EXPERIMENTAL STUDY ON THE BEHAVIOUR OF REINFORCED CONCRETE DEEP BEAMS WITH LARGE CIRCULAR OPENINGS STRENGTHENED USING CFRP

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for the award of the degree of
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ABSTRACT

This experimental research was conducted to study the behaviour of unstrengthen RC deep beams with openings and strengthened using Carbon Fiber Reinforced Polymer (CFRP). Strengthening configuration of CFRP-wrap used in this study were U-wrap and surface-wrap which applied with one layer of CFRP and in vertical alignment (90^{o}). Four RC deep beams which included a solid control beam, a beam with two large circular openings, beams with two large circular openings strengthened using U-wrap and surface-wrap were tested to failure under four-point loading. All the beam specimens were in a dimension of 120 x 600 mm and 2400 mm in length. The support and loading point were located at 300 mm and 800 mm from the edge of the RC deep beams, respectively. Circular openings was designed with a standard of 0.45h which considered as large circular openings in a diameter of 270 mm that located 435 mm from the edge of the RC deep beams. Shear span-to-depth ratio (a/h) in this study was 0.83 in which the distance between the loading point and the support was 500 mm in order for the beam specimens to fail in shear region. RC deep beam with large circular openings, NS-BCO greatly reduced the beam strength, approximately 51.20 % as compared to the control beam. On the other hand, RC deep beam with circular openings strengthened using U-wrap, UW-BCO increases the beam strength up to almost 85.0 % as compared to NS-BCO. Hence, the most effective strengthening method was U-wrap, UW-BCO which re-gained the beam strength up to 90.28 % as compared to control beam.

ABSTRAK

Kajian eksperimen telah dijalankan untuk mengkaji tingkah laku bertetulang rasuk yang mendalam konkrit yang tidak diperkukuhkan dengan pembukaan dan diperkukuhkan menggunakan Serat Karbon Mengukuhkan Polimer (CFRP). Konfigurasi pengukuhan CFRP-meledingkan yang digunakan dalam kajian ini adalah U-meledingkan dan permukaan-meledingkan yang ditampal dengan satu lapisan CFRP dan dengan penjajaran menegak, (90^o). Empat bertetulang rasuk yang mendalam konkrit adalah termasuk rasuk kawalan pepejal, rasuk dengan dua pembukaan bulat besar, rasuk dengan dua pembukaan bulat besar diperkukuhkan menggunakan u-meledingkan dan permukaan-meledingkan diuji dengan kegagalan di bawah empat mata muatan. Semua spesimen rasuk berada dalam dimensi 120 x 600 mm dan 2400 mm dalam panjang. Sokongan dan muatan titik terletak 300 mm dan 800 mm dari tepi bertetulang rasuk yang mendalam konkrit, masing-masing. Pembukaan bulat direka dengan taraf 0.45h yang dianggap pembukaan bulat yang besar dalam garis pusat 270 mm yang terletak 435 mm dari tepi bertetulang rasuk yang mendalam konkrit. Rentang ricih nisbah kedalaman (a / h) dalam kajian ini adalah 0.83 di mana jarak antara titik beban dan sokongan adalah 500 mm supaya spesimen rasuk gagal di rantau ricih. Bertetulang rasuk yang mendalam konkrit dalam dengan pembukaan bulat besar, NS-BCO dikurangkan kekuatan rasuk, kira-kira 51.20% berbanding dengan rasuk kawalan. Sebaliknya, bertetulang rasuk yang mendalam konkrit dengan pembukaan bulat diperkukuhkan menggunakan U-meledingkan, UW-BCO meningkatkan kekuatan rasuk sehingga hampir 85.0 % berbanding dengan NS-BCO. Oleh itu, kaedah pengukuhan yang paling berkesan adalah U-meledingkan, UW-BCO dengan pengembalian kekuatan rasuk hampir 90.28% berbanding dengan rasuk kawalan.

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LIST OF SYMBOLS

l_o	Clear span
Ø	Diameter
l	Effective span
δ_u	Ultimate deflection
P_u	Ultimate load
δ_y	Yield deflection
P_y	Yield load

LIST OF ABBREVIATION

a	Shear span (Distance between support and loading)
ACI	American Concrete Institute
AFRP	Aramid fiber-reinforced polymer
B	Bottom of shear span-near loading point
BCO	RC deep beam with circular openings
C	Mid of shear span
CAN	Canadian
CFRP	Carbon fiber-reinforced polymer
d	Effective depth
FRP	Fiber-reinforcement polymer
FS	FRP strengthening
H or h	Depth
I.S.	Indian Standard
LVDT	Linear Variable Displacement Transducer
NDS	New Zealand Standard
NS	No strengthening
OPC	Ordinary Portland Cement
RC	Reinforced concrete
S	Satisfactory failures
SS	Surface strengthening
T	Top of shear span-near support
U	Unsatisfactory failures
UMP	Universiti Malaysia Pahang

UiTM	Universiti Teknologi Mara
UW	U-wrap

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

In this 21st century, we realised that traditional methods are replaced by modern method from time to time and become more friendly use. Reason is the modern method have more advantaged then traditional method. In civil engineering field, there have been a trend that RC deep beams with openings are implanted for ease the installation of building services. The difference between RC beam and RC deep beam, is the depth of RC deep beam can be comparable with its own length but the dimension of RC beam is not limited. RC beam/deep beam can be classified into simply supported beam and continuous beam that based on the design standard, same goes with its own dimension. Function of the RC beam and RC deep beam are the same, which are to transfer the load that applied on itself to the column. Application of RC deep beam are normally for tall building structure (floor diaphragms, shear walls, wall footings, transfer gird & pile caps) and offshore structure.

Building services are installed through the RC deep beam with openings. RC deep beam with different shape of openings are for different kind of building services. As an example, circular openings are for the installation of piping, ducts, computer networks, telephone circuits and power cable. Moreover, Mansur & Tan (1999) state that square and rectangular openings are for air-conditioning services. Behaviour of RC deep beam such as stiffness, ultimate load capacity, first cracking, cracks pattern, failure mode and load-deflection curve are affected with openings through itself.

Openings can be classified into two that are pre-planned openings and post planned openings. This both method can leaded to major cost saving for the construction project in the end. Pre-planned openings is which the shape, location and size of openings are decided on the design stage before the RC deep beams are constructed to formed the structural building. During the design stage, internal strengthening is the best choice to strengthen up the RC deep beams with openings. As for the post-planned openings, drilling process is conducted for the RC deep beam to have openings. This method usually applied on reconstructed and newly constructed structural building which involved relocation of building services. In this situation, external strengthening is commonly used to strengthen up the RC deep beams with openings, since it is not economical and kind of costly to reconstruct the whole structural building.

Advantages of pre-planned openings and post-planned openings have the same advantages that are headroom can be reduced by passing the piping and ducts utility through the RC deep beams with openings instead of hanging its down below the RC deep beam which are covered by ceiling causes increases of headroom; Cost saving can be done at the cost of installation building services with reduced the length of piping and ducts by passing through the RC deep beams with openings. Moreover, major cost saving and improvement on structural capacity by frame supports undergoes gravity loading & seismic excitation can only be done in pre-planned openings. These openings reduced the headroom, height of the building and faintly in weight of concrete beams which bring to such advantages.

This experimental study is based on the pre-planned openings. Hence, the RC deep beams with large circular openings must apply external strengthening. External strengthening can be classified into traditional method and modern method. Referring to the traditional method, steel plate can be installed on to the RC beams by adhesive bonding and bolted construction. This can increases the serviceability & ultimate load capacity of the RC beam section and available for maintenance & inspection. Disadvantaged of using steel plate as external strengthening are taking part of corrosion that become heavy when come in bigger size and need specialized in handling & installation.

After FRP is invented and proved that it can increases the strength of RC beam through previous experimental researches, it have replaced the steel plate to become a modern method. FRP can be classified into CFRP, GFRP and AFRP that contains carbon fibers, glass fibers and aramid fiber which the products come in the form of sheets, laminates, wraps and strips. The application for the CFRP is mainly on active strengthening to withstand the loads are constantly loaded; For GFRP is on passive strengthening to resist the seismic wave that transfer from earthquake, explosion and volcano eruption; AFRP can be applied in the field of blast mitigation and prevent bridge columns from collapse due to impact of vehicles. Thus, according to the applications of FRP the most suitable used for external strengthening in RC deep beams with openings is CFRP. The advantages of using CFRP are good in long-term behaviour, fatigue behaviour, alkali resistance & wear behaviour, resist to corrosion, light in weight and have high tensile strength & deformation capacity. Here come the disadvantages of CFRP that are cost for installation of CFRP is expensive and degradation is occurred when expose to high temperature.

1.2 PROBLEM STATEMENT

Experimental study on behaviour of RC deep beams with openings have been widely carry out under condition such as with difference shape of openings, size of openings and location of openings. There are merely data and result collect regarding the experimental study on behaviour of RC deep beams with large circular openings strengthened using CFRP. RC deep beam is come with restrict in depth which the openings of larger circular shape on it affect the behaviour of RC deep beam that causes the beam on failure mode and lead to structural building failure. This experimental study is related to the post-planned openings for the installation of building services. Normally, large circular openings are for the passes of utility pipe and ducts which are bigger in size through the RC deep beam. Openings causes reduction of RC deep beam in stiffness and ultimate load capacity that lead to exorbitant cracking and deflection. According to Campione & Minafò (2012), the failure mode was confirmed when the cracks started at the mid shear span and propagated to become two diagonal cracks which appeared between the curve contour of the circular openings and the edge of base plates. Problems can be solve by strengthen the openings region on the RC deep beam with difference arrangement and configuration of CFRP wraps which have the ability to regain the beam strength.

1.3 RESEARCH OBJECTIVE

The main purpose of this experimental study is to study the behaviour of RC deep beams with large circular openings. Objectives of this experimental study are stated as below:

i. To determine the behaviour of RC deep beams with large circular openings (without CFRP and strengthening using CFRP wrap) in term of load-deflection behaviour, crack pattern and failure mode.
ii. To identify the effects of openings in term of size, shape and location.
iii. To identify the most effective strengthening configuration using CFRP in RC deep beams with openings.

1.4 SCOPE OF STUDY

The scope of this experimental study is to study the behaviour of RC deep beams with large circular openings strengthened using CFRP. Rectangular RC deep beams that are simply supported with total of 4 are tested to failure mode under four-point loading. Those 4 RC deep beams are cast into solid RC deep beam (act as a control beam), RC deep beam with large circular openings and 2 RC deep beams with large circular openings strengthened using CFRP. Large circular openings with diameter of 270 mm and the supports are located 300 mm start from both edge of the RC deep beam. In order to have failure mode on shear region instead of flexural region, the point loads are located a = 500 mm from the both supports by taking the formula of shear span-to-depth ratios, a/H = 0.83. External strengthening by using difference arrangement and configuration of CFRP are to determine the percentage of the beam strength regain. Dry application method have been used to applied the CFRP (Sikawrap-300C) after the mid-viscous Sikadur-330 resin have been applied uniformly on the surface of RC deep beams that need to be strengthened with thickness of 3 mm. All rectangular RC deep beams have the identical dimension of width (120 mm), depth (600 mm) and length (2400 mm). Data and results are collected to analyse the ultimate load capacity, load-deflection, crack patterns and failure mode of each RC deep beams. Hence, comparison can be made between each other.

1.5 RESEARCH SIGNIFICANCE

Data and results of ultimate load capacity, load-deflection, crack patterns and failure mode are gained from this experimental study. Based on this data and results, the location of openings on RC deep beam by drilling process on reconstructed and newly constructed structural buildings should be avoided on shear region that near to the column (act as supports) which have the highest percentage in reduction of beams stiffness, ultimate load capacity and strength. On this experimental study, circular openings are used because it is the most utilisable shape that used in building services that applied in all the tall buildings. Moreover, large circular openings are for the installation of pipes, ducts and power cables that bigger in diameter. Since, RC deep beams with openings cause reduction in beams stiffness, ultimate load capacity and strength, external strengthening using CFRP wrap is applied. When facing this problems in real case, engineers can used the most effective method to strengthen up the RC deep beams with large circular openings because the installation of CFRP is expensive.

CHAPTER 2

LITERATURE REVIEW

2.1 DESIGN STANDARD FOR DIMENSION OF RC DEEP BEAMS

RC deep beam is a beam which have a dimension that in depth which bigger than the regular beam and may corresponding with its own length. Functions of the RC deep beam are to transferred and withstand loads which are higher than the capable of regular beam. Normally, the application of RC deep beams are on tall building structures and offshore structures. As an example: floor diaphragms, shear walls and wall footings who act as the load which sit on the RC deep beams for it to carried and transferred load to the columns; In foundation, RC deep beams act as a transfer girder between pile caps to connected all the pile caps together. A foundation are formed and to transfer load to the piles who hold on to the soil. Design standard for dimension of RC deep beams can be based on Building Code Requirements for Structural Concrete (ACI 318-83) revised 1986, Canadian Code (CAN3-A23.3-M84), CIRIA Guide 2 (1977), Indian Standard Code (I.S.-456-2000), New Zealand Standard Code (NDS-3101-2006) and Draft Eurocode & CEB-FIP Mode Code.

2.1.1 Building Code Requirements for Structural Concrete (ACI 318-83) revised 1986 and New Zealand Standard Code (NDS-3101-2006)

Based on Kong (2002) and Kore & Patil (2013), RC deep beam can be classified in to simply supported beam & continuous beam. Those beams are designed to test on shear strength & flexural strength. The loads are applied on the top surface of the RC deep beam with supports at the bottom. According to Building Code Requirements for Structural Concrete, the design standard for dimension of simply supported beam and continuous beam on shear strength come with formula of clear span, l_o over effective depth, d smaller than 5.0. For flexural strength, the formula for simply supported beam and continuous beam are different with l_o / h smaller than 1.25 and l_o / h smaller than 2.5.

On the other hand, the formula for designed the dimension of RC deep beam under New Zealand Standard Code can be tested for both shear strength and flexural strength. The formula is l_o / d smaller than or equal to 3.6 for both simply supported beam and continuous beam are listed in.

2.1.2 Canadian Code (CAN3-A23.3-M84)

Canadian Code and Building Code Requirements for Structural Concrete have similar formula on design standard for RC deep beam on flexural strength test. For the shear strength, the distance from the load applied to the support must be smaller than 2d in order to have more than 50% of shear occurs at the supports. This ensured RC deep beam tested to fail in the shear mode that based on the shear-span over depth ratios concept listed in Kong (2002).

2.1.3 Draft Eurocode & CEB-FIP Mode Code

Design standard for dimension of RC deep beam did not stated in the Draft Eurocode but it referred to the design standard of CEB-FIP Mode Code in the book of Kong (2002). CEB-FIP Mode Code can be tested on both shear strength & flexural strength with l_o / h smaller than 2.0 (simply support beam) and l_o / h smaller than 2.5 (continuous beam).

