understand their contributions: Ductility tests, Strength tests, and Failure Mechanism.

As a result of those tests it can be concluded that CFRP reinforcement at 45° (forty five degrees) is the most suitable and gives better results than those at 90° (ninety degrees) or horizontal orientations. At 45° (forty five degrees) the CFRP sheets displayed higher contribution of shear capacity in terms of strength, and proved to give larger deflections at ultimate in comparison with the others, it also proved to be more ductile.

To further support the claim that 45 degree CFRP inclination provides better external strengthening in beams, a study by Gyuseon, Jongsung and Hongseob (2007) was made. For this particular study the beams had a 220 x 250 mm2 with a span of 2 meter stressed using two point loads. The CFRP had a number of different arrangements and inclinations, most notably 45 and 90 degrees. According to the study beams using CFRP strips at 45 degree inclination proved to have higher increment in shear strength and also prevented diagonal cracking from happening, vertical cracking occurred instead.

CHAPTER 3

RESEARCH METHODOLOGY

As stated before, for the purpose of conducting this study four (4) reinforced concrete beams were used, whereby three of them were attached with a carbon fiber reinforced polymer (CFRP) at different inclination angles and the one beam without CFRP was used as control beam. The purpose of having a control beam for testing is to provide an indication of the loading which will induce failure of a given RC beam without CFRP external reinforcement. The result obtained will be used as a baseline to understand the type of improvements created on the beams performance after attaching CFRP.

3.1 BEAM DETAILS

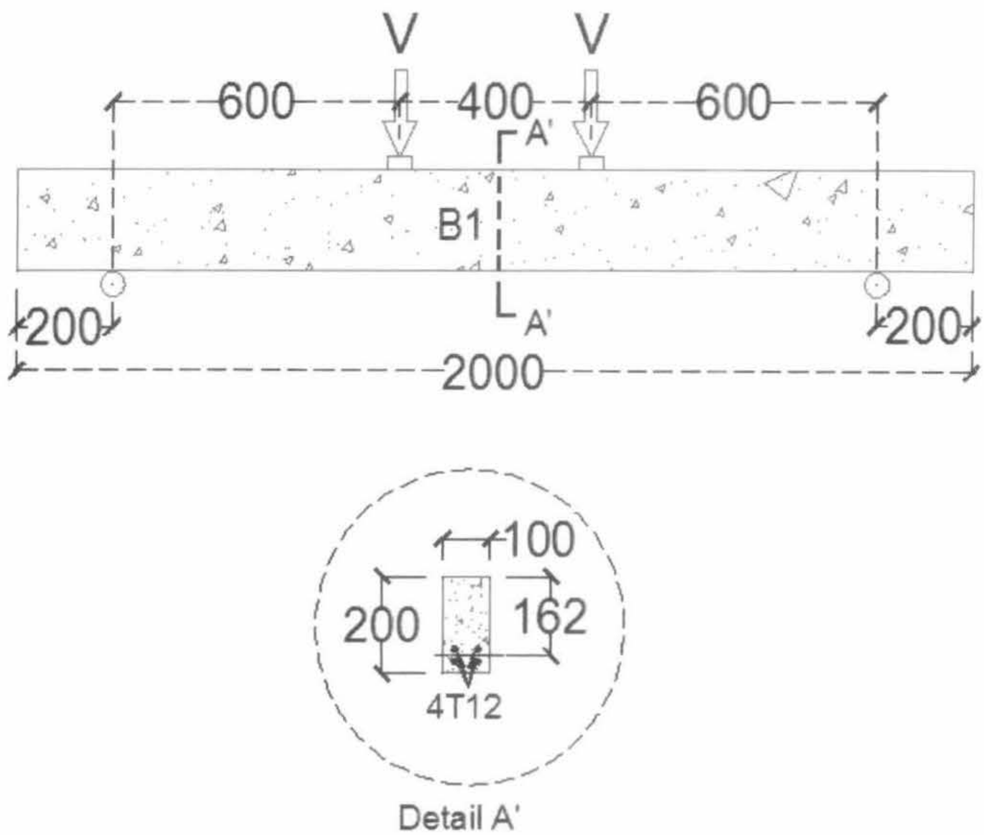


Figure 3 : Beam Section details and loading schemes

From the figure above we can see that the beams will have a 100 x 200 mm^2 rectangular size with 2000 mm of length with 4 T12 steel bars. The shear span is observed to be 600mm measured from the support to the nearest point load. For this particular project the study of shear failure shall be done according to the following shear span to depth ratio of:

$$a_v/d = 3.7$$

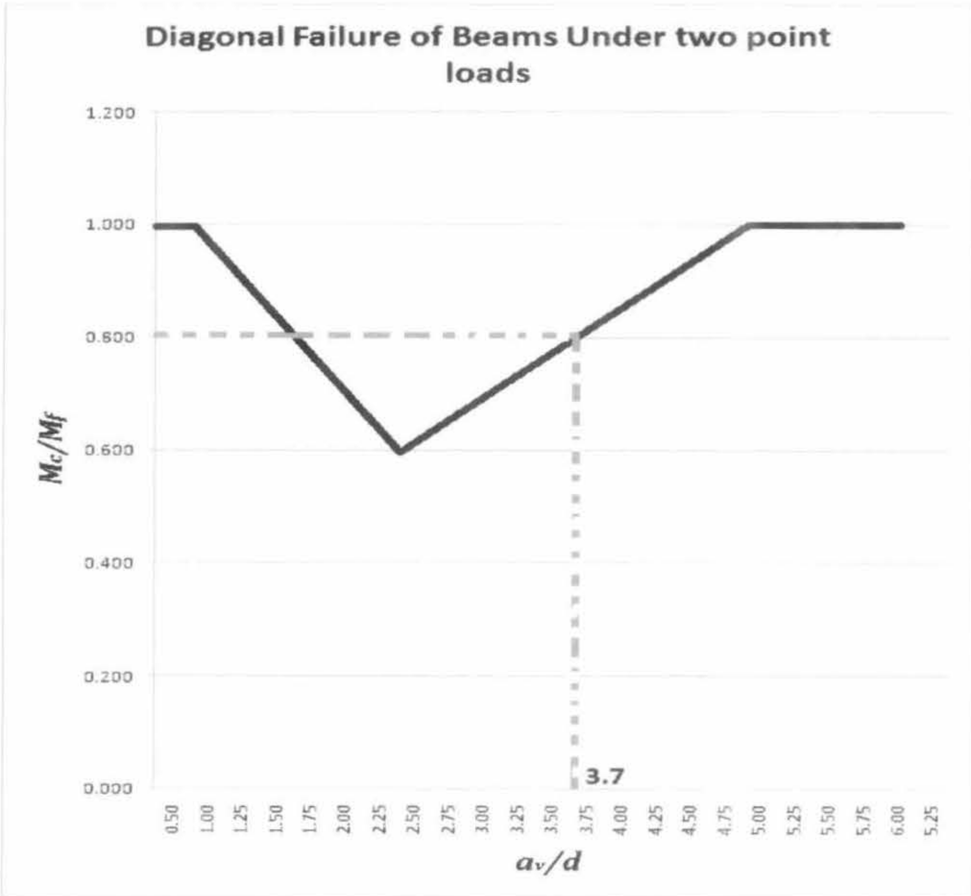


Figure 4 : Shear span to depth Ratio Graph

3.1.1 BEAM CALCULATIONS

The beam design calculations to prove the suitability of the beam section which are according to BS code 8110 are as follows:

• Beam Size: 100mm (b) x 200mm (h) x 2000mm (l)

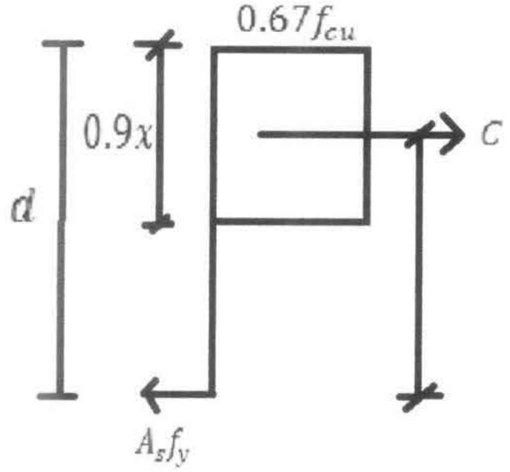
• Reinforcement: 4T12

• Cover 20 mm:

• Effective depth = 162mm

• A_s= 452.38 mm2

f_y = 519.1 MPa & f_{cu}= 36.18 MPa



Neutral Axis

T = C

T = A_sf_y= 452.38 mm2 * 452.38 N/mm2 = 234835.31 N

C = 0.67fcu * 0.9*X*b = 0.67 * 36.18 N/mm2 *0.9 * X * 100mm

Since T=C

234835.31 N == 0.67 * 36.18 N/mm2 *0.9 * X * 100mm

X = 120.20mm

BS 8110 states that for under-reinforcement X ≤ 0.5d

120.20 mm ≤ 0.5 (162mm) = 81 mm Over reinforced

Lever Arm

Z = d – 0.5*(0.9*X) = 175mm – (0.5*0.9*120.20mm) = 107.91mm

Maximum Moment Mu = 0.67fcu * 0.9Xb*Z = 28.30 KN.m

Moment M = T*Z = 234835.31 N * 107.91 mm = 25.34 KN.m

3.2 BEAM ARRANGEMENT WITH CFRP

The rest of the beams that will be externally reinforced with carbon fiber reinforced polymer (CFRP) will come presented as such:

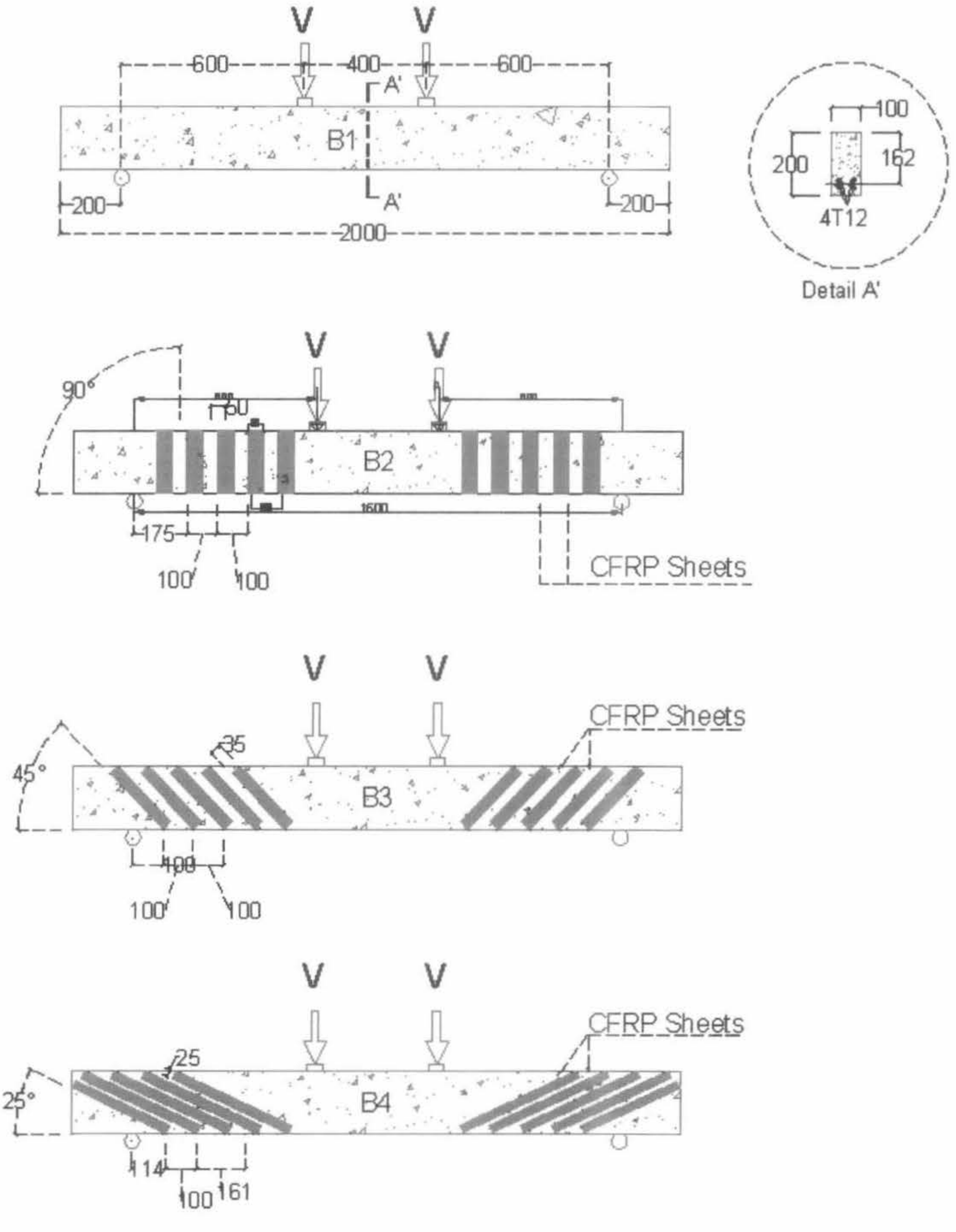


Figure 5 : RC Beam - CFRP Set Up for 90, 45 and 25 deg CFRP plate inclination

3.3 RESEARCH ACTIVITIES

In this research topic in order to effectively study the shear strengthening contribution of CFRP on reinforced concrete beams a number of tasks had to be done until the testing date where the results would be collected.