2.1.4 CIRIA Guide 2 (1977) and Indian Standard Code (I.S.-456-2000)

Kong (2002) and Kore & Patil (2013) stated that RC deep beam which are simply supported beam and continuous beam can be categorized by the formulas of effective span, l over depth, h smaller than 2.0 and 2.5. The value of effective span must be chosen from which the value is smaller with the distance between center of supports or 1.15 times the clear span. Differences between CIRIA Guide 2 & Indian Standard Code and Building Code Requirements for Structural Concrete & Canadian Code are:

- The formulas under CIRIA Guide 2 & Indian Standard Code can be used to design dimension of RC deep beam that tested on shear strength & flexural strength but formulas by Building Code Requirements for Structural Concrete & Canadian Code can only tested on flexural strength.
- There are slightly difference between the formulas of (CIRIA Guide 2 & Indian Standard Code) and (Building Code Requirements for Structural Concrete & Canadian Code) are the clear span changed to effective span.

2.2 OPENINGS

The trend of this few years on the design of concrete structure is RC deep beam with openings. Openings can be classified into pre-planned openings and post-planned openings which openings are through the RC deep beams for the installation of buildings services. Advantages of the openings are to ease the installation of building services that in turn come with financial saving. In balance, openings also bring negative impact that stiffness and ultimate load capacity of RC deep beams can be reduced or affected due the shape of openings, size of openings and location of openings. Location of loading and support also play importance part in controlling the shear span-to-depth ratio (a/H) which causes the RC deep beam to be failed in shear region or flexural region.

2.2.1 Shape of Openings

Shape of openings through the RC deep beam are mainly depend on the type of building services. There are many shape in this world but the shape of openings for building services that come in usable are circular, square and rectangular. As stated in Chin, Shafiq, & Nuruddin (2011), building services such as installation of piping, ducts, computer networks, telephone circuits and power cables are suitable for circular openings. Moreover, square and rectangular openings are normally for air-conditioning services only.

2.2.2 Size of Openings

Saksena & Patel (2013), Pimanmas (2010) and Somes & Corley (1974) reported that the size of circular openings can be classified as large when the diameter of circular bigger than the value of 0.25h. Based on Figure 2.1, different diameter of circular openings (0.55h and 0.45h) under L/4 distance from the support are tested on shear region. The test showed that 0.55h of circular openings decreases 52% of strength as compared to the solid RC deep beam; 0.45h of circular openings decreases 21% of strength as compared to the solid RC deep beam.

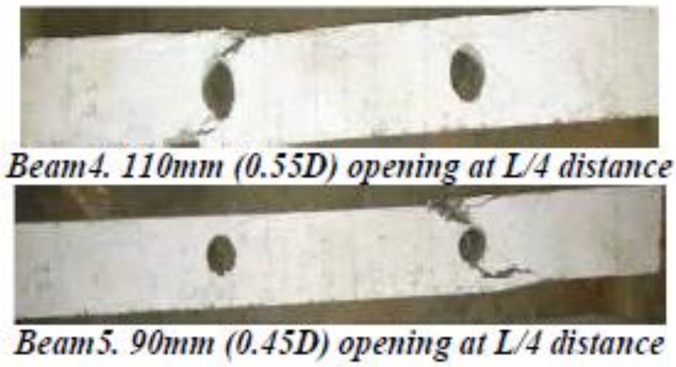


Figure 2.1: a) Beam 4. 110 mm (0.55D) openings at L/4 distance and b) Beam 5. 90 mm (0.45D) openings at L/4 distance

Source: Saksena & Patel (2013)

El Maaddawy & Sherif (2009) conducted a studies on thirteen RC deep beam with rectangular openings with/without CFRP strengthening. They have provided 3 size of rectangular openings that are 150 mm x150 mm, 200 mm x 200 mm and 250 mm x 250 mm. The size of the openings are getting bigger determined by the ratio of openings size over depth which are 0.3, 0.4 and 0.5. Based on the RC deep beams with openings, 21% of average ultimate load capacity is reduced for openings size from 150 mm to 200 mm. As for openings size from 150 mm to 250 mm, the results showed that 51% reduction of average ultimate load capacity is occurred.

2.2.3 Location of Openings, Loadings and Supports

RC deep beam is tested to fail on shear region under four-point loadings with loadings applied on top surface of the RC deep beam and supports at the bottom. Referring to the research done by Saksena & Patel, (2013) the location of circular openings are placed on a distance from the support with L/2, L/4 and L/8 as shown in Figure 2.1 and 2.2. The results indicated that circular openings (0.55h and 0.45h) with L/8 distance decreases 62% and 31.82% of strength as compared to solid RC deep beam. Moreover, circular openings (0.55h) with L/2 distance (centre span of the beam) showed that no effect on ultimate load capacity as compared to solid RC deep beam.

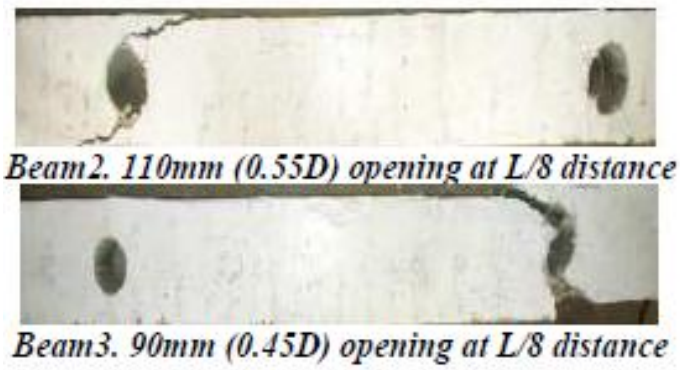


Figure 2.2: a) Beam 2. 110 mm (0.55D) openings at L/8 distance and b) Beam 3. 90 mm (0.45D) openings at L/8 distance

Source: Saksena & Patel (2013)

For the location of loadings and supports, the distance between loading and support with rectangular openings is ranged with low shear span-to-depth ratio (a/H) between 0.5 and 2.0 stated in Campione & Minafò (2012) and Kong (1970). Experimental research done by Campione & Minafò (2012) are RC deep beams with circular opening located within the shear span and mid –span section. Shear span-to-depth ratio, $\frac{a}{H} = \frac{131.6}{480}$ = 0.27 where shear span is the distance between loading and support as shown in Figure 2.3. The low shear span-to-depth ratio is to ensure that the RC deep beam with opening are tested to fail on shear region instead of flexural region. For circular opening placed at the mid-span section, the results showed that no influence to the ultimate load capacity; as for the circular opening placed within the shear span, about 18% to 30% of ultimate load capacity is reduced.

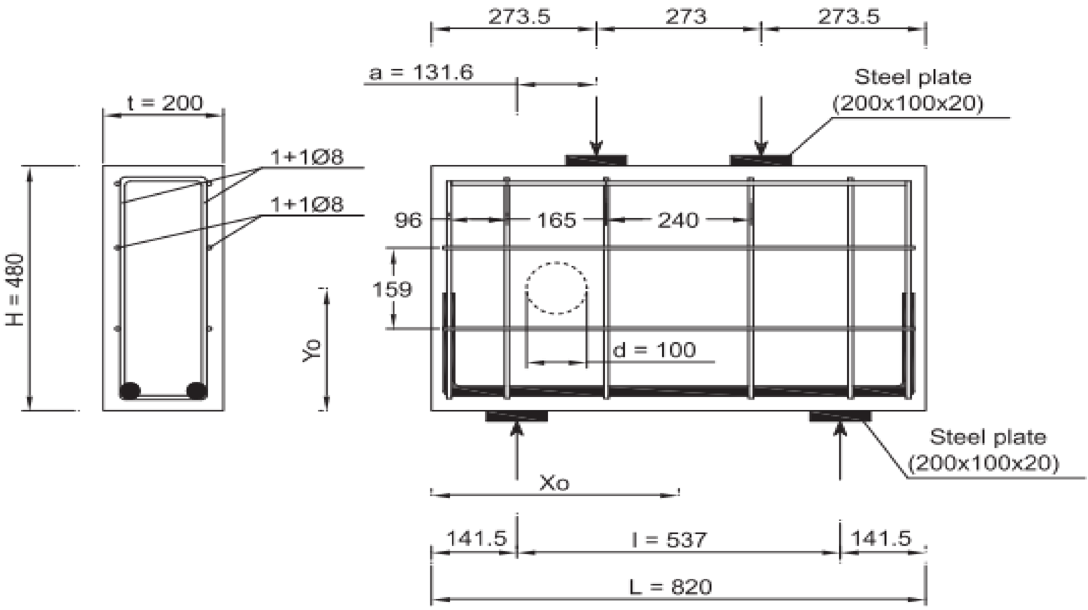


Figure 2.3: Typical specimen details (unit: mm)

Source: Campione & Minafò (2012)

2.3 BEHAVIOUR OF RC DEEP BEAMS

Crack patterns, load-deflection, ultimate load capacity and failure mode are the behaviour of RC deep beam that are collected as results after the experimental tested. The behaviours are affected by with/without existence of openings, shape of openings, size of openings, location of openings and distance between loading & support.

2.3.1 Behaviour of Solid RC Deep Beam

Based on Figure 2.12, specimen 4 is a control beam which cast by the Campione & Minafò (2012) in the experimental research. The reinforced steel bar frame of specimen 4 is installed with 2Ø18 of main reinforcement and 4Ø8 of transverse steel. Under four-point loading test, specimen 4 is with first visual cracking load of 500 kN and ultimate-load capacity of 1091.56 kN. Initial flexural crack is observed in the mid-span section at about 25% of maximum load. From the observation, specimen 4 is exhibited brittle failure with the main cracks leading to failure following the load path by the line joining the loading and the support point. In addition, cracks were observed before failure from the edge of the bearing plate due to high compressive stresses. Load-deflection curve of specimen 4 from Figure 2.5 is behaved liner behaviour which indicated it exhibited as brittle behaviour with zero degree of interruption of natural load path.

Figure 2.4: Specimen 4

Source: Campione & Minafò (2012)

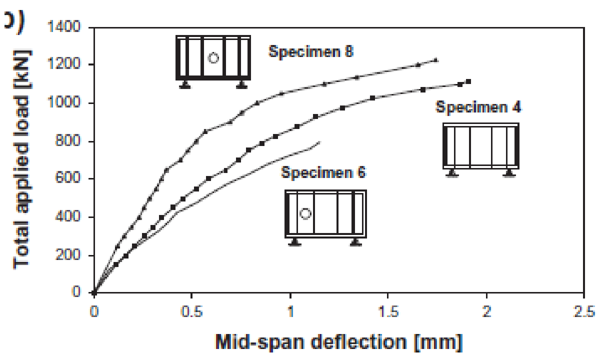


Figure 2.5: Load-deflection curve of specimen 4

Source: Campione & Minafò (2012)

According to the experimental done by Chin, Shafiq, & Nuruddin (2011), the control beam, CB failed in shear region as shown in Figure 2.6. In the experimental, flexural cracks are appeared at the tension zone and propagated vertically up to the neutral axis of the beam. Based on the observation, the flexural cracks growth in numbers followed by the formation of diagonal cracks. The crack width increased before failure, bringing an abrupt brittle failure at the shear region. Furthermore, large diagonal shear cracks formed from the loading point towards the support as the bottom reinforcements yielded with a failure load of 115.67 kN which can use as ultimate-load capacity.

Figure 2.6: Crack patterns and failure mode of control beam

Source: Chin, Shafiq, & Nuruddin (2011)

2.3.2 Behaviour of RC Deep Beams with Openings

Specimen 9 and 10 that done by Campione & Minafò (2012) are with one circular opening that located within the shear span and at the mid-span section by referring to Figure 2.12. The first visual cracking load are 250kN and 650kN but for the ultimate load capacity are at 1038.14kN and 1249.14kN. For the specimen 9, the first visible crack appeared about 22% of ultimate capacity load. The cracks are started on bottom curved contour of the opening and propagated within a small length toward the bearing region which bring harmless to failure. As for specimen 10, many cracks appeared between the loading and support before failing. When further incremental loading on both specimen, two diagonal cracks are propagated from the edge of the bearing plate and go tangentially toward the edge of curved contour of the opening which leading to failure (see Figure 2.7).

Figure 2.7: Specimen 9 after testing

Source: Campione & Minafò (2012)

By comparing the load-deflection curve between the specimen 9 and 10 as shown in Figure 2.8, specimen 10 have 18% ultimate load capacity greater than specimen 9. Both of the load-deflection curve showed almost the same slope with non-linear behaviour that diffused of cracks before failing.

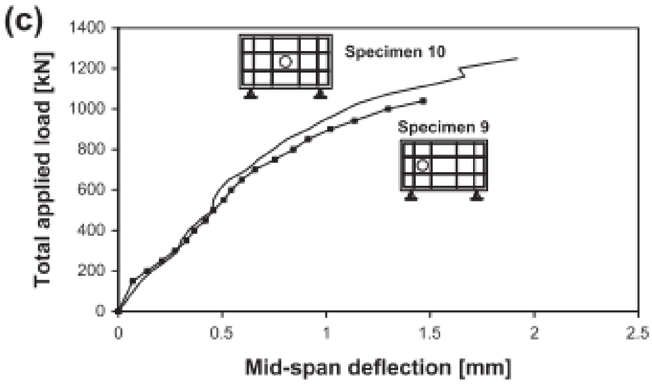


Figure 2.8: Load-deflection curve for specimen 9 and 10

Source: Campione & Minafò (2012)

Under the research done by El Maaddawy & Sherif (2009), behaviour of RC deep beams with rectangular openings are depended on the openings size. Based on Figure 2.9, as the openings size increases from 150 mm to 250 mm the first visual cracking load (kN) and ultimate load capacity (kN) shows decreases. Moreover, the ultimate deflection (mm) increases as the openings size increases. First visual cracking usually appeared within 31% to 51% of ultimate load capacity on both corners of the rectangular openinsg that line up with the loading and support. Furthermore, the degree of interruption of natural load path by the openings can affect the first visual cracking load. Cracking load of specimen group A have 47% less than the average of specimen group B and C because it have a higher degree of interuption of natural load path by the openings.

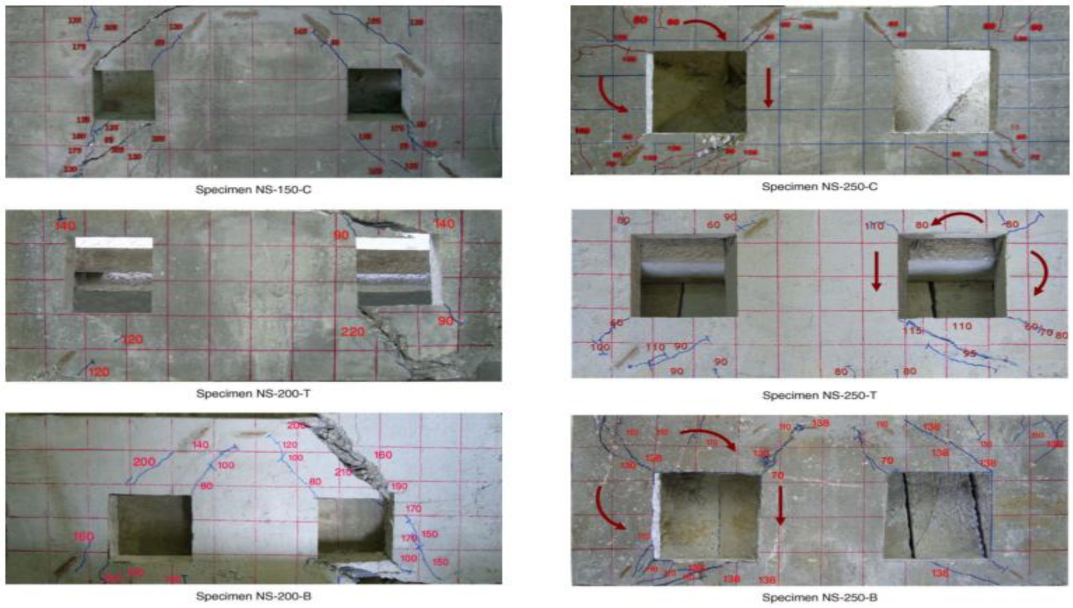
Group	Specimen	Cracking[a] load(kN)	Ultimate load(kN)	Ultimate deflection(mm)
[A]	NS-150-C	85	205.2	3.2
	NS-200-C	50	163.0	4.1
	NS-250-C	40	106.6	5.7
	FS-200-C	–	270.6	5.2
	FS-250-C	–	182.0	5.4
[B]	NS-150-T	110	260.2	2.4
	NS-200-T	90	220.0	3.2
	NS-250-T	60	127.6	3.8
	FS-250-T	–	219.4	6.3
[C]	NS-150-B	105	291.4	3.0
	NS-200-B	80	210.7	3.1
	NS-250-B	70	137.9	4.1
	FS-250-B	–	186.6	5.7

Figure 2.9: Test Results

Source: El Maaddawy & Sherif (2009)

Failure mode of the RC deep beam with rectangular openings mainly depended by the openings size and classifeid into mode A and mode B as shown in Figure 2.10. Under the openings size of 150 mm and 200 mm, the RC deep beams with a diagonal crack appeared at the corners of the openings toward the loading and support caused to sudden failed (mode A). For failure mode B under the openings size of 250 mm, relative rotation of three different part of the beam is the main source for the failure to occurred.

Load-deflection curve can be affected by the degree of interruption of natural load path by the openings. Specimen group A with high degree of interruption of natural load path by the openings come with non-linear relationship of load-deflection curve. This indicated that high percentage of cracks appeared, widening and diffusing. When come to specimen group B and C that with low degree of interruption of natural load path by the openings, the load-deflection curve is presented almost linear relationship.



a) Failure mode A **b) Failure mode B**

Figure 2.10: a) Failure mode A and b) Failure mode B

Source: El Maaddawy & Sherif (2009)

2.4 STRENGTHENING METHOD

Strengthening method for RC deep beam can be classified into two that are internal strengthening and external strengthening. Internal strengthening are usually used in pre-planned openings for RC deep beam such as vertical stirrups, horizontal stirrups or strut-and-tie method (see Figure 2.11). For external strengthening, it is suitable in post-planned openings for RC deep beams. Various external strengthening materials that use nowadays are carbon fiber-reinforced polymer (CFRP), fiber-reinforced polymer (FRP), glass fiber-reinforced polymer (GFRP) and aramid fiber-reinforced polymer (AFRP).

Moreover, steel plate are also one of the external strengthening that can applied on RC deep beam.

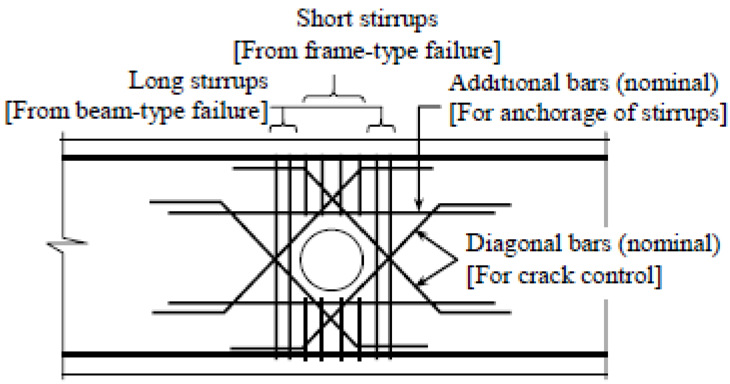
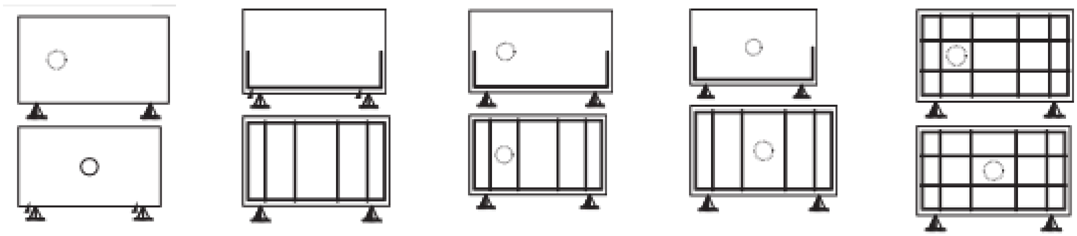


Figure 2.11: Internal strengthening for pre-planned opening of RC deep beam with opening

Source: Kong (2002)

2.4.1 Internal Strengthening

According to Campione & Minafò (2012), the specimens are using 2Ø18 of main reinforcement, 2Ø8 of horizontal stirrups and 4Ø8 of vertical stirrups as shown in Figure 2.12. After the specimens are tested, solid RC deep beam and RC deep beam with circular opening at the mid-span section showed 15 % increases in ultimate load capacity with the presence of vertical stirrups. Unfortunately, the installed of horizontal stirrups in solid RC deep beam and RC deep beam with circular opening at the mid-span section are inefficient in increasing the ultimate load capacity. Moreover, with circular opening within the shear span, the vertical stirrups are inefficient. When come to the horizontal stirrups, it give 20% increases in ultimate load capacity.



1 & 2 3 & 4 5 & 6 7 & 8 9 & 10

Figure 2.12: Details of specimens

Source: Campione & Minafò (2012)

2.4.2 External Strengthening

CFRP strengthening system which is the following sub-section that will explain further on external strengthening method. Fibre orientation of CFRP can be classified into two that are vertical alignment, strengthening, (90^o) and horizontal alignment strengthening, (0^o). In addition, strengthening configuration of CFRP is divided into U-wrap, L-wrap and Surface-wrap. These wrapping schemas increases the ultimate load capacity which depended on the number of layers applied. Vertical alignment strengthening, (90^o) is perpendicular to the longitudinal axis of the RC deep beam to prevent the growth of potential cracks which in turn increases the ultimate load capacity and acted as an anchorage for horizontal, (0^o) CFRP sheets. When come to effectiveness, horizontal alignment strengthening, (0^o) is less effective than vertical alignment strengthening, (90^o) (Alferjani et al, 2014). Nowadays, vertical alignment strengthening, (90^o) have been widely used in CFRP strengthening system.

Referring to the experimental research done by El Maaddawy & Sherif (2009), the 4 RC deep beam with rectangular openings are strengthened using CFRP. From Figure 2.13, single layer of CFRP are applied with vertical alignment strengthening, (90^o) and horizontal alignment strengthening, (0^o) in U-wrap. U-wrap of CFRP with single layer for RC deep beam with openings give increases in beam strength, 66% - 71% of strength gained for the openings located at the center of shear span; 72% of highest strength gained for the openings located at the top of shear span near support where the shear force are carried by the bottom part of the beam which fully wrapped by CFRP; 35% of lowest strength gained for the openings located at the bottom of shear span near loading point where the shear force are carried by the upper part of the beam which partially wrapped by CFRP.

Stiffness of the RC deep beam with rectangular openings strengthened with CFRP exhibited increases in stiffness. For the openings located at the mid shear span, the stiffness of strengthened specimen (250 mm openings size) is almost similar to the unstrengthen specimen (200 mm openings size); stiffness of strengthened specimen (200 mm openings size) is higher than the unstrengthen specimen (150 mm openings size). Based on the recorded results, only a slightly increases in stiffness for the openings located at the top of shear span near support and bottom of shear span near loading point.

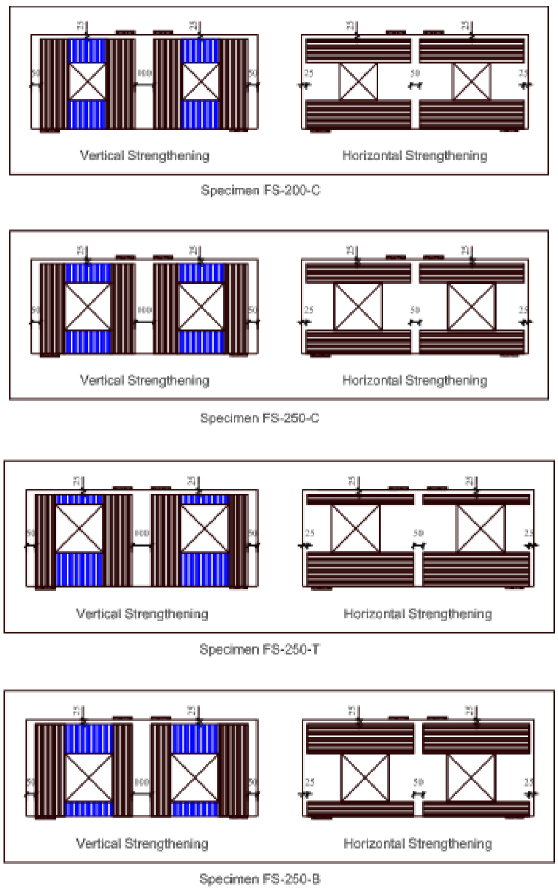


Figure 2.13: CFRP strengthening scheme

Source: El Maaddawy & Sherif (2009)

Failure mode of RC deep beam with rectangular openings strengthened with CFRP is the top part of the CFRP which partially debonding from the concrete when the beam sudden failed with diagonal cracks at the openings chords toward the support and loading. The CFRP sheets exhibited ruptured and debonding from the RC deep beam with openings located at the mid shear span. In addition, CFRP sheets that bonded at the bottom part of the beam are observed ruptured for openings located at the top of shear span near support; for openings located at the bottom of shear span near loading point, the CFRP sheets that bonded at upper part of the RC deep beam exhibited partially debonding. Failure mode of U-wrap CFRP on all above are shown in Figure 2.14.

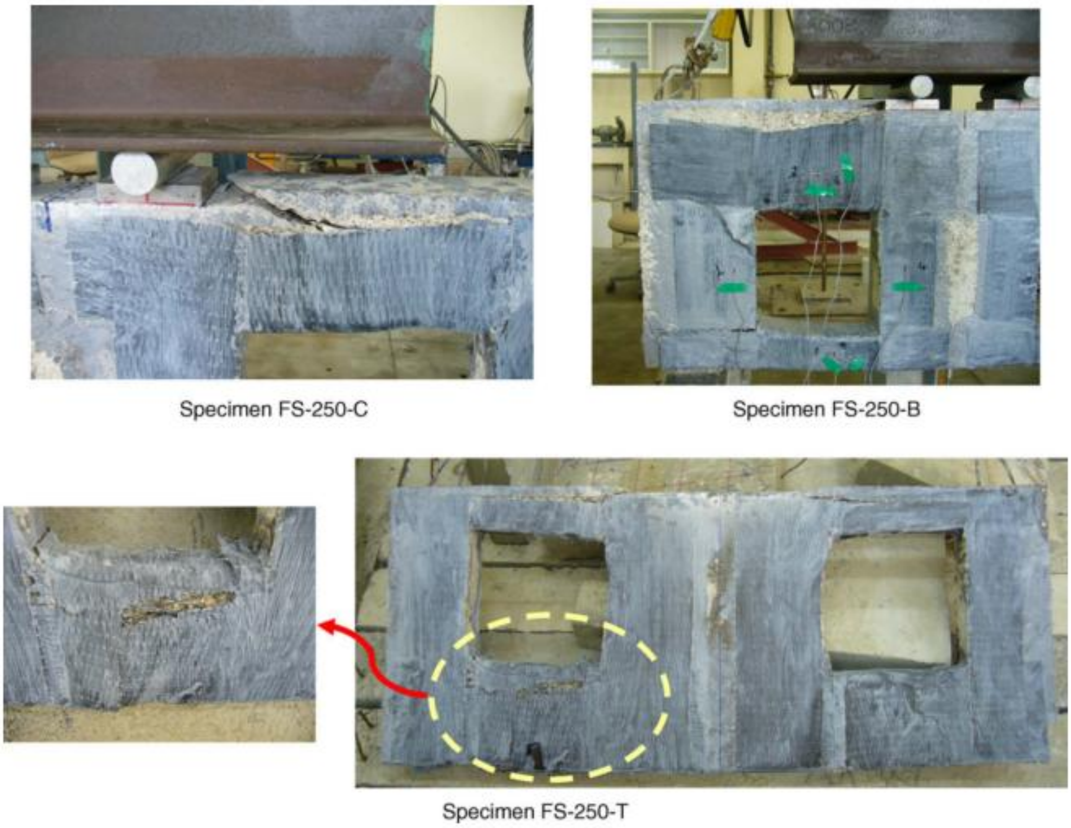
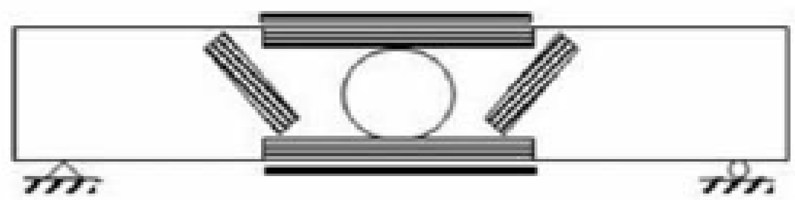


Figure 2.14: Failure modes of the CFRP-strengthened beams

Source: El Maaddawy & Sherif (2009)

Based on the experimental study done by the Chin, Shafiq, & Nuruddin (2011), the RC deep beam with circular opening is strengthened using CFRP laminates. The circular opening with diameter of 230 mm is located at the mid-span of the RC deep beam. Strengthening configuration of CFRP laminates are based on the crack patterns of the tested un-strengthened beams with opening. Thus, RC deep beam with circular opening at flexure (C-cfrp-f) is externally strengthened with CFRP laminates which placed at above and below the opening with fibers oriented in a direction parallel to the longitudinal axis of the beam, diagonally adjacent to the opening and at tension and compression zone of the beam (see Figure 2.15). During the four-point loading test, flexural cracks are appeared at the tension region but do not appeared in the area which restricted by CFRP laminates. When the load continue increases, the diagonal cracks were appeared at the right span with widening of cracks before failure. Figure 2.16 presents the sudden shear failure which occurred due to the formation of diagonal shear crack with width of approximately 15 mm. Moreover, formation of diagonal cracks caused crushing of concrete near the support along with yielding of bottom reinforcement.