In this section a full description of these activities is given for assessment of the research activities and the knowledge behind carrying out the required tasks. The activities that have taken place are as follows:

1. Beam Specimen Preparation
    i. Preparation of formworks and Bar Bending
    ii. Preparation of concrete Covers
    iii. Casting and Curing period
2. Beam CFRP set up,
3. Test Set UP
4. Testing

3.2.1 BEAM SPECIMEN PREPARATION

After finalizing the details and dimensions of the test beams and with the approval of the research supervisor Dr. Teo Wee, formwork and bar bending tasks were carried away by a team of hired contractors under close watch by the author of this report. The bar distribution inside the beam can be seen on the figure that follows:

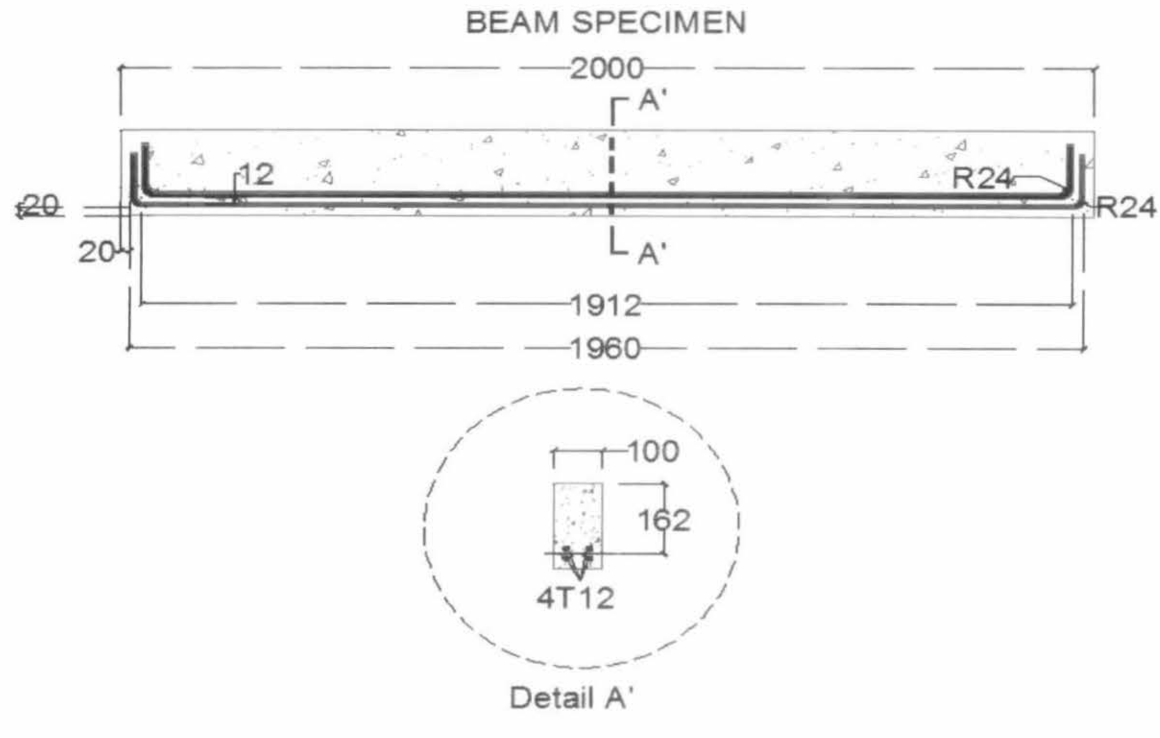


Figure 6 : Beam Specimen Drawing

After the completion of the formwork and bar bending tasks, the process of producing concrete covers that would provide restraints and correct positioning of the reinforcement bars within the formwork followed. This task along with creating the necessary steel hooks (for crane lifting purposes) were both carried out by the author with the assistance of the respective laboratory technicians at block 13, 15, and 21.

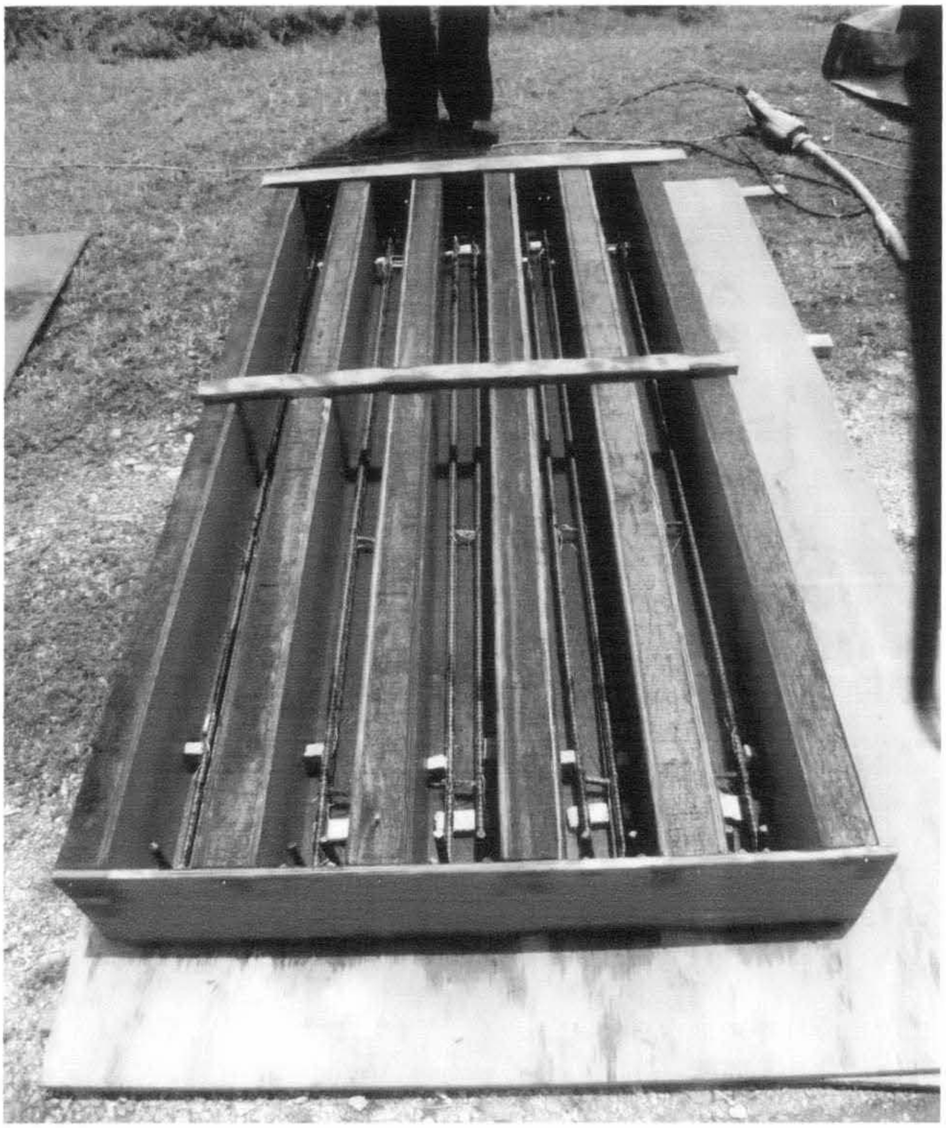


Figure 7 : Beam Formwork with reinforcement bars and concrete cover

With everything in place casting works began, and due to the quantities needed and the fact that all beams had to be casted at the same time an outside ready mixed concrete supplier was hired.

Figure 8 : Beam Concrete Casting

After the concrete casting works, the beam specimens were left to dry outside under the protection of a canvas against heavy rain and sunlight. The beams were then transported from the location of the casting to a location adjacent to the concrete laboratory at block 13, where they were left to observe a required curing period of 28 days which is needed to allow the concrete to achieve its maximum strength.

Figure 9 : Beam being placed at curing location

3.2.2 BEAM – CFRP SET UP

The process of attaching the CFRP begins by taking into consideration a number of factors with the end goal of coming out with the best CFRP arrangement in a manner that follows the objectives of the experiment and at the same time in a manner that maintains the cost effectiveness of its use.

3.2.3 CFRP

In order to start cutting the CFRP strips, it was important to determine the arrangements on the beams to be tested, and then based on that particular arrangement the dimensions of all CFRP strips were calculated and used as directions during the cutting process. The Process of cutting the CFRP sheets based on length was done at block 13 initially and then precision cutting to determine the correct width was done at block 21 within UTP's premises.

After obtaining the all the necessary sheets for strengthening, the process of attaching the CFRP sheets on the area to be strengthened by the beam could follow. However, ensuring proper storage of the sheets and proper cleaning before attachment is also an important step of the procedures of this research. According to the instruction written on Sika® CarboDur® Plates product data sheet, it's a must to store the plates at a location with no direct sunlight exposure and maximum temperature of 50 °C. The CFRP sheets used in this research were placed indoors at block 13 at a room with air conditioning throughout the most part of the day.

Further instructions also touched on cleaning methods for the CFRP, and according to Sika® CarboDur® product data sheet a Sika® Colma Cleaner ought to be used to wipe the surface of the plates. Since this product was unattainable for various reasons a cleaning agent made of Methanol was used instead, methanol is one of the components of the recommended cleaner though at short amounts. Due to the number of risks involved in handling such chemicals, personal protective equipment were used.