(a) C-cfrp-f

Figure 2.15: Strengthening configuration of C-cfrp-f

Source: Chin, Shafiq, & Nuruddin (2011)

Figure 2.16: Failure mode of C-cfrp-f

Source: Chin, Shafiq, & Nuruddin (2011)

2.5 SUMMARY

The information's that stated as below are to fill up the gaps between the literature reviews and use to conduct this experimental study. After go through all the design standard for dimension of RC deep beam, the Building Code Requirements for Structural Concrete (ACI 318-83) revised 1986 is chosen because the experimental study of RC deep beams are with dimension of width (120 mm), depth (600 mm) and length (2400 mm). The design condition is fulfilled under simply supported beam with $\frac{l_o}{d} = \frac{2400mm}{572mm}$ equal to 4.20 smaller than 5.0 tested on shear strength. In addition, circular openings is designed with a standard of 0.45h which considered as large circular openings in a diameter of 270 mm that located 435 mm from the edge of the RC deep beams. Moreover, shear span-to-depth ratio (a/h) is 0.83 in which the distance between the loading point and the support is 500 mm in order for the beam specimens to fail in shear region. Thus, the support and loading point are located at 300 mm and 800 mm from the edge of the RC deep beams, respectively. Furthermore, strengthening configuration of CFRP-wrap use in this study are U-wrap and surface-wrap which applied with one layer of CFRP and in vertical alignment (90^o).

CHAPTER 3

METHODOLOGY

3.1 OVERVIEW

In this chapter, materials characteristics, specimen details, laboratory testing, experimental works and methodology chart are discussed in details in order to carry out the experimental study with expected data and results. Slump test and compressive test were conducted to support this experimental study with the data and results that were collected. Procedure of the experimental works are explained in details with support of methodology chart. Thus, the progress of experimental study are cleared for understanding.

3.2 MATERIALS CHARACTERISTICS

In this section, the materials that used in this experimental study to build the RC deep beams with large circular openings are mainly focus on reinforcement steel bar and ready-mix concrete. Moreover, CFRP and epoxy resin that as the strengthened materials for the RC deep beam also discussed.

3.2.1 Reinforcement Steel Bars

For the reinforcement steel frame, the RC deep beams were installed with 2T10 of compression reinforcement bar, 2T16 of tension reinforcement bar, 7 vertical link of R6-300 and 3 horizontal link of R6-150. The nominal yield strength for the compression & tension reinforcement bars were 500 N/mm^2 and the vertical & horizontal link were

275 N/mm^2. Reinforcement steel frame was formed by tie all the reinforcement bars together according to the planning.

Figure 3.1: Reinforcement steel bars of T10, T16 and R6

3.2.2 Concrete

The RC deep beams were cast using ready-mix concrete ordered from Hanson Building Materials Malaysia Sdn. Bhd. that located at No. A71, 1st Floor, Jalan Teluk Sisek, 25050 Kuantan, Pahang. In the ready-mix concrete, ordinary portland cement (OPC) with a 28 days compressive strength of 35 N/mm^2 was used because it was common and widely used in the concrete construction. Ready-mix concrete was produced by the combination of ordinary portland cement, aggregates, sand, water and additives. In this experimental study, a total 2 m^3 of ready-mix concrete was ordered. Hence, all the RC deep beam were cast with the same batch of ready-mix concrete in order to obtain the same concrete strength and uniformity. Furthermore, the spacer block were cast with the combination of ordinary portland cement, fine sand and water as shown in Figure 3.3. Then, the thickness of the spacer block was same as the concrete cover that was 20 mm.

Figure 3.2: All RC deep beams were cast with same batch of ready-mix concrete

Figure 3.3: Spacer block

3.2.3 CFRP and Epoxy Resin

Two of the RC deep beams with circular openings were strengthened using CFRP which classified as surface strengthening (SS-BCO) and U-wrap strengthening (UW-BCO). Figure 3.4 presents the CFRP that come in one roll with thickness of 0.13 mm and provided with 230 kN/mm^2 of tensile E-modulus of fibers. Before the CFRP laminates were applied on the RC deep beams, surface preparation of the RC deep beams must be conducted. Surface preparation with experimental works of grinding, sandblasting and cleaning were to ensure proper bonding with the surface of the RC deep beams. A thickness of 3 mm of epoxy resin (Sikadur 330) was applied on to the concrete surface and left for 1 week of curing in order for the epoxy resin to fully harden. Sikadur 330 was divided into component A and component B as shown in Figure 3.5, epoxy resin was formed with mixing 4 part of component A and 1 part of component B. Mechanical properties of the epoxy resin were 55 MPa of tensile strength, 1724 MPa of tensile modulus, 79 MPa of flexural strength and 3450 MPa of flexural modulus.

Figure 3.4: Carbon fiber-reinforced polymer (CFRP)

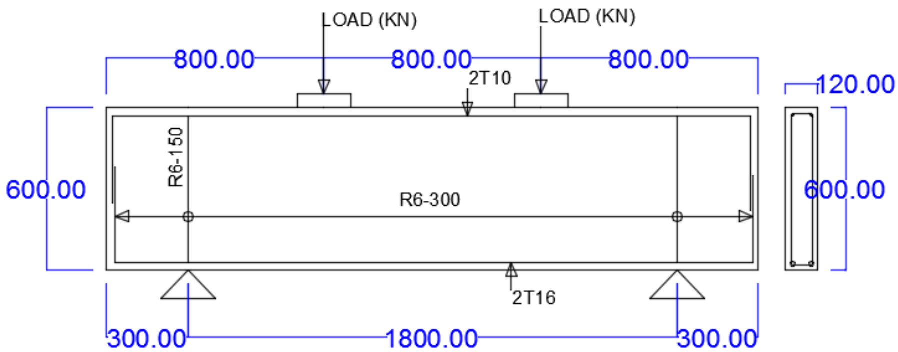
Figure 3.5: Sikadur 330 of component A and B

3.3 SPECIMEN DETAILS

Test specimens with total of 4 rectangular RC deep beams were cast with a dimension of width (120 mm), depth (600 mm) and length (2400 mm). The effective depth and effective span of the RC deep beams were 572 mm and 1800 mm, respectively with 20 mm of concrete cover. In this experimental study, the circular openings was designed with standard of 0.45h that bigger than 0.25h which considered as a large circular openings with diameter of 270 mm. Circular openings were located 435 mm from the edge of the RC deep beams which within the shear region. This condition causes the failure modes of RC deep beams failed under shear region.

3.3.1 Arrangement of Reinforcement Steel Bars

Details of reinforcement steel frame for control beam and RC deep beams with circular openings as shown in Figure 3.6 and 3.7. From the figures, it's give a clear picture about the arrangement of reinforcement steel bars.



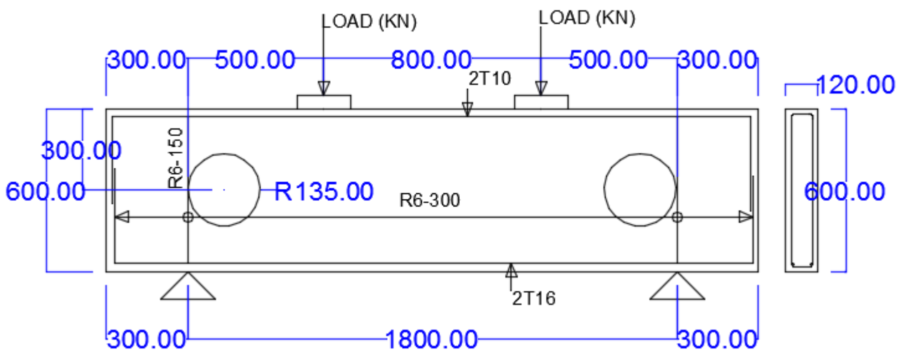


Figure 3.6: Arrangement of reinforcement steel bars from AutoCAD software

Figure 3.7: Arrangement of reinforcement steel bars from experimental works

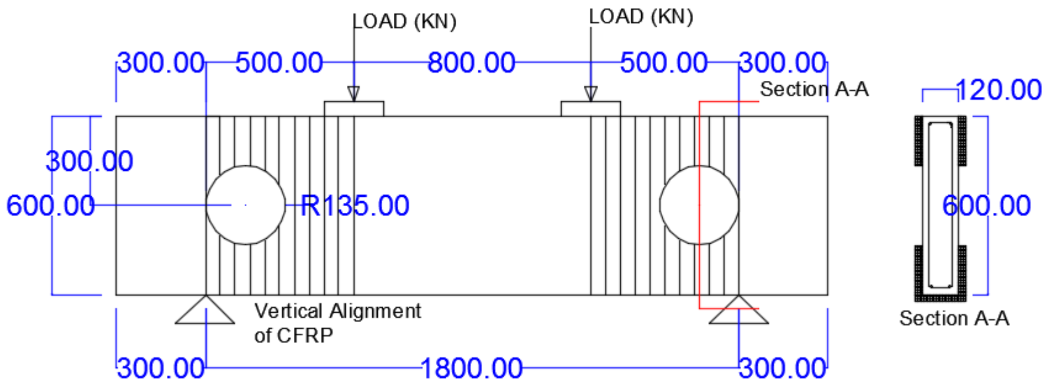
3.3.2 Strengthening Configuration of CFRP-Wrap

RC deep beams with circular openings that strengthened using CFRP wrap were SS-BCO and UW-BCO. One layer of CFRP wrap was applied in vertical alignment, (90^{o}) instead of horizontal alignment, (0^{o}) which the vertical alignment, (90^{o}) was perpendicular to the diagonal cracks that propagated form the loading point towards the openings and from openings to the support. Vertical alignment, (90^{o}) of CFRP act as a resistance to the natural load path of diagonal cracks that increases the stiffness and strength of the RC deep beams. Failure mode of RC deep beams with circular openings was appeared of diagonal cracks within shear region. Thus, the area of CFRP wrap applied was the shear region that located from the support to the loading point. Differences between the SS-NCO and UW-BCO can be clearly observe from the Figure 3.8 and 3.9 that SS-BCO with one side of surface-wrap and UW-BCO with both side plus bottom part of U-wrap.

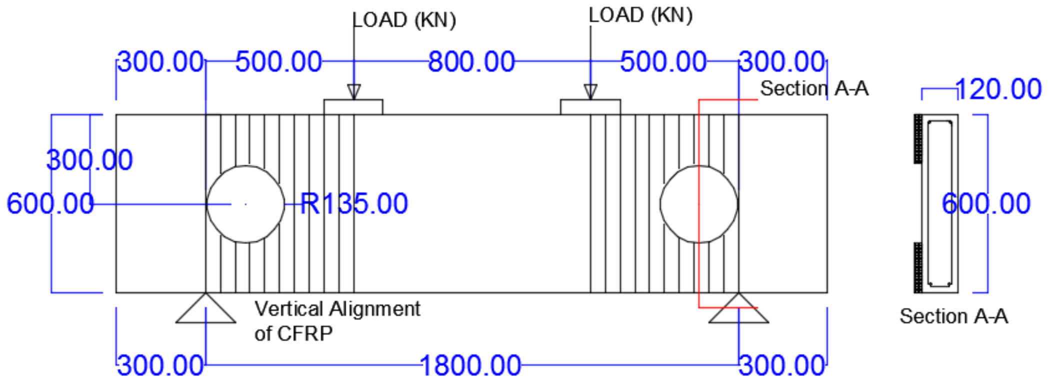
a) Front view of UW-BCO **b) Back view of UW-BCO**

c) Front view of SS-BCO **d) Back view of SS-BCO**

Figure 3.8: a) Front view of UW-BCO b) Back view of UW-BCO c) Front view of SS-BCO and d) Back view of SS-BCO



a) Strengthening configuration of U-wrap for UW-BCO



b) Strengthening configuration of surface-wrap for SS-BCO

Figure 3.9: a) Strengthening configuration of U-wrap for UW-BCO and b) Strengthening configuration of surface-wrap for SS-BCO

3.4 PREPARATION OF RC DEEP BEAMS

In this subtopic, the process of experimental works for total of 4 RC deep beams to be cast out are listed. The experimental works for the 4 RC deep beams were divided into 6 stages that were formworks; reinforcement steel bars; large circular openings; preparation work before concreting & curing; concreting, casting & curing process; and dismantle of formworks & preparation work before four-point loading test. Before started the experimental works, we must understand and follow the rules in the laboratory. Then, the way of operated the machines in the laboratory must be known with wearing of safety tools to prevent any accident or injured happen. For example, we must wear safety jacket and safety boots in the laboratory.

3.4.1 Formworks for 4 RC deep beams

Before started with cutting of plywood's and woods (1x2 inch), the formworks plan must be out first. Based on the formworks plan, the dimension (length, width and height) that needed were drawn or marked on the plywood's and woods (1x2 inch). After done the marking part, the plywood's were cut according to the dimension by using the bend saw machine as shown in Figure 3.11. For the woods (1x2 inch), the suitable machine to cut it was miter saw with wearing of safety goggles, safety ear muffs, safety gloves and respiratory protection dust mask. Then, the plywood's and woods (1x2 inch) that had been cut according to the dimension were combined to form the formworks based on the plan with the help from hammer and nails. The completed formwork for 4 RC deep beams are presents in Figure 3.12.

a) Plywood's **b) Woods (1x2 inch)**

Figure 3.10: a) Plywood and b) Woods (1x2 inch)

Figure 3.11: Bend saw machine

Figure 3.12: Completed formworks for 4 RC deep beams

3.4.2 Reinforcement Steel Bars for 4 RC Deep Beams

After completed the formworks, the progress of cutting and bending of reinforcement steel bars was started. Based on the details of RC deep beams, the reinforcement steel frame was tied together with 2T10 (compression reinforcement steel bar), 2T16 (tension reinforcement steel bar), seven vertical links of R6-300 and three horizontal links of R6-150. The compression and tension reinforcement steel bars were cut by using steel cutting machine after the required length was marked as shown in Figure 3.13. Problem that we faced was the bar bending machine in the laboratory had been broken down. Hence, the laboratory technician had come out with a solution by setting up a table with equipment's that can grip still the reinforcement steel bars. Then, using a hollow steel bar to lock up the length that needed to bend and pushed it by human power in order to bend the reinforcement steel bars. As for the R6 links, it can be cut and bended into rectangular shape links by using plaier. Both end loops of the rectangular shape links were tied by a steel wire by using steel wire tie tool. Figure 3.14 give the completed reinforcement steel frame which the frame was tied together with steel wire according to the plan.

Figure 3.13: Progress of cutting reinforcement steel bars by using steel cutting machine

Figure 3.14: Completed reinforcement steel frame

3.4.3 Large Circular Openings for 3 RC Deep Beams

Details of the RC deep beams were with large circular openings. In order to create the large circular openings, polystyrene was shaped into circular with diameter of 270 mm by using polystyrene cutter. The shaped polystyrene were glued together to form a height of more than 120 mm. This can prevented the concrete from covered the circular openings and ease the process of dismantle formworks. Referring to the Figure 3.15, the circular shape polystyrenes were glued to the base of formworks. Thus, the 3 RC deep beams can created with large circular openings.

a) Before concreting

b) After concreting

Figure 3.15: Formworks with circular polystyrene that a) Before concreting and b) After concreting

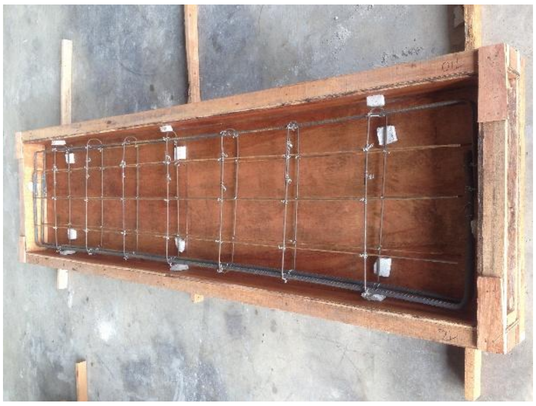
3.4.4 Preparation Work before Concreting and Curing

In the preparation work before concreting and curing, the completed reinforcement steel frame were installed into the formworks. Before that, the edge of formworks were pasted with silicon glue by using silicon glue gun as shown in Figure 3.16. This silicon glue sealed up the gap that between the combinations of plywood's and woods (1x2 inch) to prevent the leakage of concrete during concreting. Day before concreting, all the surface of formworks were painted with a layer of oil. The function of oil was to prevent the concrete stick to the formworks and ease dismantle of formworks. Then, come to installation of reinforcement steel frames into the formworks with spacer block that act as the concrete cover of 20 mm. Figure 3.17 presents the formworks with reinforcement steel frame and circular polystyrene which applied with oil and silicon glue.

a) Silicon glue and silicon glue gun

b) Edge of formwork sealed with silicon glue

Figure 3.16: a) Silicon glue and silicon glue gun and b) Edge of formwork sealed with silicon glue



a) Control Beam

b) RC deep beam with circular openings

Figure 3.17: Formworks with reinforcement steel frames and circular polystyrenes which applied with oil and silicon glue a) Control beam b) RC deep beam with circular openings

3.4.5 Concreting, Casting and Curing Process

On the concreting day, slump test and preparation of 12 cube for compressive test were done first when the ready-mix concrete was reached. Then, the concrete was poured into the concrete trolley and transferred to all the 4 formworks by following the sequence.

Concrete vibration machine was used to push the concrete all the way fitted into the formworks. This can prevented the formation of honeycomb concrete and formation of void in the concrete. After that, the surface of the concrete were smoothed by using concrete trowel as shown in Figure 3.18. In order to prevent the concrete from cracking, the concrete were having a curing period for 28 days. Concrete cracking was due to the hot atmosphere, drying wind or chemical reaction in the ready-mix concrete that released heat which evaporated the water and leaded to cracking. Figure 3.19 shows that wet gunny bags were used to cover the 4 RC deep beams to prevent losses of water from the concrete. Progress of spraying water twice a day for wetted the gunny bags was lasted for 28 days in order to ensure the concrete was moisture within 24 hours.

a) Vibrating the concrete

b) Smoothing the concrete surface

Figure 3.18: Concreting works with a) Vibrating the concrete and b) Smoothing the concrete surface

Figure 3.19: Curing process of 4 RC deep beams

3.4.6 Dismantle of Formworks and Preparation Work before Four-Point Loading Test

Before the four-point loading test, the 4 RC deep beams were go through dismantle of formworks after the curing period as shown in Figure 3.20. For the control beam and NS-BCO, they were painted white and drawn with grid line as shown in Figure 3.21. This can clearly showed out the cracks pattern after the four-point loading test. Strain gauges were pasted perpendicular to the assumed diagonal cracks which leaded the RC deep beams to failure and at the mid-bottom part of the RC deep beams. Furthermore, SS-BCO and UW-BCO were applied with CFRP-Wrap. Rough surface on both of the RC deep beams were grinded by using hand grinding machine following by sandblasting by using sandpaper machine. This two method can provided a smooth surface on the SS-BCO & UW-BCO which ensure that the CFRP with epoxy resin can pasted uniformly and bonded to the concrete surface.

Figure 3.20: Dismantle of formworks

a) CB

b) NS-BCO

Figure 3.21: RC deep beams with white paint, grid line and strain gauges a) CB and b) NS-BCO

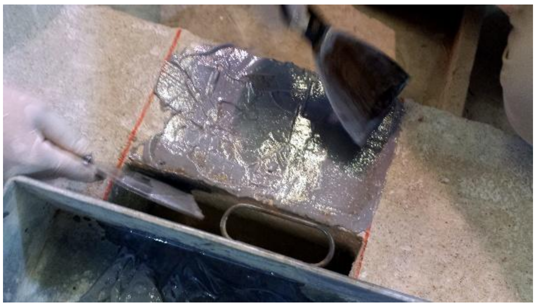
3.4.7 Preparation of Carbon Fiber Reinforce Polymer (CFRP) Application

Step of applying CFRP and epoxy resin on the RC deep beams can be referring to Figure 3.22. After the grinding and sandblasting process, the surface of RC deep beams were cleaned with a wet clothes to remove the dust. Quantity of the sikadur 330 used was weighed by using weighing machine with 4 part of component A and 1 part of component B which were mixed uniformly to formed epoxy resin. The epoxy resin was applied on the surface of the RC deep beams and surface of CFRP by using brick concrete cement towel. Then, the CFRP with epoxy resin were pasted on the surface of RC deep beams that with epoxy resin to form a thickness of 3 mm. Resin roller was rolled on the surface of CFRP with epoxy resin to form a uniformly surface and made sure that the CFRP with epoxy resin was bonded to the concrete surface.

a) Grinding, sandblasting and cleaning

b) 1 part of component B with 4 part of component A (Sikadur 330)

c) Mixed uniformly to formed epoxy resin



d) Applying of CFRP and epoxy resin to the concrete surface

Figure 3.22: Step of applying CFRP and epoxy resin a) Grinding, sandblasting and cleaning b) 1 part of component B with 4 part of component A (Sikadur 330) c) Mixed uniformly to formed epoxy resin and d) Applying of CFRP and epoxy resin to the concrete surface

3.5 LABORATORY TESTING

The tests that were conducted in the laboratory under this experimental study is listed in Table 3.1. Data and results that were collected from both of the test were used to support this experimental study. In this topic, procedure and results of slump test & concrete compression test are explained and presented in details. In the following section, Table 3.2 presents the test matrix in this experimental study.

Table 3.1: Test that conducted in this experimental study

Category of Test	Types of Test
Fresh concrete test	Slump test
Hardened concrete test	Concrete compression test
Four-point loading test	Four point loading by using magnus frame of 500 kN until failure

Table 3.2: Test matrix

Test	Standard	Equipment	Testing age (day)	Sample size (mm)	No. of specimen
Workability	BS EN 12350-2:2009	Slump cone, base plate, tamping rod and scoop	Fresh (within 2 hours")	-	1 per batch
Compressive strength	BS EN 12390-3:2009	Compression machine	3, 7, 14 and 28	150 x 150 x150	3 cubes per testing age
Four-point loading test	BS EN 12390-5:2009	Magnus frame	28	120 x 600 x 2400	CB, NS-BCO, SS-BCO and UW-BCO

3.5.1 Slump Test

Slump test was conducted after the arrival of the ready-mix concrete. The main objectives of the slump test were to measure workability of the concrete and determined the slump of cohesive concrete that from low to high workability. The procedure of slump test was carried according to BS EN 12350-2:2009.

Procedure of slump test:

i. Before the slump test was conducted, the apparatus such as slump cone, base plate, tamping rod and scoop were cleaned.
ii. The base plate along with slump cone on top of it were placed on a smooth, horizontal, rigid and non-absorbed surface that free from shock & vibration.

iii. In position, the slump cone was hold by both leg by giving pressure to the both bottom ear of slump cone. Concrete was filled into the slump cone by using the scoop with each approximately 1/3 of the height of the slump cone in three layers.

iv. Each layer, the concrete inside the slump cone was tamped 25 strokes by using tamping rod. The 25 strokes were distributed uniformly over each layer.

v. After the last layer had been tamped, the excessive concrete on top of it can be removed by rolling motion of the tamping rod.

vi. Excessive concrete that fallen on the surface of the base plate or leaked from the lower edge of the slump cone were cleaned before the slump cone was removed.

vii. The slump cone was slowly pulled upwards in vertical direction within 5 to 10 seconds. This process was to impact minimum lateral or torsional movement to the concrete.

viii. Difference between height of the slump cone and highest point of the slump was measured immediately by using a measuring tape after the removal of slump cone.

3.5.2 Concrete Compression Test

Concrete compression test was conducted after the slump test with according to BS EN 12390-3:2009. A total 12 cubes with 150 mm x 150 mm x 150 mm (width x height x length) were prepared as shown in Figure 3.23. Before the concrete was filled into the mould, a layer of oil was brushed in the inner layer of the mould for ease the cube pulled out of the mould and prevent the concrete stick with the mould. Then, the concrete was filled into the mould by using the scoop with each approximately 1/3 of the height of the mould in three layers. Each layer of the concrete inside the mould was tamped 25 strokes with distributed uniformly by using tamping rod. After the last layer had been tamped, the excessive concrete on top of it can be removed by rolling motion of the tamping rod. Four batch with 3 prepared cubes of each batch were put into a curing tank for curing period of 3 days, 7 days, 14 days and 21 days for concrete compression test. Before the compression test, the moulds were pulled out of the cubes by air pressure using air compression.

Figure 3.23: Cubes with 150 mm x 150 mm x 150 mm (width x height x length)

The main objective of the concrete compression test was to determine the compression strength of hardened concrete specimen. In concrete compression test, the cubes were tested to failure under compression load at specified load. Failure mode and ultimate load were recorded and observed during the testing process. The procedure of concrete compression test was carried according to BS 1881: Part 127:1990.

Procedure of concrete compression test:

i. The dimension and weight of each cube were measured.
ii. Surface of the cube, upper and lower bearing plate inside the compression machine were cleaned.
iii. The cube was placed at the center of the lower bearing plate. After that, ensure the both plates gripped the cube in position.
iv. Set up the compression machine to apply continuously load and without stock until the cube failed under compression load.
v. After the concrete compression test was done, the ultimate load and type of failure of the cube were recorded.
vi. All step above (i – vi) were repeated for other cube.

Figure 3.24: Concrete compression test that tested with compression machine

3.5.3 Four-Point Loading Test

The 4 RC deep beams were tested to failure undergoes four point loading by using magnus frame. Magnus frame in laboratory UMP was installed with a point load of 500 kN but with frame that can only sustained up to 270 kN. Hence, only NS-BCO can get the full results but not SS-BCO which not reached failure mode yet. In UiTM, the magnus frame was installed with point load and frame that can up to 500 kN that the full results of CB and UW-BCO were collected. Four-point loading test were the same as shown in Figure 3.25. The RC deep beams was sustained with 2 support that were 1800 mm apart and the load was transferred through a spreader beam with 2 point loading that 800 mm apart which located under the spreader beam. Reason of the point load was located with shear span of 500 mm started from the support was to made sure that the RC deep beams were failed under shear region. Shear span of 500 mm was calculated by taking the formula of shear span-to-depth ratio, $\frac{a}{H}$ = 0.83.

For the preparation work before four-point loading test was conducted in UMP laboratory, Faculty of Civil Engineering & Earth Resources, the linear variable displacement transducer (LVDT) was located at the mid-bottom part of the RC deep beams for monitoring the deflection. In addition, the setup of LVDT in UiTM laboratory, Faculty of Civil Engineering & Earth Resources was different. A total 4 LVDT were used which LVDT 1 was located at the spreader beam and the remaining 3 LVDT were located at the bottom part of the RC deep beams. The 3 LVDT were LVDT 2, 3 & 4 which the LVDT 3 located at the mid-bottom part of the RC deep beams with LVDT 2 & 4 located beside it.