CFRP PRODUCT CHARACTERISTICS

<table>
<tr><td>Appearance/ Colour:</td><td colspan="4">Carbon fiber reinforced polymer with an epoxy matrix, black.</td></tr>
<tr><td rowspan="3">Type</td><td colspan="4">Tensile E-Modulus: 165000 N/mm^3</td></tr>
<tr><td>Type</td><td>Width</td><td>Thickness</td><td>Cross Sect. Area</td></tr>
<tr><td>Sika CarboDur S1014</td><td>100mm</td><td>1.4mm</td><td>140 sq.mm</td></tr>
<tr><td>Density</td><td colspan="4">1.60 g/cm^3</td></tr>
<tr><td rowspan="8">Mechanical Properties</td><td colspan="4">(Obtained from Longitudinal direction)</td></tr>
<tr><td colspan="2" rowspan="2"></td><td colspan="2">Sika CarboDur</td></tr>
<tr><td>E-Modulus:</td><td>Tensile Strength</td></tr>
<tr><td colspan="2">Mean Value (N/mm^2)</td><td>165000</td><td>3100</td></tr>
<tr><td colspan="2">Min Value (N/mm^2)</td><td>> 160000</td><td>> 2800</td></tr>
<tr><td colspan="2">5% Fractile - Value (N/mm^2)</td><td>162000</td><td>3000</td></tr>
<tr><td colspan="2">95% Fractile - Value (N/mm^2)</td><td>180000</td><td>3600</td></tr>
<tr><td colspan="2">Strain at break* (min. value)</td><td colspan="2">> 1.70%</td></tr>
<tr><td rowspan="3">Consumption:</td><td colspan="4">Sika CarboDur + SikaDur - 30</td></tr>
<tr><td>Width of Plate (mm)</td><td colspan="2">SikaDur - 30</td><td></td></tr>
<tr><td>50</td><td colspan="2">0.25 - 0.35 Kg/m</td><td></td></tr>
</table>

Table 2: CFRP Product Characteristics

3.2.4 BONDING ADHESIVE

As a bonding mechanism, an adhesive for bonding reinforcement from Sika called Sikadur®-30 was used. This bonding adhesive comes in two parts: part as a white wet paste, and part B as a dark wet mixture. The combination of these two parts shall yield a light grey mixture that resembles an ordinary concrete mixture. The mixing of the two SikaDur – 30 parts was done following recommendations from the factory of 3:1 in favor of Part A. Due to the fact that part B of Sikadur®-30 works mainly as a fast drying agent of the adhesive it can create poor workability during its use if the adhesive mix is of large quantities, here a chart illustrating the pot life of the adhesive:

Temperature	+8°C	+20°C	+35°C
Potlife	~ 120 minutes	~ 90 minutes	~ 20 minutes
Open time	~ 150 minutes	~ 110 minutes	~ 50 minutes

Figure 10 : Pot Life of Bonding Adhesive

Here the potlife is defined as the period that follows right after mixing the resin (part a) and the hardener (part b). Factors that affect the potlife include temperature, mixed quantities. Basically for an improvement in workability, the mixing should be done at lower temperatures and in smaller amounts. As a solution to improve the workability of an already mixed bonding adhesive would be to chill the resin and hardener before mixing at a location with temperatures not less than 5°C. With these instructions in mind throughout this research the maximum portion mixed was of 800 grams, but it was observed that 400 grams (300 grams of resin, 100 grams of hardener) is the best quantity that favors better workability according to the lab's conditions.

SUMMARY OF PRODUCT CHARACTERISTICS

Colours	Part A:	white	
	Part B:	black	
	Parts A+B mixed:	light grey	
Density	Parts A+B mixed:	1.65 kg/l + 0.1 kg/l	
Compressive Strength			(According to EN 196)
		Curing temperature	
	Curing time	+10°C	+35°C
	12 hours	-	80 - 90 N/mm2
	1 day	50 - 60 N/mm2	85 - 95 N/mm2
	3 days	65 - 75 N/mm2	85 - 95 N/mm2
	7 days	70 - 80 N/mm2	85 - 95 N/mm2
Shear Strength	*Concrete failure (~ 15 N/mm2)		(According to FIP 5.15)
		Curing temperature	
	Curing time	+15°C	+35°C
	1 day	3 - 5 N/mm2	15 - 18 N/mm2
	3 days	13 - 16 N/mm2	16 - 19 N/mm2
	7 days	14 - 17 N/mm2	16 - 19 N/mm2
	*18 N/mm2 (7 days at +23°C)		(According to DIN 53283)
Tensile Strength			(According to FIP 5.15)
		Curing temperature	
	Curing time	+15°C	+35°C
	1 day	18 - 21 N/mm2	23 - 38 N/mm2
	3 days	21 - 24 N/mm2	25 - 30 N/mm2
	7 days	24 - 27 N/mm2	26 - 31 N/mm2
Bond Strength	On concrete: concrete failure (> 4 N/mm2) (According to FIP (Fédération Internationale de la Précontrainte))		
E-Modulus	Compressive: 9'600 N/mm2 (at +23°C) (According to ASTM D695) Tensile: 11'200 N/mm2 (at +23°C) (initial, According to ISO 527)		

Table 3 : Bonding Adhesive Product Characteristics

3.2.4 APPLICATION OF CFRP ON BEAM

According to the instructions on the product data sheet from Sika® CarboDur® the surface of the reinforced concrete beam to be strengthened must be level and even, with the help of a BOSCH angle grinder the RC beams to be strengthened with CFRP were ground to make their rough surface even to ease the bonding between the concrete and the epoxy. One way of ensuring that the surface is even is to place a flat metal plate or any flat object and observe how it lies on the beam's ground surface. Besides being even, the surface must also be clean from any dust, moisture, grease or oil; and it should show open textured surface. After cleaning the surface, make markings of the exact location where the CFRP will be attached with a pencil and reinforce those marking with a marker for visibility purposes.

After ensuring that the beam's surface is in order the following should be ready:

- CFRP sheet plates cut into the designed dimensions from strengthening;
- A tray of a mixture of Sika® Dur - 30® bonding adhesive, 400 grams per portion.
- Concrete mixing Spatulas, and two extra CFRP sheets.

The bonding adhesive is placed on the CFRP sheet surface that was subject of cleaning (the surface must be dry) at a thickness of over 3-5mm to allow it to be pressed against the concrete. Most of the bonding adhesive should be put on the middle of the CFRP sheet to allow it to be spread evenly to its sides. After placing the adhesive on the plate, the CFRP sheet plate is attached on the surface by to be strengthened with the face containing the adhesive facing the concrete surface, to achieve proper and an even bond between the CFRP and the reinforced concrete beam the plate must be pressured using an entire hand or both it the width of the plate allows it.

After completing the attachment on one side of the beam, the beam specimen was left to cure the adhesive for 24 hours. After a day, the other side of the beam was attached with the CFRP plates in the same manner explained in the previous paragraph. Since the sticking process was done while the beam was turned horizontally, small concrete blocks (30mm in thickness) were placed to hold the beam up in areas of the beam surface besides the area strengthened by the CFRP sheet plates. Again 24 hours were given to allow the adhesive to bond the CFRP and the beam concrete surface properly, after the beam was turned into the natural vertical position in order for a required 7 (seven) days curing period to take place before testing.

3.3 BEAM SPECIMEN

The picture bellow showcases how a beam attached with CFRP looks like; from the picture we can see the inclinations of the CFRP. The nearest beam comes attached with CFRP sheets at a 90 degree angle, the middle beam comes attached with CFRP at 25degree angle, and the furthest one shows a CFRP inclination at 45 degrees. The wires attached to the CFRP are merely strain gauges.

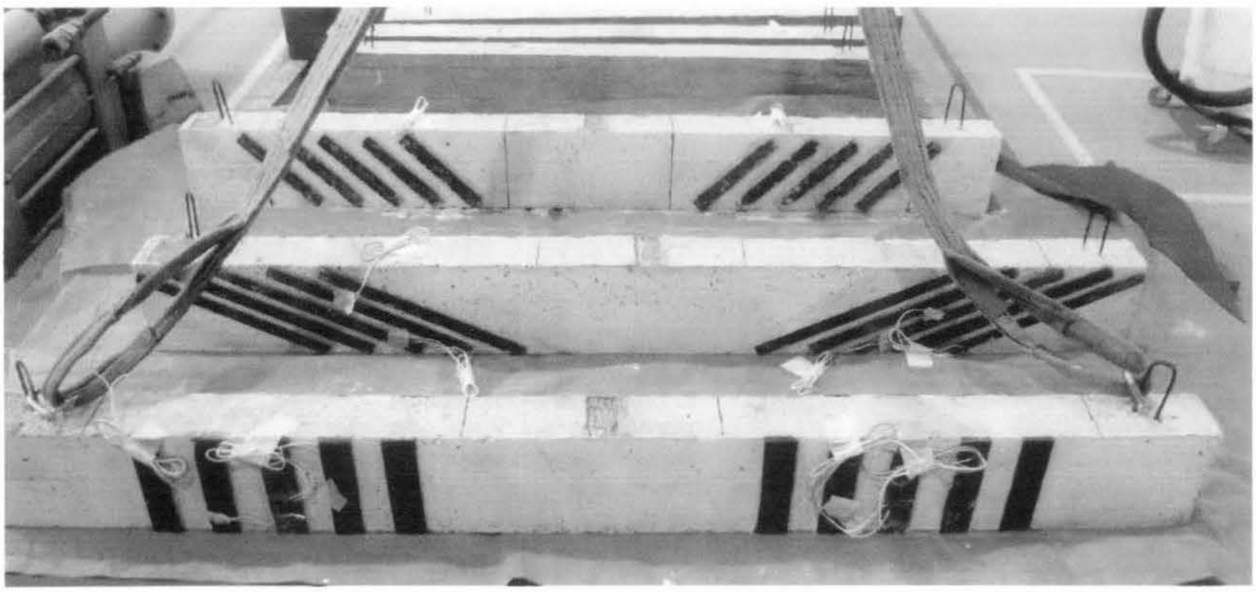


Figure 11 : RC beam strengthened with CFRP

3.4 GANTT CHART & KEY MILESTONES

Timeline for FYP 1

No	Detail/ Week	1 19/05/2011	2	3	4	5	6	7	Semester Break	8	9	10	11	12	13	14 22/07/2011
1	Selection of Project Topic	■	■													
	Preliminary Research Work		■	■	■	■										
2	Submission of extended Proposal Defense						●									
3	Proposal Defense									■ ○						
4	Contacting Concrete Suppliers/Comtractors										■	■				
5	Making of beam formworks												■	■		
6	Beam Casting Works															■
7	Submission of Interim Draft Report														●	
8	Submission of Interim Report															●

Table 4: Gantt chart 1of 2

Timeline for FYP2

No	Detail/ Week	1	2	3	4	5	6	7	Semester Break	8	9	10	11	12	13	14
1	Beam Curing Period	■	■	■	■	■										
	CFRP Cutting, Beam Set Up							■	■							
2	Tests on Beams									■	■					
	Submission of Progress Report									●						
3	Analysis of results, interpretation											■	■			
4	Pre – EDX												●			
5	Submission of Draft Report															
6	Submission of Dissertation (soft bound)														●	
7	Submission of Technical Paper														●	
8	Oral Presentation														●	
9	Submission of Project Dissertation (Hard Bound)															●

Table 5 : Gantt chart 2 of 2

■ PROCESS
● MILESTONE

3.5 TOOLS USED TO CONDUCT THIS RESEARCH

Material/Tools	Description/Purpose of Use	Quantity
Main Materials for research specimen		
Ready Mix Concrete	RC Beam Casting, Test Cubes	1 m^3
Carbon Fiber Reinforced Polymers	Reinforced Concrete Beam External Shear Reinforcement	15 x 0.100 m^2
12mm Reinforcement Bars	Beam Bottom Reinforcement	63m
6mm steel bars	To produce beam hooks	12.5 m
SikaDur -30 Black	Reinforcement with Beam Bonding Adhesive	2 Kg
SikaDur -30 White	Reinforcement with Beam Bonding Adhesive	650 grams
Methanol	Wipe Clean CFRP surface for beam attachment	1 Liter
Sand Paper	Clean the CFRP surface	5
Electrical Wire	To connect strain gauges to the data logger	20 meters
Strain Gauges	To be attached on CFRP	12

Table 6 : Materials

Material/Tools	Description/Purpose of Use	Quantity
Specimen Delineation and Marking		
Pencils	Drawing and Marking	2
Non-permanent Markers	Drawing and Marking	3
Rulers	Measurements	1
Measuring Tape	Measurements	2
Tape	Marking	1

Material/Tools	Description/Purpose of Use	Quantity
Beam Specimen Preparation		
BOSCH Jigsaw Cutter	Formwork Preparation	1
Bar Bender Apparatus	Bar Bending/ Beam Hook bending	1
BOSCH Circular Saw	Reinforcement Bar/ Hook/ CFRP cutting	1
Rock Cutter	Concrete cover Cutting	1
Rock Precision Cutter	Concrete cover Cutting	1
Concrete Compaction Machine	Ready Mix Concrete compaction	1
Engine Oil	Formworks inner wall lubrication	2 liters
Brushes	Engine Oil Use	2

Material/Tools	Description/Purpose of Use	Quantity
CFRP Cutting/Epoxy		
BOSCH Circular Saw	CFRP cutting based on length	1
Steel Precision Cutter	Cut the CFRP sheets based on width	1
Steel Tray	Epoxy Mixing	1
Spatula	Concrete Mixing, Epoxy Mixing	5

Table 7 : Drawing/ Cutting/Beam Specimen tools

CHAPTER 4

RESULTS AND DISSCUSSION

4.1 REINFORCEMENT BAR TENSILE TEST

Apart from setting up the beam specimens for testing, as part of the research procedure the reinforcement bars were put trough a tensile test with the purpose of verifying the steel yield strength.

The Area of the steel reinforcement bars is:

$$A_{s,Rebar} = \frac{\pi D^2}{4} = 113.1 \text{ mm}^2$$

Three steel reinforcement bars samples of 60 cm length were used for the testing and the results are as follows:

As it can be observed in the graph bellow, sample 1 with an elastic limit stress of 59.817 KN and an ultimate stress of 72.753KN. According to these readings the following can be calculated:

1. Steel Yield Strength = 59.817KN/113.1mm^2 = 528.9 MPa
2. Ultimate Yield Strength = 72.753KN /113.1 mm^2 = 643.3 MPa

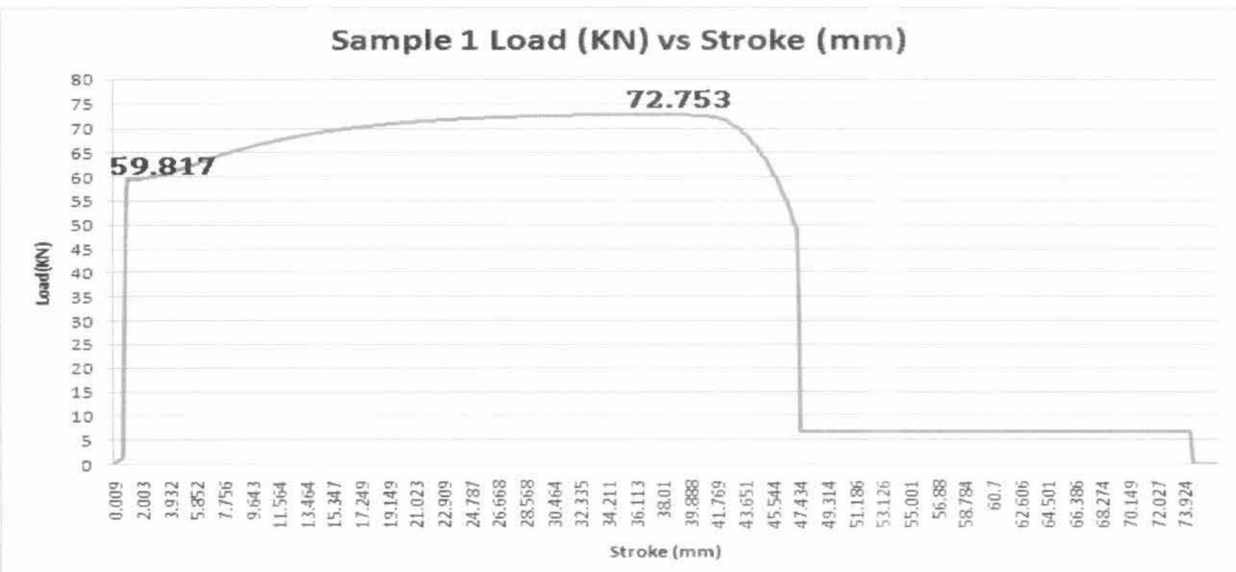


Figure 12 : Steel Sample 1

Sample 2:

The graph bellow shows that sample 2 with has an elastic limit stress of 57.53 KN and an ultimate stress of 70.86KN. According to these readings the following can be calculated:

1. Steel Yield Strength = 57.53 KN /113.1mm^2 = 508.67 MPa
2. Ultimate Yield Strength = 70.86KN /113.1 mm^2 = 626.6 MPa

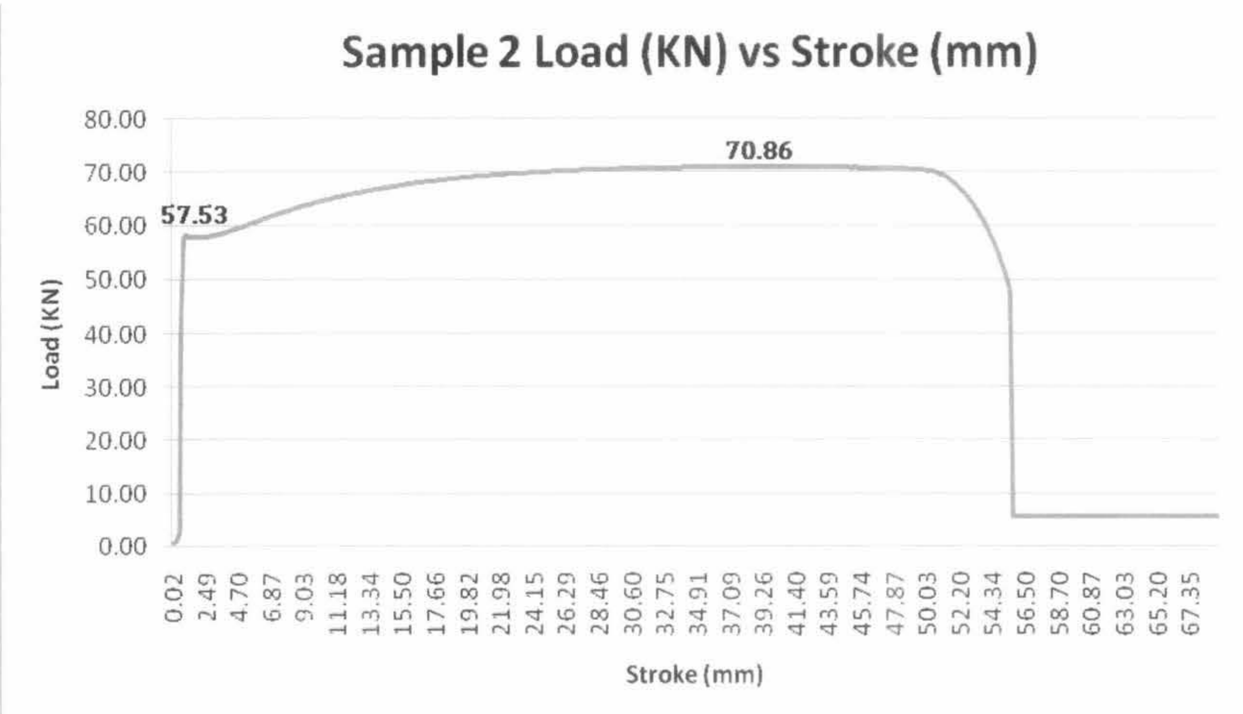


Figure 13 : Steel Sample 2

Sample 3:

The graph bellow shows that sample 2 with has an elastic limit stress of 58.79 KN and an ultimate stress of 71.59 KN. According to these readings the following can be calculated:

1. Steel Yield Strength = 58.79 KN /113.1mm^2 = 519.81 MPa
2. Ultimate Yield Strength = 71.59 KN /113.1 mm^2 = 623.98 MPa

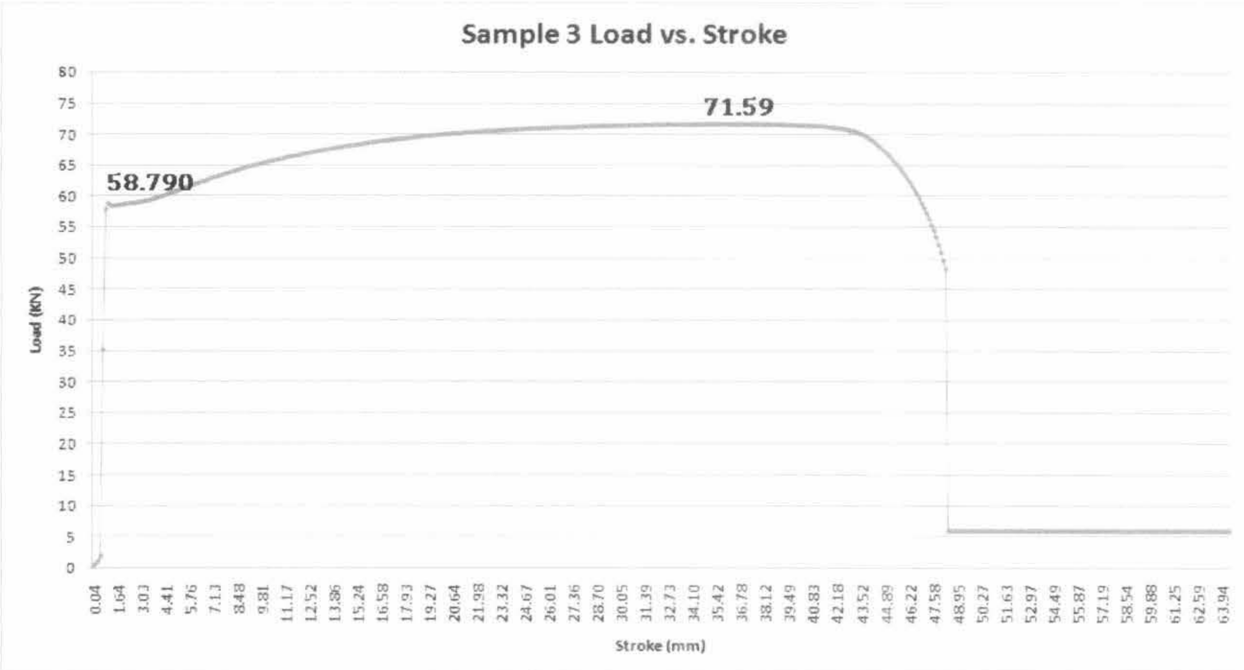


Figure 14 : Steel Sample 3

Here is a summary of the results obtained from the steel tensile tests carried:

Steel Tensile Test Results				
	Sample 1	Sample 2	Sample 3	Average
Yield Strength (MPa)	528.9	508.67	519.81	519.1
Ultimate Strength (MPa)	643.3	626.6	613.98	631.3

Table 8 : Summary of Steel Tensile Tests

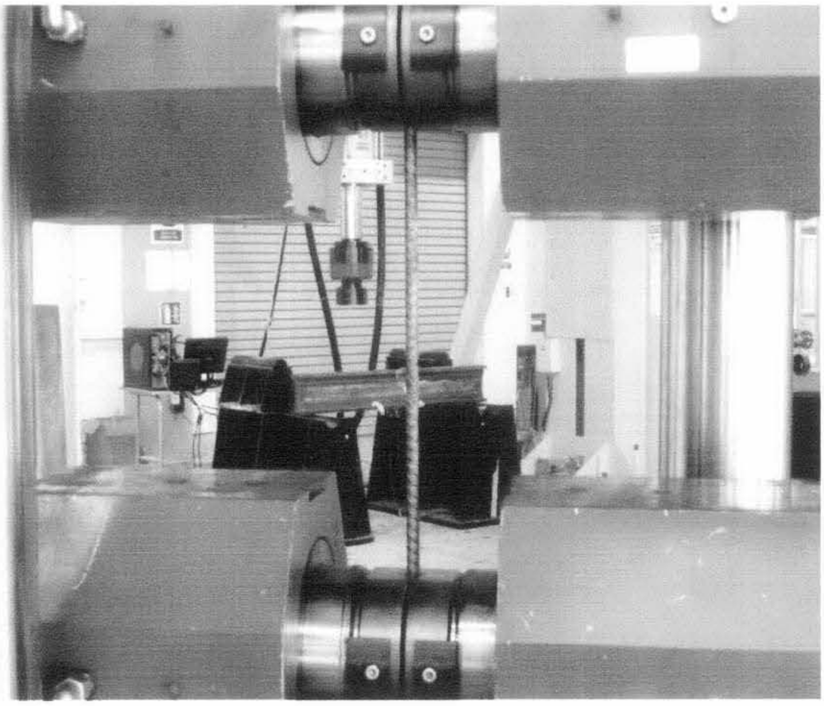


Figure 15 : Steel Tensile Test

Figure 16 : Steel Tensile Test Failure Point

4.2 LOAD DEFLECTION CURVE

Before making any further comments the experimental data failed to be validated by the predictions made, the load deflection curve ought to be analyzed for all 4 beams.