Strain gauges were connected to the computer for collecting the data during the testing. For NS-BCO, there were total of three strain gauge installed. Two of the strain gauge were installed perpendicular to the diagonal shear cracks which located at the top left & top right of the NS-BCO and the remaining strain gauge was installed located at mid-bottom part of the NS-BCO. Moreover, there were four strain gauge installed for the UW-BCO which perpendicular to the diagonal shear cracks. The strain gauge were located at top left & right and bottom left & right of the UW-BCO. Hence, the load versus strain graphs can be plotted. During the four-point loading test, the appeared of cracks were marked down along with the current load (kN) value. Crack patterns, propagation of cracks and failure modes were observed, recorded and taking photos as proof.

a) In UMP (NS-BCO)

b) In UiTM (CB)

Figure 3.25: Four-point loading test a) In UMP (NS-BCO) and b) In UiTM (CB)

3.6 RESEARCH FLOW CHART

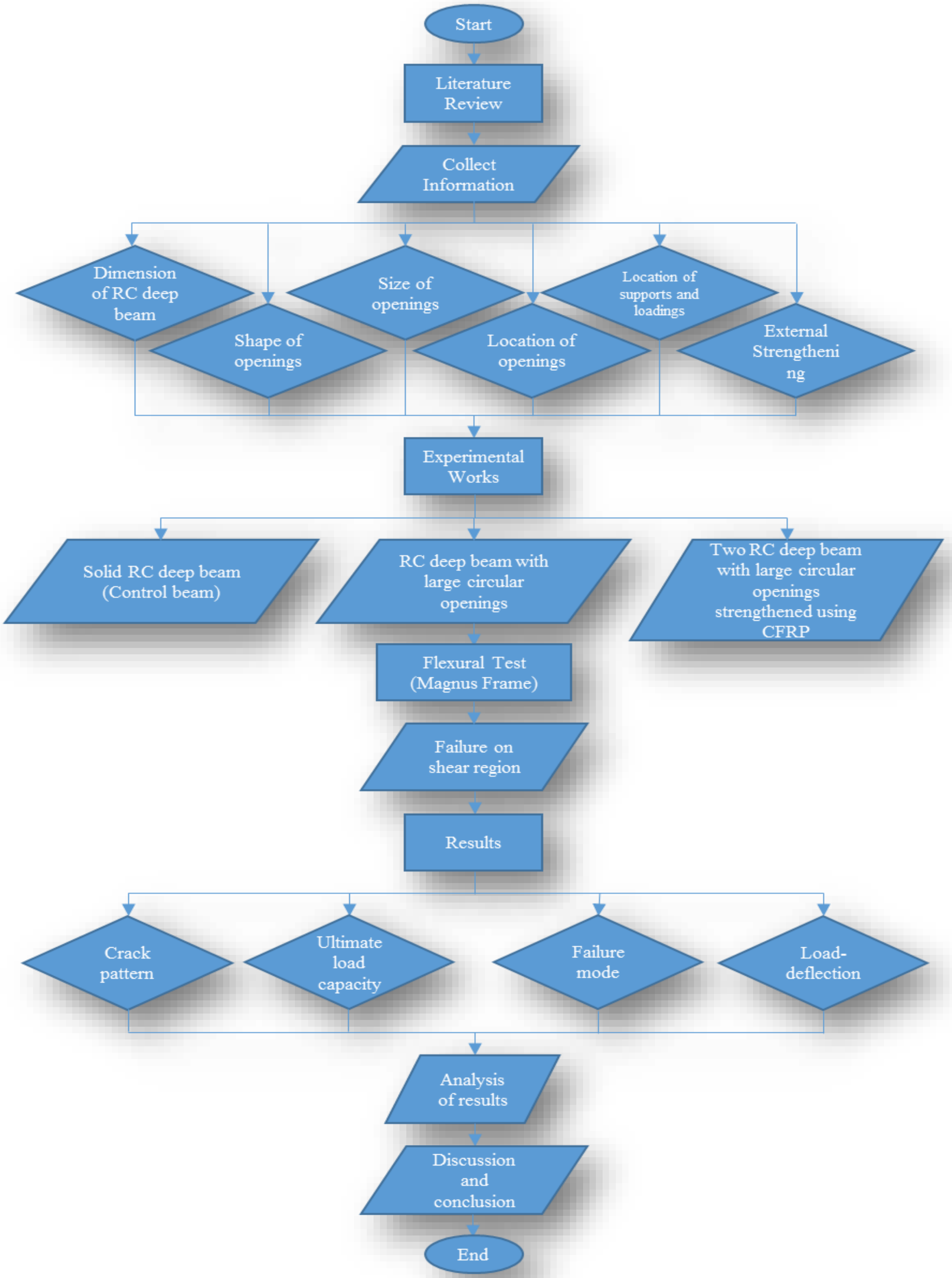


Figure 3.26: Methodology chart

CHAPTER 4

RESULTS AND DISCUSSION

4.1 OVERVIEW

In this chapter, all the result and data that collected from the laboratory testing are discussed. Results of slump test is discussed under the workability of the concrete and as for concrete compression test is discussed under the compression strength of hardened concrete specimen. Moreover, results and data that collected under four-point loading test for the 4 RC deep beams are discussed under subtopic of crack pattern & failure mode, load-deflection curve behaviour, ultimate-load capacity, load versus strain behaviour and effective strengthening method.

4.2 SLUMP TEST

Slump test were conducted to measure the workability of concrete and to determine the slump of cohesive concrete that from low to high workability. Based on the Figure 4.1, there are three type of slump which were true slump, shear slump and collapse slump. The workability of three type of the slump were true slump with low workability, shear slump with medium workability and collapse slump with high workability. Results of slump test that collected on this experimental study were acceptable with true slump (low workability) and difference between height of the slump cone and the highest point of the slump was 80 mm which can referring to the Figure 4.2. After the results of slump test was acceptable, the concreting works were carried on.

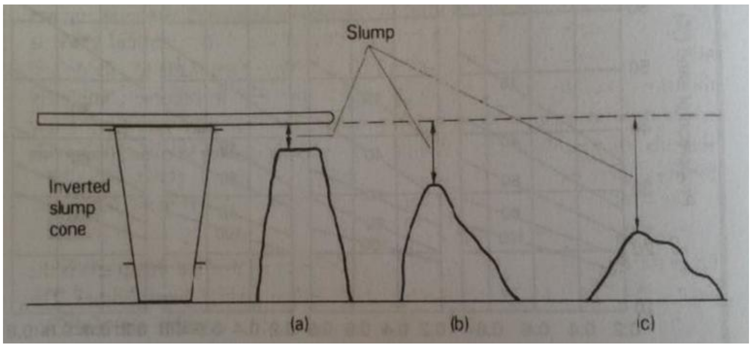


Figure 4.1: Types of slump

Source: *The book Civil Engineering & Laboratory Manual* (2011)

Figures 4.2: Slump test

4.3 CONCRETE COMPRESSION TEST

The concrete compression test was conducted to determine the compression strength of hardened concrete specimen. Based on Figure 4.3, types of failure mode can be classified into satisfactory failure, S and unsatisfactory failure, U. From the Figure 4.4, all the cubes after testing were classified under satisfactory failure and for the full results of concrete compression test can referred to appendix A.

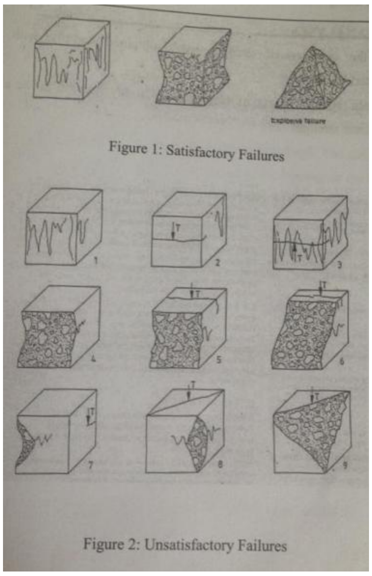


Figure 4.3: Type of failure mode for concrete compression test

Source: *The book Civil Engineering & Laboratory Manual* (2011)

a) C1 (3 days)

b) C4 (7 days)

c) C7 (14 days)

d) C12 (28 days)

Figure 4.4: Cubes after concrete compression test a) C1 (3 days) b) C4 (7 days) c) C7 (14 days) and d) C12 (28 days)

By referring to Figure 4.5, the average compressive strength of the 4 batch cubes were 29.39 N/mm^2 (3 days), 37.51 N/mm^2 (7 days), 42.53 N/mm^2 (14 days) and 43.54 N/mm^2 (28 days). The graph of sample age versus M35 concrete cube compressive strength showed a curve graph that the compressive strength of the cubes in 28 days had reached 43.54 N/mm^2 which more than the ready-mix concrete, ordinary portland cement (OPC) with a 28 days compressive strength of 35 N/mm^2. In conclusion, the results of concrete compression test were satisfactory.

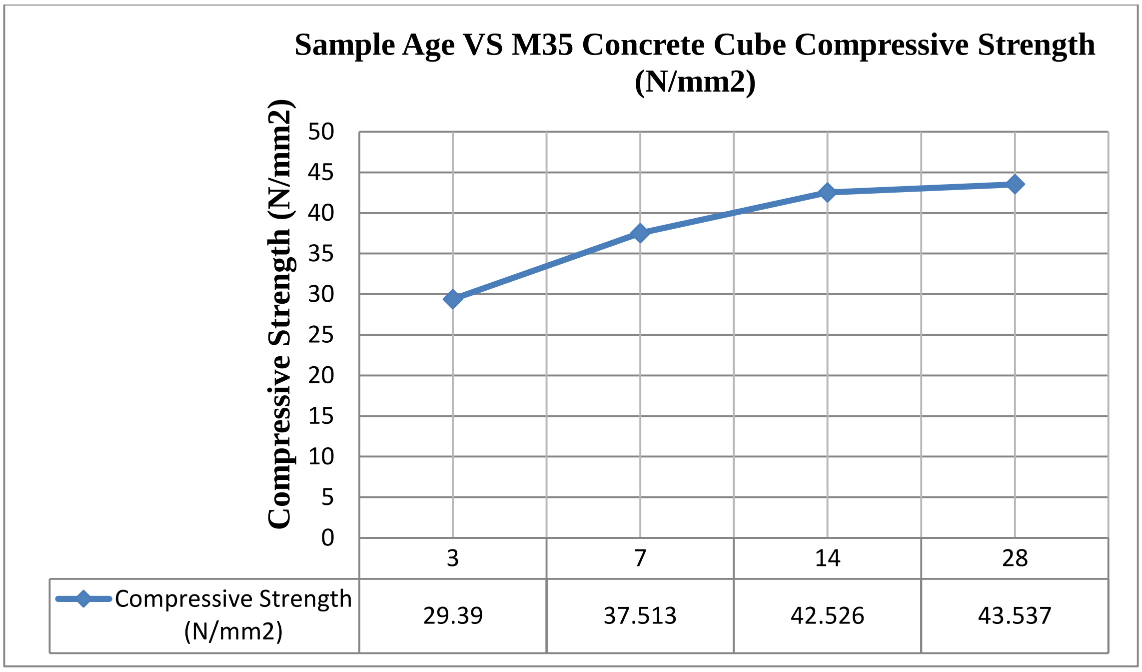


Figure 4.5: Graph of sample age (days) versus M35 concrete cube compressive strength (N/mm^2)

4.4 BEHAVIOUR OF LOAD-DEFLECTION CURVE

Load-deflection curve were plotted for the 4 RC deep beams base on the data that were collected after the four-point loading test. Behaviour of the load-deflection curve can be classified into two; linear behaviour and non-linear behaviour which were control by the degree of interruption of the natural load path. Based on the load-deflection curve, the stiffness of the RC deep beams can be determined and RC deep beams can be classified into brittle behaviour and ductile behaviour. Data of yield point, P_y (kN), yield deflection δ_y (mm), ultimate load, P_u (kN) and ultimate deflection, δ_u (mm) were summarised in Table 4.1 based on the 4 RC deep beams of load-deflection curve.

From the load-deflection curve, the curve can be divided into elastic behaviour and plastic behaviour. In the post cracking stages that before the yield point, the load-deflection curve behaved linear elastic. After the yield point, the load-deflection curve behaved non-linear which categorised as plastic behaviour that can divided into yielding region and strain hardening region. When further increases in load, the RC deep beams was exhibited strain hardening until the ultimate load was reached. RC deep beams was counted failure if the curve passed the strain hardening region.

Table 4.1: Data of yield point, yield deflection, ultimate load and ultimate deflection for 4 RC deep beams

RC Deep Beams	Yield point, P_y (kN)	Yield Deflection, δ_y (mm)	Ultimate Load, P_u (kN)	Ultimate Deflection, δ_u (mm)
CB	272.92	7.24	425.12	12.79
NS-BCO	107.11	3.00	207.47	8.00
UW-BCO	241.16	10.00	383.80	14.73
SS-BCO	179.54	7.04	239.26	10.06

4.4.1 CB

As shown in Figure 4.6, the overall load-deflection curve of CB behaved linear behaviour that indicated the CB was brittle and with high stiffness. When the curve reached beyond the ultimate load point of 425.12 kN it was curved downwards with sudden increases in deflection which behaved as non-linear behaviour. This was happened because of two independent diagonal shear cracks meet each other and formed sudden failure. The CB was categorised as linear elastic when in the post cracking stage with yield point of 272.92 kN and yield deflection of 7.24 mm. Based on the theory, CB with zero degree of interruption of the natural load path indicated low rate of cracks in term of widening, growth and propagation. However, due to the CB behaved as brittle, high rate of flexural cracks were appeared. In conclusion, the CB with brittle behaviour and linear behaviour of load –deflection curve can withstand load up to 425.12 kN with maximum deflection of 12.79 mm.

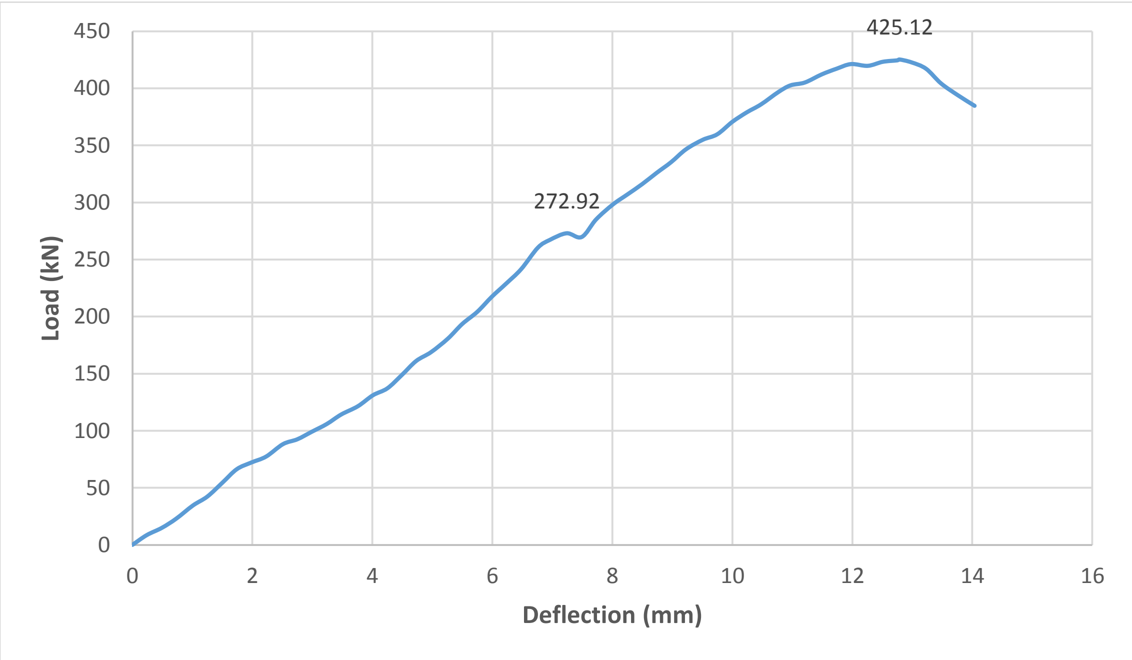


Figure 4.6: Load-Deflection Curve of CB

4.4.2 NS-BCO

The load-deflection curve of NS-BCO is shown in Figure 4.7. Based on Figure 4.7, the load-deflection curve of the NS-BCO developed a large deformation in the post yield range which indicated the NS-BCO was ductile behaviour. NS-BCO with yield point of 107.11 kN and yield deflection of 3.00 mm were lower than the CB with yield point of 272.92 kN and yield deflection of 7.24 mm. Thus, the ultimate-load capacity of NS-BCO with 207.47 kN was lesser than the CB with 425.12 kN. This can concluded that overall of the load-deflection curve of NS-BCO behaved as non-linear behaviour. Furthermore, NS-BCO with high degree of interruption of the natural load path was caused by the large circular openings and leaded the load-deflection curve to behave as non-linear behaviour. In comparison of stiffness, the load-deflection curve of CB was exhibited stiffer than the NS-BCO in the post cracking stage. This can be proved by maximum deflection of CB with 12.97 mm was 30.31% higher than the maximum deflection of NS-BCO with 8.00 mm. In conclusion, the NS-BCO was exhibited ductile behaviour with non-linear load-deflection curve.