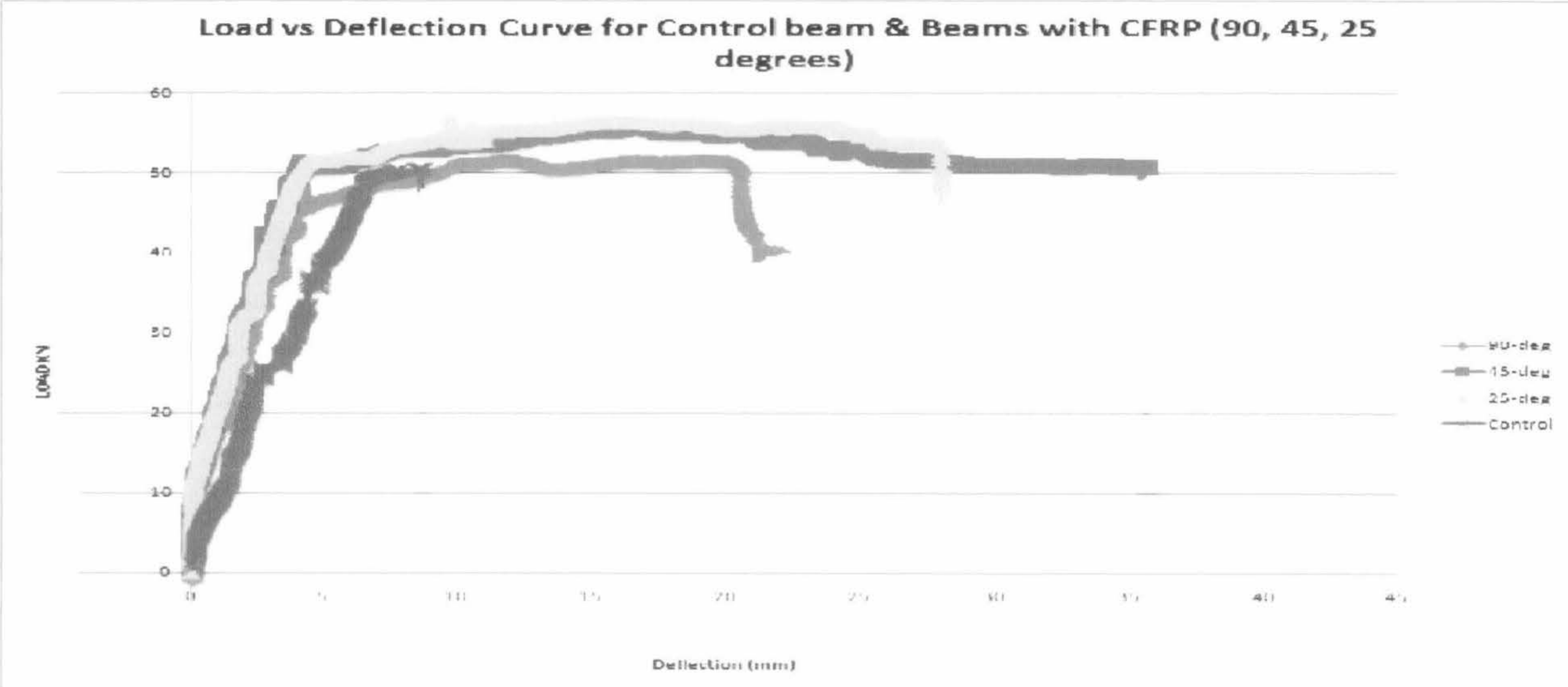


Figure 17 : Load vs. Deflection Curve for all beams

By analysis of the figure shown in the previous page, the following statements can be made:

- The control beam has a curve that only goes slightly beyond its yield strength and it also registers the shortest span of all beams.
- The RC beam reinforced with CFRP at 90 degrees registers an improvement over the control beam with a slightly higher ultimate load. It definitely has a longer curve span which gives indication of improvement as far as ductility is concerned.
- The beams with CFRP at an inclined angle of 45 and 25 degrees have very similar behavior. This might be due to their inclination pattern which offers better diagonal shear cracking control. The one with CFRP at 25 degrees definitely has slight advantage in terms of ultimate failure load. But the one with CFRP at 45 degrees is definitely more ductile judging from the span of its deflection curve.

4.3 FAILURE MODE AND DIAGONAL CRACKING CONTROL OF EACH BEAM

In this section pictures taken from the experiments shall be the subject of discussion in order to understand the cracking control and the cracking patterns of each beam.

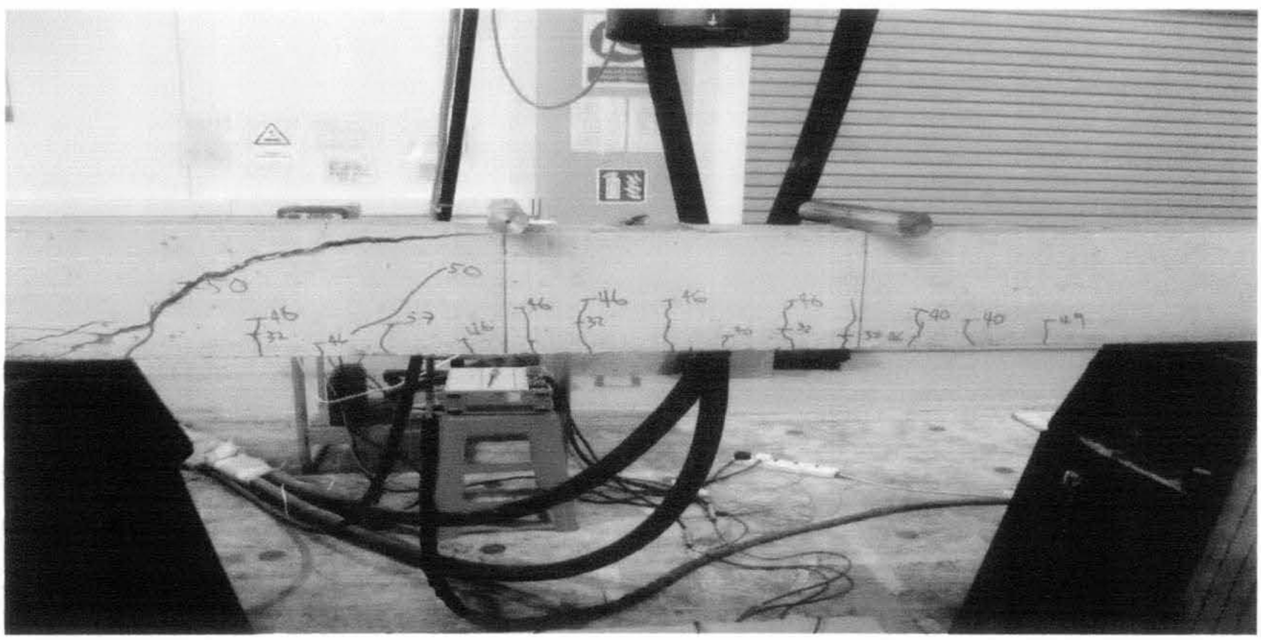


Figure 18 : Control Beam Cracking

From the picture it can be observed that the beam registered a diagonal shear crack with an average distance of 3.5 mm extending from the point load all the way to the main support. A number of small cracks can be seen in the flexural zone, but the most prominent ones can be seen at the side where the shear crack occurred.

By testing the control beam first an initial idea was obtained in terms of how an RC beam undergoes shear failure, and expectations were drawn on how the next beams should perform as far as shear cracking control and ultimate failure load is concerned. To note that the sear crack happened very suddenly and prior to the opening the cracks that lead to shear failure were small in width and were hard to be noticed from a distance of 1 meter.

The fact that the control beam failed in shear is justifiable and expected if the chosen a/d ratio of 3.7 is taken into account. According to Kotsovos (1983) a beam with such a/d ratio and a steel reinforcement ratio of $\rho_s = 2.8\%$ can be considered to have a mode of failure characterized by a diagonal crack that initiates from a flexural crack nearest to the support and extends itself towards the point load. The diagonal crack shown in Figure 18 is clearly in line with the analogy explained by Kotsovos and in addition to that, the sudden drop in loading shown in the load deflection curve of the control beam clearly suggests shear failure.

The figure bellow depicts the second beam of this project strengthened with CFRP at 90 degrees, as it can be noted in the shear span area only a single small crack has appeared which seems to cross one of the CFRP sheets. A number of cracks do appear on the middle span or flexure zone and this due to the lack of CFRP within this area. This beam underwent flexural failure marked by concrete crushing in the compression zone on top of the beam. The flexural failure was induced due to the amount of CFRP reinforcement used which clearly was too strong thus forcing the beam to fail in bending.

Figure 19 : RC beam strengthened with CFRP at 90 degrees.

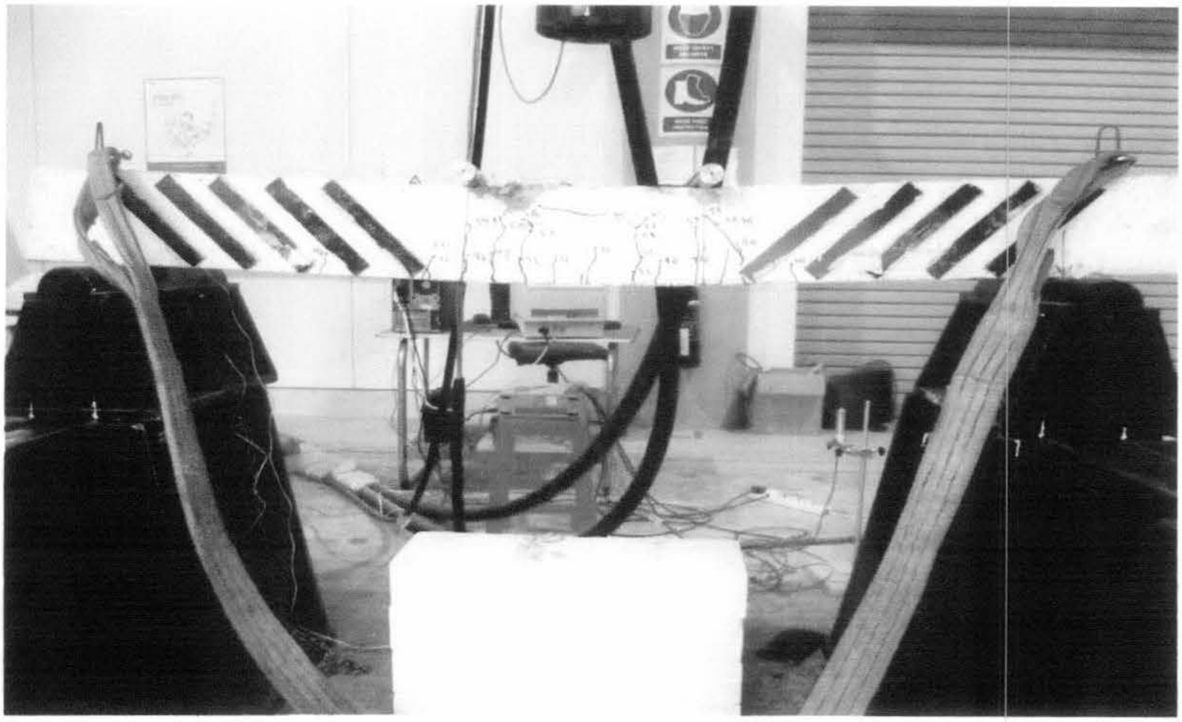


Figure 20: RC Beam with CFRP at 45 degrees

The beam with CFRP at 45 degrees performed slightly better than the one with vertical CFRP strips, its ultimate failure load was increased and at the shear spans area the only visible cracks seen were right at the edges of some of the strips that were located near the point load. The cracks in question were vertical in nature, and not like the diagonal one that the control beam presented. In terms of mode of failure it can be said that it resembled that of the 90 degrees which was marked by failure in bending and not shear as it was expected.

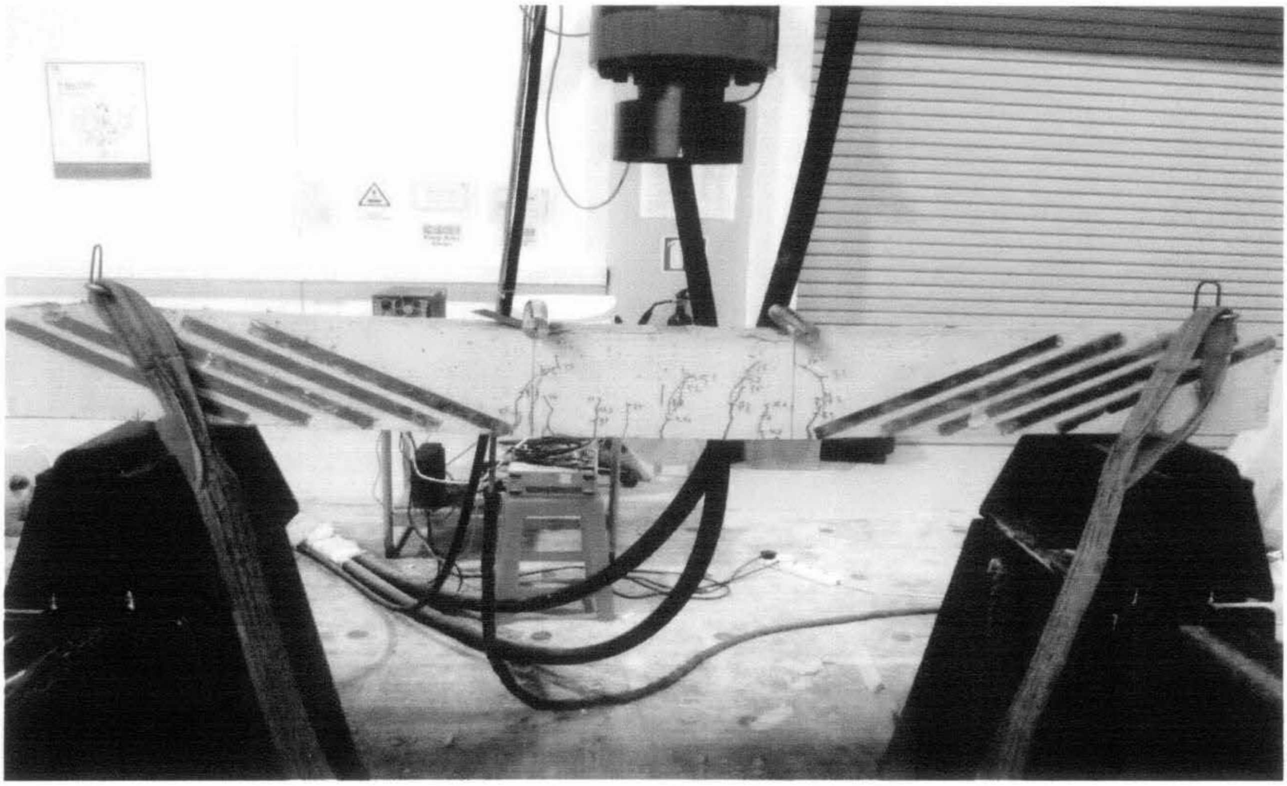


Figure 21 : RC Beam reinforced with CFRP at an angle of 25 degrees

For the last beam which is the one with CFRP at 25 degrees, cracking could only be observed at the flexural area almost in the same trend as the rest but with less abundance. No cracking was observed at the areas where CFRP was attached suggesting that this arrangement offers even better cracking control under the same testing parameters in comparison with the previously discussed arrangements. Flexural failure marked the mode of failure which was of no surprise if we observe all CFRP reinforced beams.

As a general observation, from the images taken all three reinforced beams controlled cracking pretty well, and as the angle of CFRP inclination got shallower the number of cracks reduced. During the experiment it was observed that the reinforced beams underwent excessive bending at the middle span. As we can see from the pictures, all beams failed in bending due to the high amount of CFRP used. Ultimate failure was often registered when the concrete crushed at upper parts of the beam where compression was dominant. To note that the beam does come with no stirrups and top reinforcement so concrete crushing at the areas where the beam came into contact with the point loads were bound to occur.

4.4 SHEAR STRENGTH CONTRIBUTION OF CFRP: PREDICTIONS AND EXPERIMENTAL RESULTS

In order to attain the shear strength contribution of CFRP shear strengthening design considerations from ACI 440.2R-02 were used.

The Beam and CFRP design parameters are as follows:

Beam Parameters:

Width	100.00	mm
Height	200.00	mm
Effective Depth	162.00	mm
Concrete Strength	36.18	N/mm^2
Steel Rebar Strength	519.1	N/mm^2

Table 9 : Beam Parameters

CFRP Parameters

FRP Sheet Depth, *df*	=	162	mm
FRP Sheet Width, *wf*	=	50	mm
Spacing Between Sheets, *Sf*	=	100	mm
thickness per sheet, *tf*	=	1.4000	mm
tensile Strength, f_{fu}	=	3100	N/mm^2
Rupture Strain	=	0.0170	mm/mm
Modulus of Elasticity, *Ef*	=	165,000	Mpa
Beam Depth *d*	=	162	mm
CFRP Angle Inclination	=	90	deg

Table 10 : CFRP Parameters

The nominal shear strength of a beam strengthened using FRP shall be a result of adding the contribution of steel (stirrups, ties, or spirals), FRP and the concrete. For this project steel will not contribute to the nominal shear strength as stirrups, ties or spirals will not be used. The nominal shear strength will be calculated by using the following formulas:

$$V_n = V_c + V_S + V_f \qquad 1)$$

Where :

Vc shear strength contribution of concrete;
Vs shear strength contribution of steel;
Vf shear strength contribution of FRP

The shear contributions of concrete and steel will be calculated by suing the following formulas:

$$V_f = \frac{A_{fv} f_{fe} (\sin\alpha + \csc\alpha) d_f}{s_f} \qquad \text{2) ACI 440.2R-02}$$

$$V_c = \left(0.16\sqrt{f_c'} + 17.2 P_w \frac{V_u d}{M_u}\right) b_w d \qquad \text{3) ACI 318-99}$$

Where:

i. $f_c' = 0.8 f_{cu}$

ii. $P_w = \frac{A_s}{b_w d}$

iii. $\frac{V_u d}{M_u} = \frac{d}{a}$

Here's a summary of shear strengthening calculations with variations in inclination angles as well CFRP sheet spacing:

Beam	Ultimate failure Load V_{exp} (KN)	$V_{cACI318}$ (KN)	$V_{frpACI440}$ (KN)	Vn = Vc + Vf (KN)	Ultimate Moment at failure M_f (KNm)	Flexural capacity M_{fle} (KNm)	M_f/M_{fle}	Failure Mode during experiment
B1	50.42	16.05	-	16.05	30.252	25.34	1.194	Shear
B2	51.48		40.26	56.31	30.888		1.219	Flexural
B3	55.78		39.85	55.90	33.468		1.321	Flexural
B4	56.90		26.75	42.80	34.140		1.347	Flexural

Table 11 : Summary of Shear Strengthening
For detailed calculations please refer to Appendix

From the table above if we focus only on the results of the calculations to predict the failure loads we can observe the following:

- The shear contribution from the concrete is comparatively lower in comparison with that when the CFRP is attached.
- The shear contribution of steel is zero as stirrups were not used for this research, as it focuses solely on studying the contribution of CFRP.
- As the angle of CFRP and plate width decreases the shear contribution decreases as well. This is due to the fact that the shear contribution of CFRP is directly proportional to the width of the CFRP sheet and the angle of inclination. Therefore, as the angle of inclination and the width decrease the contribution will decrease as well.
- Since the shear contribution of concrete is constant for all angles, the nominal shear strength of the beam strengthened with CFRP will follow the same pattern as that of the shear contribution of CFRP, whereby it will decrease as the angle of inclination and width decrease.

As we look into the experimental results we can see that a different trend occurs than the one predicted by using the prediction models. Based on the data extracted from the experiment we can conclude the following:

- There's an increment in shear contribution as the angle of inclination gets shallower. In this case we can understand that the RC beam reinforced by using a 25 degree CFRP inclination should have a slightly higher contribution than the rest of the beams.
- There's a contrast between the experiment results and the predictions made by using the ACI code 440, but for the beam strengthened with CFRP at forty five degrees the predictions and the experimental results do resemble.

The lack of significant increase in terms of ultimate failure load could be due to the stiffness caused by the amount of external CFRP reinforcement. On Figure 17, beams with CFRP at 90, 45 and 25 degrees all showcase higher stiffness in the elastic zone; this stiffness may have caused the beams to fail in flexure with concrete crushing at the compression zone due to large deflection and bending at mid span. Therefore the increment in CFRP contribution was dictated by the amount of loads that the steel reinforcement could take. To note that none of the beams externally strengthened failed by plate debonding or CFRP rupture which have been acknowledged as common type of failure to be expected when using CFRP sheets in previous research by Khalifa (2010), Chen and Temg (2003) and Zhang (2005).

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSION

The use of CFRP plates does increase the shear capacity of an RC beam, factors such as shear span-to-depth ratio, the number of CFRP reinforcement, CFRP plate spacing may influence how significant the increase in shear contribution will be. From this study, experimental data does support improvement in ductility, in addition to favoring flexural failure which is most desired than shear failure. The results are encouraging and minor tweaks to parameters such as the shear span and less reinforcement will aid in producing more convincing results in terms of shear strengthening contribution of CFRP. When it come to failure prediction, only the failure load on the forty five degree beam could be predicted, as for the others the results were not so accurate. It should be noted that of all 3 beams strengthened with CFRP, recommendation of use should be given to 25 degree CFRP orientation which showed that it's desirable as far obtaining better shear cracking control and higher shear strength capacity.

5.2 RECOMMENDATIONS

Based on the results obtained and the reached conclusions, the following recommendations could be applicable in attaining more assuring results for this project:

1. Further testing could be done with lower shear span-to-depth ratio for the same beam dimensions which would allow the shear span to be lower in length which would create a different and more favourable scenario of load distribution from the point loads to the support. In such conditions the effectiveness of using the CFRP would be tested and the results obtained could be compared with the current findings.
2. The amount of reinforcement could be reduced as well by increasing the spacing, this would decrease the amount of stiffness observed at the reinforced area thus allowing for the load to be distributed all the way to the support.
3. Further studies should be made to validate the obtained results.