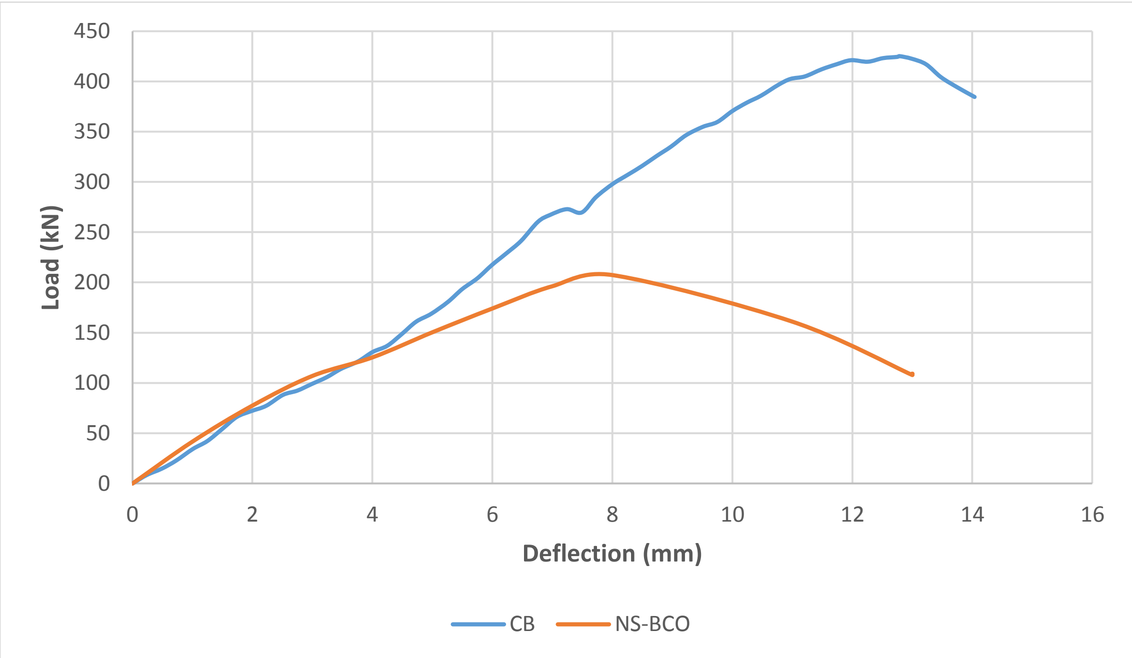


Figure 4.7: Load-deflection curve of NS-BCO

4.4.3 UW-BCO

The behaviour of the load-deflection curve of UW-BCO was same as the SS-BCO. Differences that lied between the SS-BCO and UW-BCO in the load-deflection curve was stiffness of UW-BCO was stiffer than the SS-BCO. Based on Figure 4.8, the load-deflection curve of UW-BCO was indicated as non-linear behaviour with low degree of interruption of the natural path. Moreover, low degree of interruption of the natural path always come with low rate of cracking that can proved with no flexural cracks were observed after the four-point loading test. Then, UW-BCO can classified into ductile behaviour that had improved as compared to NS-BCO and SS-BCO. Yield point were reduced by 11.64% and yield deflection was increases by 38.12% as compared to CB. The yield deflection was increases due to the development of larger deformation in the post yield stages that also caused the increases of ultimate deflection by 15.17% as compared to CB. Both of the load-deflection curve were exhibited a little bit curved downwards when reached beyond the ultimate load of 383.80 kN for UW-BCO and 425.12 kN for CB which the RC deep beams were sudden failed by two independent diagonal shear cracks joined together.

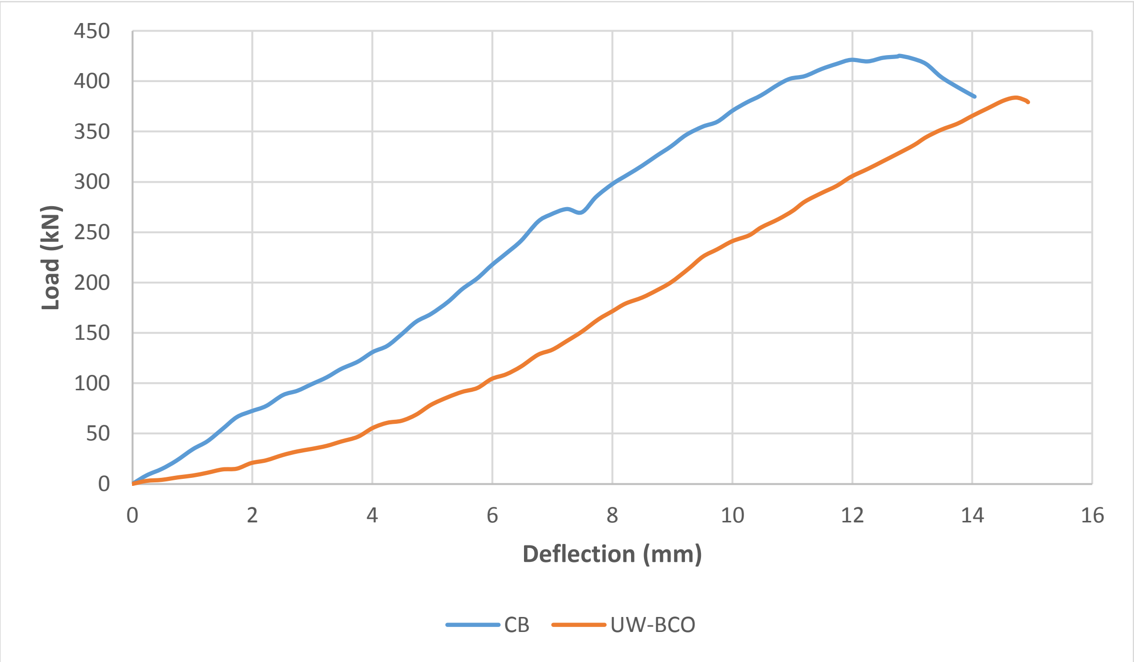


Figure 4.8: Load-deflection curve of UW-BCO

4.4.4 SS-BCO

Figure 4.9 presents load-deflection curve of SS-BCO, which the curve in post cracking stage clearly showed that the stiffness of the CB was higher than the SS-BCO. The load-deflection curve of SS-BCO showed that the SS-BCO was with ultimate load of 239.26 kN and maximum deflection of 10.06 mm. SS-BCO was with low degree of interruption of the natural path due to the natural path which interrupted by the openings were resisted by the strength of epoxy resin with CFRP. Low degree of interruption of natural path influenced the load-deflection curve to behave non-linear behaviour with low rate of cracking. This can proof by flexural cracks did not appeared on flexural region of SS-BCO after the four-point loading test. SS-BCO with non-linear behaviour of load-deflection curve indicated that SS-BCO was behaved as improved ductile as compared to NS-BCO. Furthermore, yield point and yield deflection of SS-BCO were reduced by 34.22% and 276% as compared to CB. For the CB and SS-BCO, the curve of load-deflection curved a little bit downwards when reached beyond the strain hardening region which indicated the RC deep beams were sudden failed by the two independent diagonal cracks joined together.

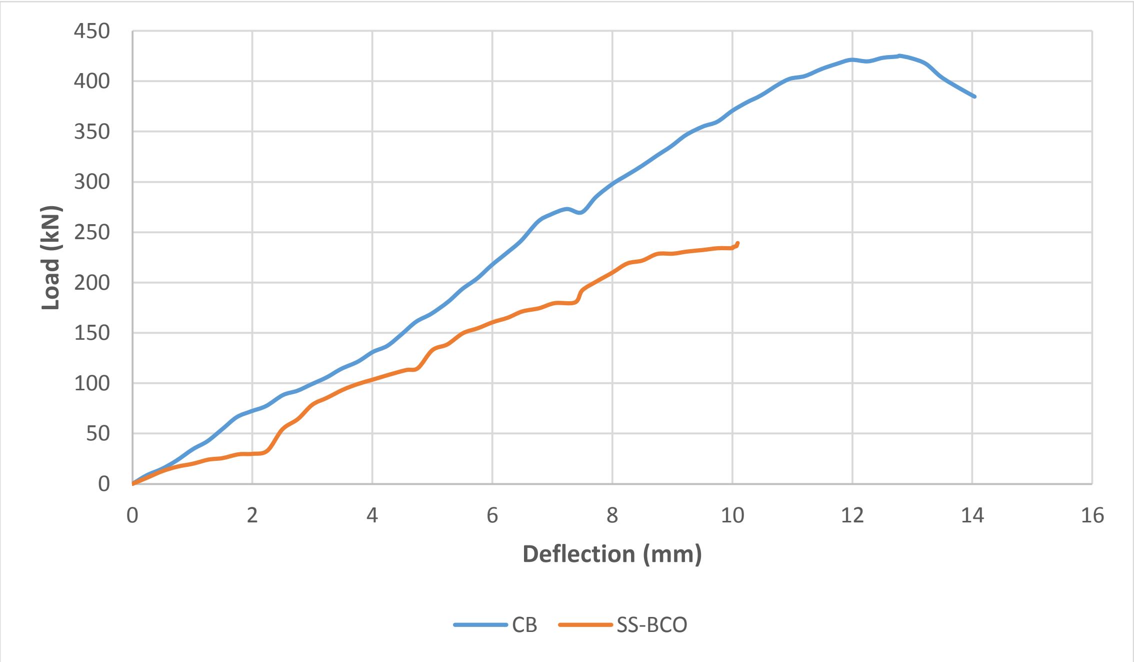


Figure 4.9: Load-deflection curve of SS-BCO

4.5 FOUR-POINT LOADING TEST

Four (4) RC deep beams which included CB, NS-BCO, UW-BCO and SS-BCO were tested to failure undergoes four-point loading. The support and loading point were located 300 mm and 800 mm from the edge of the RC deep beams, respectively. Failure modes of RC deep beams can be classified into shear failure and bending failure. All the beam specimens undergoes sudden failure by the formation of diagonal shear cracks that appeared in the shear region. Crack patterns, failure modes and behaviour of CFRP –wrap are discussed and explained on the subtopic below.

4.5.1 Crack Patterns and Failure Modes

All the beam specimens were tested to fail under shear region due to diagonal cracks or to concrete strut failure. During the four-point loading test, the propagation of cracks were observed by visual inspection. The applied loading was paused periodically for marking the cracks with current load when cracks appeared until failure happened. First visual cracking load (kN), ultimate-load capacity (kN) and failure mode for the beams are summarised in Table 4.2.

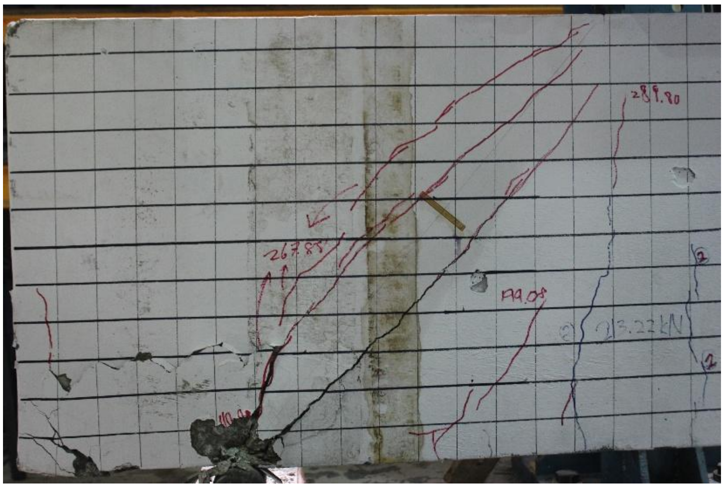
Table 4.2: First visual cracking load (kN), ultimate-load capacity (kN) and failure modes

RC deep beams	First visual cracking load (kN)	Ultimate-load capacity (kN)	Failure modes
CB	104.91	425.12	Shear
NS-BCO	109.98	207.47	Shear
UW-BCO	-	383.80	Shear
SS-BCO	-	239.26	Shear

4.5.1.1 Control Beam (CB)

During the four-point loading test, the first visual crack was appeared on 104.91 kN at the bottom right of the CB near the support. When the load continues increases, the cracks started to appear on the flexural region of the CB and propagated upwards. Propagation of the longest cracks were stopped when reached half of depth of the CB. On the same time, two independent diagonal cracks were seen propagated from loading point towards the support and from support towards the loading point at shear region. CB exhibited sudden failure at load of 425.12 kN when the two diagonal cracks meet each other with increases of load. At the support, some small pieces of the concrete were fallen out form the CB when nearly reached the failure modes. Failure mode of the CB was on the shear region by the diagonal cracks that appeared on the left view (front and back view) of the CB which can referring to Figure 4.10.

Figure 4.10: Failure mode of CB



a) Front view of CB

b) Back view of CB

Figure 4.11: Diagonal cracks that appeared on left view of the CB a) Front view of CB and b) Back view of CB

4.5.1.2 RC Deep Beam with Circular Openings (NS-BCO)

For NS-BCO, the first visual crack was at flexural region of the NS-BCO with load of 109.98 kN. The cracks on the flexural region that lied between supports were increases with continuously increases of load. Number of cracks that appeared on the flexural region of NS-BCO were reduced as compared to CB. Propagation of the longest cracks at the flexural region was stopped when reached half of depth of the NS-BCO which same condition with CB. On the same time with continuously increases of load, two independent diagonal crack were started propagated form the loading point towards the openings and from openings to the support, respectively. NS-BCO was counted failure when the two independent diagonal cracks meet each other which formed a sudden shear failure at load of 207.47 kN. Based on Figure 4.12, the failure mode of the NS-BCO was on shear region with appeared of diagonal cracks which located on the right view of the NSBCO. Formation of the diagonal cracks were along with fallen out some small pieces of concrete at upper part of the openings that presents in Figure 4.13. Hence, the maximum width of upper crack towards the loading point was 6.2 cm and maximum width of upper crack toward the openings was 1.2 cm.