CHAPTER 6

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CHAPTER 7

APPENDIX

APPENDIX 1

DETAILLED CALCULATION OF PREDICTION OF SHEAR STRENGTH CONTRIBUTION

Exercsise Sheet

Code Used: ACI 440.2R-02 CFRP 90 Degrees	**PROJECT :** Final Year Project 1	Page :	1.00 of 3.00
		Student Name :	Osorio M. Baltazar
		MATRIC NO	10516
		Lecturer :	Dr. Teo Wee
		Due Date :	
		Question No :	
		Date :	

Ref.	Calculation	Remarks

Beam Parameters

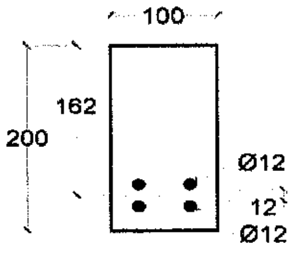

Fig 1: Beam cross Section

Width	100.00	mm
Height	200.00	mm
Effective Depth	162.00	mm
Conc Strength	36.18	N/mm^2
Steel Rebar Strength	519.10	N/mm^2
Shear Span	600.00	mm

FRP Parameters

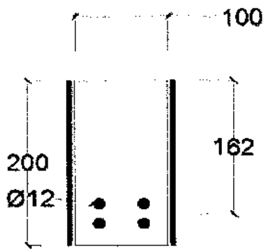

Fig 2: Beam Cross Section with 2 sides FRP wrapping

FRP Sheet Depth, *df*	=	146	mm
FRP Sheet Width, *wf*	=	50	mm
Spacing Between Sheets, *Sf*	=	100	mm
thickness per sheet, *tf*	=	1.4000	mm
tensile Strength, f_{fu}	=	3100	N/mm^2
Rupture Strain	=	0.0170	mm/mm
Modulus of Elasticity, *Ef*	=	165,000	Mpa
Beam Depth *d*	=	162	mm
CFRP Angle Inclination	=	90	deg

Table 10.1

$$C_E = 0.85$$

$$f_{fu} = C_E f^*_{fu} = 2.64 \text{ KN/mm}^2$$

$$\varepsilon_{fu} = C_E \varepsilon^*_{fu} = 0.0188$$

2. Preliminary Calculations

$$L_e = \frac{416}{(nt_f E_f)^{0.58}} = 18.05 \text{ mm}$$

$$k_1 = \left(\frac{f'_c}{27}\right)^{2/3} = 1.0474$$

$$k_2 = \left(\frac{d_f - L_e}{d_f}\right) = 0.7524$$

$$\kappa_v = \frac{k_1 k_2 L_e}{11900\varepsilon_{fu}} \leq 0.75 = 0.0636 \text{ ok}$$

$$\varepsilon_{fe} = \kappa_v \varepsilon_{fu} \leq 0.004 = 0.00120 \text{ ok}$$

	$A_{fv} = 2nt_f w_f$ = 140.00 mm^2		
	$f_{fe} = \varepsilon_{fe} E_f$ = 0.20		
	$V_c = \left(0.16\sqrt{f_c'} + 17.2P_w \frac{V_u d}{M_u}\right) b_w d$ = 16.05 KN		
	$\frac{V_u d}{M_u} = \frac{d}{a}$ = 0.27		
	$P_w = \frac{A_s}{b_w d}$ = 0.027925		
	$f_c' = 0.8 f_{cu}$ = 28.94 N/mm2		
	$4T12, \quad A_s =$ 452.39 mm2		
	V_s = 0.00		
	$V_f = \frac{A_{fv} f_{fe} (\sin \propto + \csc \propto) d_f}{S_f}$ = 40.26 KN		
(10-2)	$V_n = V_c + V_S + V_f$ = 56.31 KN		

APPENDIX 2

PRODUCT DATA SHEETS:

1. **Sikadur®-30**

Adhesive for bonding reinforcement

2. **Sika® CarboDur® Plates**

Pultruded carbon fiber plates for structural strengthening

Sika® CarboDur® Plates

Pultruded carbon fiber plates for structural strengthening

System Description

Sika® CarboDur® plates are pultruded carbon fiber reinforced polymer (CFRP) laminates designed for strengthening concrete, timber and masonry structures.

Sika® CarboDur® plates are bonded onto the structure as external reinforcement using Sikadur®-30 for normal - or Sikadur®-30 LP epoxy resin for elevated application temperatures (for details on the adhesive see the relevant Product Data Sheet).

Uses

To strengthen structures for:

Load increase:

- Increasing the capacity of floor slabs and beams
- Increasing the capacity of bridges to accommodate increase axle loads
- Installation of heavier machinery
- Stabilising vibrating structures
- Changes of building use

Damage to structural elements:

- Deterioration of original construction materials
- Steel reinforcement corrosion
- Vehicle impact
- Fire
- Earthquakes

Service improvements:

- Reduced deflection
- Stress reduction in steel reinforcement
- Crack width reduction
- Reduced fatigue

Change in structural system:

- Removal of walls or columns
- Removal of slab sections for openings

Change of specification:

- Earthquakes
- Changed design philosophy

Design or construction defects:

- Insufficient / inadequate reinforcement
- Insufficient / inadequate structural depth

Characteristics / Advantages

- Non corrosive
- Very high strength
- Excellent durability
- Lightweight
- Unlimited lengths, no joints required
- Low overall thickness, can be coated
- Easy transportation (rolls)
- Simple plate intersections or crossings
- Very easy to install, especially overhead
- Outstanding fatigue resistance
- Minimal preparation of plate, applicable in several layers
- Combinations of high strength and modulus of elasticity available
- Clean edges without exposed fibers thanks to the pultrusion process
- Approvals from many countries worldwide

Tests

Approval / Standards

Germany: Deutsches Institut für Bautechnik Z-36.12-80, 2010: General Construction Authorisation for Sika® CarboDur®.

France: CSTB - Avis Technique 3/07-502, SIKA CARBODUR SIKA WRAP

Norway: NBI Teknisk Godkjenning, NBI Technical Approval, No. 2178, 2001, (Norwegian).

Slovenia: ZAG, Technical Approval No. S418/99-620-2, za uporabo nacina ojacitev armirano betonskih in prednapetih elementov konstrukcij z dolepljenjem lamel iz karbonskih vlaken "Sika® CarboDur®" v Republiki Sloneniji (Slovenian).

Slovakia: TSUS, Building Testing and research institutes,
Technical approval No. 5502A/02/0633/0/004, 2003: Systém dodatocného zosilnovania zelezobetonovych a drevenych konstrukcil Sika CarboDur® (Slovak).

Poland: Instytut badawczy drog i mostow, technical approval No. AT/2003-04-0336, System materialow Sika® CarboDur® do wzmacniania konstrukcji obiektow mostowych (Polish).

Fib, Technical Report, bulletin 14: Externally bonded FRP reinforcement for RC structures, July 2001 (International).

USA: ACI 440.2R-08, Guide for the Design and construction of Externally Bonded FRP Systems for strengthening concrete structures, July 2008, (USA).

UK: Concrete Society Technical Report No. 55, Design guidance for strengthening concrete structures using fiber composite material, 2000 (UK).

Switzerland: SIA 166, Klebebewehrungen, 2003 /2004 (CH).

Italy: CNR-DT 200/2004 - Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Existing Structures

## Product Data	Sika® CarboDur® CFRP plates

Form

Appearance / Colour

Carbon fiber reinforced polymer with an epoxy matrix, black.

Packaging

Cut to size according parts list in nonreturnable cardboard packaging.
Supplied in rolls of 100 / 250 m in nonreturnable cardboard boxes.

Types

Sika® CarboDur® S — Tensile E-Modulus 165'000 N/mm²

Type	Width	Thickness	Cross sectional area
Sika® CarboDur® S1.525	15 mm	2.5 mm	37.5 mm²
Sika® CarboDur® S212	20 mm	1.2 mm	24 mm²
Sika® CarboDur® S214	20 mm	1.4 mm	28 mm²
Sika® CarboDur® S2.025	20 mm	2.5 mm	50 mm²
Sika® CarboDur® S512	50 mm	1.2 mm	60 mm²
Sika® CarboDur® S514	50 mm	1.4 mm	70 mm²
Sika® CarboDur® S612	60 mm	1.2 mm	72 mm²
Sika® CarboDur® S613	60 mm	1.3 mm	78 mm²
Sika® CarboDur® S614	60 mm	1.4 mm	84 mm²
Sika® CarboDur® S812	80 mm	1.2 mm	96 mm²
Sika® CarboDur® S814	80 mm	1.4 mm	112 mm²
Sika® CarboDur® S912	90 mm	1.2 mm	108 mm²
Sika® CarboDur® S914	90 mm	1.4 mm	126 mm²
Sika® CarboDur® S1012	100 mm	1.2 mm	120 mm²
Sika® CarboDur® S1014	100 mm	1.4 mm	140 mm²
Sika® CarboDur® S1212	120 mm	1.2 mm	144 mm²
Sika® CarboDur® S1213	120 mm	1.3 mm	156 mm²
Sika® CarboDur® S1214	120 mm	1.4 mm	168 mm²
Sika® CarboDur® S1512	150 mm	1.2 mm	180 mm²

Sika® CarboDur® M (steel equivalent) — Tensile E-Modulus 210'000 N/mm²

Type	Width	Thickness	Cross sectional area
Sika® CarboDur® M514	50 mm	1.4 mm	70 mm²
Sika® CarboDur® M614	60 mm	1.4 mm	84 mm²
Sika® CarboDur® M914	90 mm	1.4 mm	126 mm²
Sika® CarboDur® M1014	100 mm	1.4 mm	140 mm²
Sika® CarboDur® M1214	120 mm	1.4 mm	168 mm²

Sika® CarboDur® H — Tensile E-Modulus 300'000 N/mm²

Type	Width	Thickness	Cross sectional area
Sika® CarboDur® H514	50 mm	1.4 mm	70 mm²

Storage

Storage Conditions / Shelf Life	Unlimited provided if there is no exposure to direct sunlight, dry conditions at temperatures of max. 50°C Transportation: only in original packaging or protected against any mechanical damaging

Technical Data

Density	1.60 g/cm^3
Temperature Resistance	> 150°C
Fiber Volume Content	> 68% (type S)

Mechanical / Physical Properties

Plate Properties

		Sika CarboDur		
(numbers in N/mm^2 or MPa)		S	M	H
E-Modulus*	Mean Value	165'000	210'000	300'000
	Min. Value	> 160'000	> 200'000	> 290'000
	5% Fractile-Value	162'000	210'000	-
	95% Fractile-Value	180'000	230'000	-
Tensile Strength*	Mean Value	3'100	3'200	1'500
	Min. Value	> 2'800	> 2'900	> 1'350
	5% Fractile-Value	3'000	3'000	-
	95% Fractile-Value	3'600	3'900	-
Strain at break* (min. value)		> 1.70%	> 1.35%	> 0.45%

* Mechanical values obtained from longitudinal direction of fibers.

System Information

Sika® CarboDur® + Sikadur®-30 or Sikadur®-30 LP

Application Details

Consumption

Width of plate	Sikadur®-30
50 mm	0.25 - 0.35 kg/m'
60 mm	0.30 - 0.40 kg/m'
80 mm	0.40 - 0.55 kg/m'
90 mm	0.50 - 0.70 kg/m'
100 mm	0.55 - 0.80 kg/m'
120 mm	0.65 - 1.00 kg/m'
150 mm	0.85 - 1.25 kg/m'

Dependent on the surface plane, profile and roughness of the substrate as well as any plate crossings and loss or wastage, the actual consumption of adhesive may be higher.

Substrate Quality	Evenness / plane or level: (according to FIB14) The surface to be strengthened must be levelled, with variations and formwork marks not greater than 0.5 mm. Plane and level of the substrate to be checked with a metal batten. Tolerance for 2 m length max. 10 mm and for 0.3 m length 4 mm. These tolerances shall be adapted to local guidelines. Substrate strength (concrete, masonry, natural stone) must be verified in all cases: Mean adhesive tensile strength of the prepared concrete substrate shall be 2.0 N/mm^2, min. 1.5 N/mm^2. If these values can not be reached, then see the SikaWrap® Fabric Product Data Sheets for alternative Sika® solutions. Concrete must be older than 28 days (dependent on environment and strengths).

Substrate Preparation

Concrete and masonry:
Substrates must be sound, dry, clean and free from laitance, ice, standing water, grease, oils, old surface treatments or coatings and any loosely adhering particles.

Concrete must be cleaned and prepared to achieve a laitance and contaminant free, open textured surface.

Repairs and levelling: If carbonised or weak concrete cover has to be removed or levelling of uneven surfaces is needed, the following systems may be applied:
(Details on application and limitation see the relevant Product Data Sheets)

- Protection of corroded rebars: SikaTop® Armatec® 110 EpoCem®
- Structural repair materials: Sikadur®-41 epoxy repair mortar, Sikadur®-30 adhesive or cementitious Sika® MonoTop®-412 (horizontal, vertical, overhead) or Sika® MonoTop®-438 (horizontal, top-side) range.

Timber surfaces:
Must be prepared by planing, grinding or sanding. Dust must be removed by vacuum.

Steel surfaces:
Must be prepared by blastcleaning to Sa 2.5 free from grease, oil, rust and any other contaminants which could reduce or prevent adhesion.
Use the correct primer (see table).

Be careful to avoid water condensation on the surfaces (dew point conditions). Priming can be done with Icosit-277 or with Sikagard®-63 N as temporary corrosion protection; or Icosit-EG1 as permanent corrosion protection.

	+10°C	+20°C	+30°C
1) Maximum waiting time between - Blastcleaning of steel and - Primer / or Sikadur®-30 (application without priming possible, if no corrosion protection is needed)	48 hours	48 hours	48 hours
2) Minimum waiting time between - Primer and - Sikadur®-30 application (**without** additional preparation of the Primer)	48 hours	24 hours	12 hours
3) Maximum waiting time between - Primer and - Sikadur®-30 application (**without** additional preparation of the Primer)	7 days	3 days	36 hours
4) Waiting time between - Primer and - Sikadur®-30 application (**with** additional preparation of the Primer)*	> 7 days	> 3 days	> 36 hours

*If additional preparation of the primer is necessary (4), it shall be done at earliest the day before application. After preparation of the Primer, the surface has to be cleaned / vacuumed free from dust.

Plate preparation:
Prior to the application of Sikadur®-30, solvent wipe the bonding surface with Sika® Colma Cleaner to remove contaminants. Wait until the surface is dry before applying the adhesive (> 10 minutes).

Application Conditions / Limitations

Substrate Temperature	See the Product Data Sheets of Sikadur®-30 and Sikadur®-30 LP.
Ambient Temperature	See the Product Data Sheets of Sikadur®-30 and Sikadur®-30 LP.
Substrate Moisture Content	See the Product Data Sheets of Sikadur®-30 and Sikadur®-30 LP.
Dew Point	See the Product Data Sheets of Sikadur®-30 and Sikadur®-30 LP.

Application Instructions

Mixing	See the Product Data Sheets of Sikadur®-30 and Sikadur®-30 LP.
Mixing Time	See the Product Data Sheets of Sikadur®-30 and Sikadur®-30 LP.
Application Method / Tools	See the Method Statement of Sika CarboDur®.
Cleaning of Tools	Clean all tools and application equipment with Sika® Colma Cleaner immediately after use. Cured material can only be removed mechanically.
Potlife	See the Product Data Sheets of Sikadur®-30 and Sikadur®-30 LP.
Notes on Application / Limitations	A suitably qualified Engineer must be responsible for the design of the strengthening works. **This application is structural and great care must be taken in selecting suitably experienced and trained specialist labour.** Only apply plates within the open time of Sikadur®-30. Site quality control shall be supported / monitored by an independent testing authority. Care must be taken when cutting plates. Use suitable protective clothing, gloves, eye protection and respirator. The Sika® CarboDur® system must be protected from permanent exposure to direct sunlight, to water and/or moisture and from direct contact to wet concrete. Coating: The exposed plate-surface can be painted with a coating material such as Sikagard®-550 W Elastic or Sikagard®-ElastoColor W for UV and water and/or moisture protection. Maximum permissible service temperature is approx. +50°C. Note: When using the Sika® CarboHeater together with Sikadur®-30 LP this can be increased to max. +80°C (see the Sika® CarboHeater Product Data Sheet). The instructions in the Technical Data Sheet must be followed when applying Sikadur®-30 adhesive. Note: Detailed advice on the above must always be obtained from Sika® Services AG.
Fire Protection	If required Sika® CarboDur® plates may be protected with fire resistant material.

Value Base

All technical data stated in this Product Data Sheet are based on laboratory tests. Actual measured data may vary due to circumstances beyond our control.

Health and Safety Information

For information and advice on the safe handling, storage and disposal of chemical products, users shall refer to the most recent Material Safety Data Sheet containing physical, ecological, toxicological and other safety-related data.

Legal Notes

The information, and, in particular, the recommendations relating to the application and end-use of Sika products, are given in good faith based on Sika's current knowledge and experience of the products when properly stored, handled and applied under normal conditions in accordance with Sika's recommendations. In practice, the differences in materials, substrates and actual site conditions are such that no warranty in respect of merchantability or of fitness for a particular purpose, nor any liability arising out of any legal relationship whatsoever, can be inferred either from this information, or from any written recommendations, or from any other advice offered. The user of the product must test the product's suitability for the intended application and purpose. Sika reserves the right to change the properties of its products. The proprietary rights of third parties must be observed. All orders are accepted subject to our current terms of sale and delivery. Users must always refer to the most recent issue of the local Product Data Sheet for the product concerned, copies of which will be supplied on request.

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ISO 14001 Registered

Sikadur®-30

Adhesive for bonding reinforcement

Product Description	Sikadur®-30 is a thixotropic, structural two part adhesive, based on a combination of epoxy resins and special filler, designed for use at normal temperatures between +8°C and +35°C.
Uses	Adhesive for bonding structural reinforcement, particularly in structural strengthening works. Including: ■ Sika® CarboDur® Plates to concrete, brickwork and timber (for details see the Sika® CarboDur® Product Data Sheet). ■ Steel plates to concrete (for details see the relevant Sika® Technical information).
Characteristics / Advantages	Sikadur®-30 has the following advantages: ■ Easy to mix and apply. ■ No primer needed. ■ High creep resistance under permanent load. ■ Very good adhesion to concrete, masonry, stonework, steel, cast iron, aluminium, timber and Sika® CarboDur® Plates. ■ Hardening is not affected by high humidity. ■ High strength adhesive. ■ Thixotropic: non-sag in vertical and overhead applications. ■ Hardens without shrinkage. ■ Different coloured components (for mixing control). ■ High initial and ultimate mechanical resistance. ■ High abrasion and shock resistance. ■ Impermeable to liquids and water vapour.

Tests

Approval / Standards	Deutsches Institut für Bautechnik Z-36.12-29, 2006: General construction authorisation for Sika® CarboDur®. IBMB, TU Braunschweig, test report No. 1871/0054, 1994: Approval for Sikadur®-30 Epoxy adhesive. IBMB, TU Braunschweig, test report No. 1734/6434, 1995: Testing for Sikadur®-41 Epoxy mortar in combination with Sikadur®-30 Epoxy adhesive for bonding of steel plates. Testing according to EN 1504-4

Product Data

Form

Colours	Part A:	white
	Part B:	black
	Parts A+B mixed:	light grey

Packaging	6 kg (A+B): pre-batched unit

Storage

Storage Conditions / Shelf-Life	24 months from date of production if stored properly in original unopened, sealed and undamaged packaging in dry conditions at temperatures between +5°C and +30°C. Protect from direct sunlight.

Technical Data

Chemical Base

Epoxy resin.

Density

1.65 kg/l ± 0.1 kg/l (parts A+B mixed) (at +23°C)

Sag Flow

(According to FIP (Fédération Internationale de la Précontrainte))

On vertical surfaces it is non-sag up to 3-5 mm thickness at +35°C.

Squeezability

(According to FIP (Fédération Internationale de la Précontrainte))

4'000 mm^2 at +15°C at 15 kg

Layer Thickness

30 mm max.

When using multiple units, one after the other. Do not mix the following unit until the previous one has been used in order to avoid a reduction in handling time.

Change of Volume

Shrinkage:
0.04% (According to FIP (Fédération Internationale de la Précontrainte))

Thermal Expansion Coefficient

Coefficient W:
2.5×10^{-5} per °C (temp. range -20°C to +40°C)

Thermal Stability

Glass transition temperature:

(According to FIP (Fédération Internationale de la Précontrainte))

Curing time	Curing Temperature	TG
7 days	+45°C	+62°C

Heat deflection temperature: (According to ASTM-D 648)

Curing time	Curing Temperature	HDT
3 hours	+80°C	+53°C
6 hours	+60°C	+53°C
7 days	+35°C	+53°C
7 days	+10°C	+36°C

Service Temperature

-40°C to +45°C (when cured at > +23°C)

Mechanical / Physical Properties

Compressive Strength

(According to EN 196)

	Curing temperature	
Curing time	+10°C	+35°C
12 hours	-	80 - 90 N/mm^2
1 day	50 - 60 N/mm^2	85 - 95 N/mm^2
3 days	65 - 75 N/mm^2	85 - 95 N/mm^2
7 days	70 - 80 N/mm^2	85 - 95 N/mm^2

Shear Strength

Concrete failure (~ 15 N/mm^2) (According to FIP 5.15)

	Curing temperature	
Curing time	+15°C	+35°C
1 day	3 - 5 N/mm^2	15 - 18 N/mm^2
3 days	13 - 16 N/mm^2	16 - 19 N/mm^2
7 days	14 - 17 N/mm^2	16 - 19 N/mm^2

18 N/mm^2 (7 days at +23°C) (According to DIN 53283)

Tensile Strength

(According to DIN 53455)

	Curing temperature	
Curing time	+15°C	+35°C
1 day	18 - 21 N/mm^2	23 - 28 N/mm^2
3 days	21 - 24 N/mm^2	25 - 30 N/mm^2
7 days	24 - 27 N/mm^2	26 - 31 N/mm^2

Bond Strength

On steel > 21 N/mm^2 (mean values > 30 N/mm^2) (According to DIN EN 24624) on correctly prepared substrate, ie. blastcleaned to Sa. 2.5

On concrete: (According to FIP (Fédération Internationale de la Précontrainte)) concrete failure (> 4 N/mm^2)

E-Modulus

Compressive: 9'600 N/mm^2 (at +23°C) (According to ASTM D695)
Tensile: 11'200 N/mm^2 (at +23°C) (initial, According to ISO 527)

System Information

System Structure

Sika® CarboDur® System:
For Application Details of Sika® CarboDur® Plates with Sikadur®-30, see the Sika® CarboDur® Product Data Sheet.

Application Details

Substrate Quality

See the Product Data Sheet of Sika® CarboDur® Plates.

Substrate Preparation

See the Product Data Sheet of Sika® CarboDur® Plates.

Application Conditions / Limitations

Substrate Temperature

+8°C min. / +35°C max.

Ambient Temperature

+8°C min. / +35°C max.

Material Temperature

Sikadur®-30 must be applied at temperatures between +8°C and +35°C.

Substrate Moisture Content

Max. 4% pbw

When applied to mat damp concrete, brush the adhesive well into the substrate.

Dew Point

Beware of condensation!

Substrate temperature during application must be at least 3°C above dew point.

Application Instructions

Mixing

Part A : part B = 3 : 1 by weight or volume

When using bulk material the exact mixing ratio must be safeguarded by accurately weighing and dosing each component.

Mixing Time

Mix parts A+B together for at least 3 minutes with a mixing spindle attached to a slow speed electric drill (max. 600 rpm) until the material becomes smooth in consistency and a uniform grey colour. Avoid aeration while mixing. Then, pour the whole mix into a clean container and stir again for approx. 1 more minute at low speed to keep air entrapment at a minimum. Mix only that quantity which can be used within its potlife.

Application Method / Tools

See the Product Data Sheet of Sika® CarboDur® Plates.

Cleaning of Tools

Clean all tools and application equipment with Sika® Colma Cleaner immediately after use. Hardened / cured material can only be mechanically removed.

Potlife

(According to FIP (Fédération Internationale de la Précontrainte))

Temperature	+8°C	+20°C	+35°C
Potlife	~ 120 minutes	~ 90 minutes	~ 20 minutes
Open time	~ 150 minutes	~ 110 minutes	~ 50 minutes

The potlife begins when the resin and hardener are mixed. It is shorter at high temperatures and longer at low temperatures. The greater the quantity mixed, the shorter the potlife. To obtain longer workability at high temperatures, the mixed adhesive may be divided into portions. Another method is to chill parts A+B before mixing them (not below +5°C).

Notes on Application / Limitations

Sikadur® resins are formulated to have low creep under permanent loading. However due to the creep behaviour of all polymer materials under load, the long term structural design load must account for creep. Generally the long term structural design load must be lower than 20-25% of the failure load. Please consult a structural engineer for load calculations for your specific application.

Value Base

All technical data stated in this Product Data Sheet are based on laboratory tests. Actual measured data may vary due to circumstances beyond our control.

Health and Safety Information

For information and advice on the safe handling, storage and disposal of chemical products, users shall refer to the most recent Material Safety Data Sheet containing physical, ecological, toxicological and other safety-related data.

Legal Notes

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