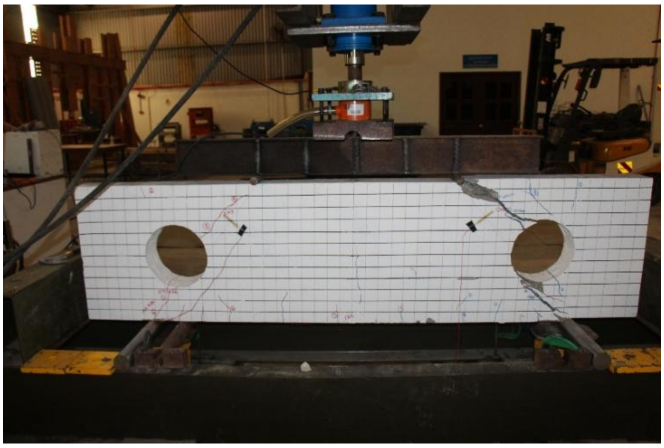
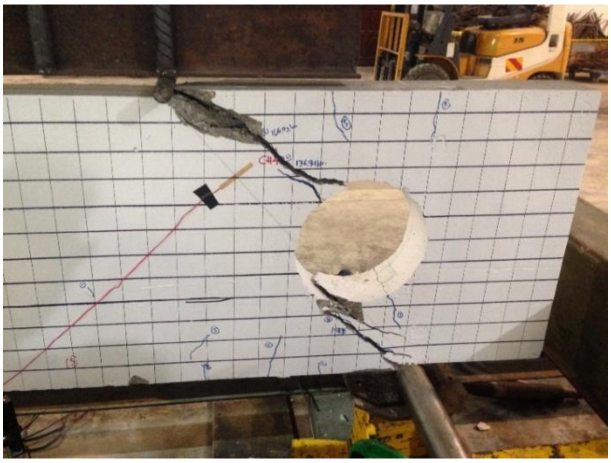
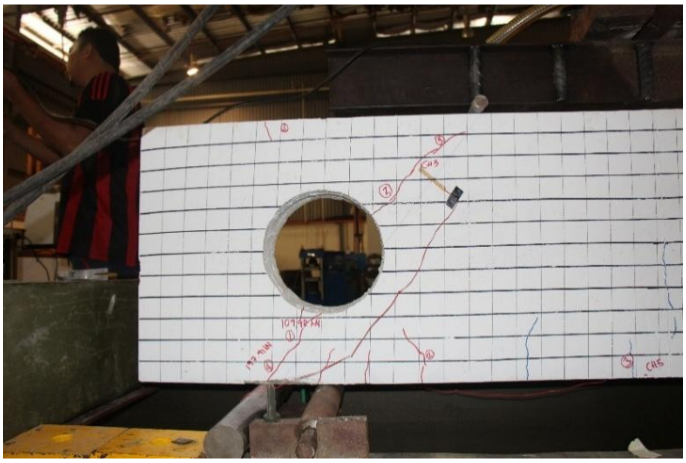


Figure 4.12: Failure mode of NS-BCO



a) Right view of NS-BCO



b) Left view of NS-BCO

Figure 4.13: Diagonal cracks appeared on NS-BCO a) Right view of NS-BCO and b) Left view of NS-BCO

4.5.1.3 RC Deep Beam with Circular Openings Strengthened Using U-Wrap (UW-BCO)

Shear region of UW-BCO was strengthened using one layer U-wrap of CFRP that covered both side and bottom part of the UW-BCO. After the four-point loading test was conducted, the flexural cracks did not appeared on the flexural region of UW-BCO which same condition as the SS-BCO as compared to CB and NS-BCO. Reason of this condition happened was the vertical alignment, (90^o) of CFRP that applied on the concrete surface with high strength of epoxy resin (Sikadur 330) had interrupted and resisted the degree of interruption of the natural load path of diagonal cracks. Due to continuously increases of load, two independent diagonal cracks were propagated through the CFRP with epoxy resin from loading point towards openings and from openings to support; from support towards openings and from openings to loading point. Sudden shear failure on right view of the UW-BCO was occurred at load of 383.80 kN when this two independent diagonal cracks joined together and caused failure of UW-BCO that is shown in Figure 4.14. Before the UW-BCO was failed, the diagonal cracks caused the CFRP with epoxy resin exhibited peeling off with concrete instead of debonding that occurred on both side of the UW-BCO. This had proved that the UW-BCO was applied with sufficient amount of epoxy resin with CFRP that had high strength which grabbed strongly on the surface of concrete caused the peeling off with concrete that can referring to Figure 4.15.

Figure 4.14: Failure mode of UW-BCO

a) Front view

b) Back view

Figure 4.15: CFRP with epoxy resin that peeling off with concrete from UW-BCO a) Front view and b) Back view

4.5.1.4 RC Deep Beam with Circular Openings Strengthened Using Surface-Wrap (SS-BCO)

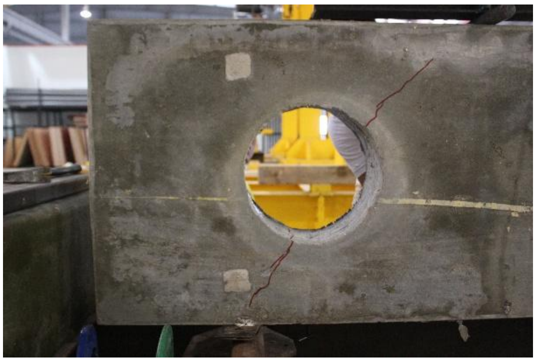
SS-BCO was strengthened with one layer of CFRP within the shear region on front surface of the SS-BCO. When undergoes the four-point loading test, there were no cracks founded on the flexural region as compared to CB and NS-BCO. This was because the degree of interruption of the natural load path of flexural cracks were interrupted & resisted by the strength of epoxy resin (Sikadur 330) and vertical alignment, (90^o) of CFRP that applied perpendicular to the diagonal cracks. Two independent of diagonal cracks were observed on front and back view of the SS-BCO which propagated from the loading point towards the openings and from the openings to the support, vice versa. Propagation of the two independent diagonal cracks were cracked through the CFRP and epoxy resin but not caused debonding of CFRP with epoxy resin from the concrete surface with increases of load. Due to limitation of the magnus frame which the frame can only withstand up to 270 kN, the SS-BCO was no tested to failure and the test was stopped at the load of 207.47 kN. From the observation, the SS-BCO was predicted to fail on shear region when two independent diagonal cracks meet together and caused sudden failure on right view of the SS-BCO with increases of load beyond 207.47 kN. This prediction can be supported by the fact of that propagation of diagonal cracks that appeared on the right view of the SS-BCO were longer and clearer that the left view of the SS-BCO which presents in Figure 4.16 and 4.17. Unfortunately, the behaviour of the CFRP on the surface of the concrete cannot be predicted up to beam failure.

a) Front view

b) Left view **c) Right view**

Figure 4.16: Diagonal cracks on front view of SS-BCO a) front view b) left view and c) right view

a) Back view



b) Left view **c) Right view**

Figure 4.17: Diagonal cracks on back view of SS-BCO a) Back view b) Left view and c) Right view

4.6 ULTIMATE-LOAD CAPACITY

Ultimate-load capacity of RC deep beam is the maximum load that a beam specimen can withstand up to failure. From the load-deflection curve, the ultimate-load capacity of a beam specimen can be determined at the maximum strain hardening region and peak point of the curve before it curve downward which indicated the failure of beam specimen occurred. The reduction, increases and re-gained in strength of beam specimens are summarised in Table 4.3.

Table 4.3: Reduction, increases and re-gained strength of beam specimens

RC deep beams	Ultimate-load capacity (kN)	Reduction in strength (%) as compared to CB	Increases in strength (%) as compared to NS-BCO	Strength re-gained (%) as compared to CB
CB	425.12	-	-	-
NS-BCO	207.47	51.20	-	-
UW-BCO	383.80	-	85.0	90.28
SS-BCO	239.26	-	15.32	56.28

Based on the control beam, the maximum load that can withstand before failure was 425.12 kN. Large circular openings that created on the NS-BCO had reduced the area of the NS-BCO and increases the degree of interruption of the natural path. Hence, NS-BCO had a reduction of beam strength about 51.20 % as compared to CB. For the comparison with NS-BCO, the UW-BCO and SS-BCO increases the beam strength 85.0 % and 15.32 %, respectively. Moreover, UW-BCO and SS-BCO re-gained the beam strength approximately to 90.28 % and 56.28 % respectively as compared to CB. This was because the strength of one layer of CFRP in vertical alignment, (90^o) with 3 mm of epoxy resin that applied on the surface of UW-BCO and SS-BCO had lower the degree of interruption of the natural path. Thus, reduced the growth & widening of cracking and increases the strength of the UW-BCO and SS-BCO. Reason that caused the UW-BCO had the highest in strength increases and re-gained was the strengthening configuration of CFRP. U-wrap can resisted the degree of interruption of natural path on both side of the UW-BCO and tension force on bottom part of the UW-BCO which SS-BCO can only resisted the degree of interruption of natural path on one side by surface-wrap.

4.7 SUMMARY FOR EFFECTIVE STRENGTHENING METHOD

All the beam specimens were having sudden shear failure with a little bit curved downwards after the peak point of the curve which caused by the diagonal shear cracks. Flexural cracks were appeared at the CB and NS-BCO but not UW-BCO and SS-BCO. This was because the natural path of propagation flexural cracks were resisted by the strength of CFRP with epoxy resin. Based on Figure 4.18, the CB had the highest in beam stiffness and ultimate-load capacity of 425.12 kN which the curve was plotted linearly in the comparison of load-deflection curve. As for the NS-BCO, UW-BCO and SS-BCO, the curve were plotted non-linearly. Thus, the CB was behaved as brittle behaviour, NS-BCO was behaved as ductile behaviour and UW-BCO & SS-BCO behaved as improved ductile behaviour as compared to NS-BCO. From the observation, the UW-BCO had the highest value in deflection of 14.73 mm but with second highest in ultimate-load capacity of 383.80 kN which indicated that the U-wrap was strong in strength than surface-wrap. Hence, U-wrap was the most effective strengthening method which can resisted this beam specimen from failure about a period which the period was longer than surface-wrap.

Furthermore, CB and NS-BCO were appeared with growth, widening and propagation of cracks by brittle behaviour of CB and high degree of interruption of natural load path caused by large circular openings for the NS-BCO, respectively. Thus, CB was with linearly curve but NS-BCO was with large deformation of curve. In addition, the UW-BCO and SS-BCO had lower the degree of interruption of natural load path as compared to NS-BCO. Hence, the flexural cracks that appeared at NS-BCO were not existed at UW-BCO & SS-BCO and both the curve were had slightly in deformation as compared to NS-BCO.

In conclusion, NS-BCO reduced the beam strength about 51.20 % as compared to CB. For SS-BCO, increases the beam strength about 15.32 % as compared to NS-BCO and re-gained the beam strength about 56.28 % as compared to CB. Thus, the most effective strengthening method was U-wrap that the UW-BCO had the highest in increases the beam strength approximately 85.0 % as compared to NS-BCO and re-gained beam strength approximately 90.28 % as compared to CB.

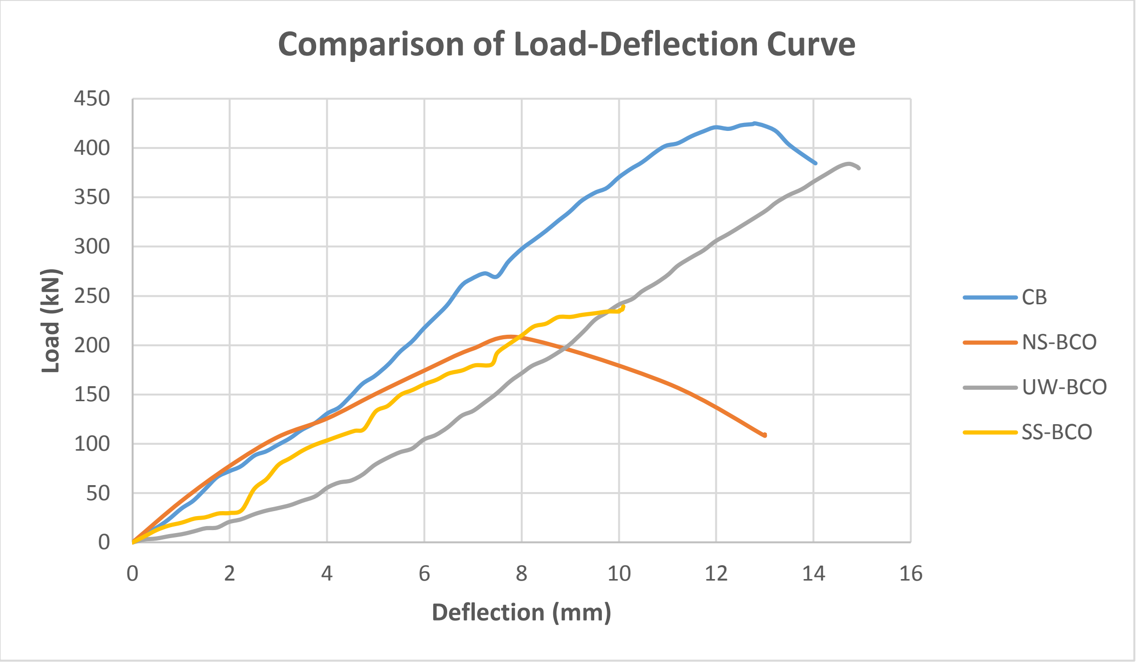


Figure 4.18: Comparison of load-deflection curve

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 OVERVIEW

This subtopic discuss about the conclusion and recommendations. Based on the research objective of this experimental study, results & discussion from chapter 4, a conclusion is made. Recommendations are listed to minimize the reduction of beam strength for RC deep beam with circular openings and to find out the most effective strengthening method by using CFRP. Thus, in the future can bring benefits to the method of post-planned openings for RC deep beams.

5.2 CONCLUSION

After the 4 RC deep beams were tested to failure under four-point loading test, the results are discussed under chapter 4. Then, conclusion are made in chapter 5 based on the research objectives in chapter 1.

i. Behaviour of RC deep beam with large circular openings (NS-BCO) was behaved as ductile behaviour. Thus, non-linear behaviour of load-deflection curve was formed with reduction in beam stiffness and deflection. NS-BCO with ultimate-load capacity of 207.47 kN reduced the beam strength approximately 51.20 % as compared to CB. Moreover, behaviour of RC deep beam with large circular openings strengthened using CFRP (UW-BCO and SS-BCO) shows improvement in ductile behaviour as compared to NS-BCO. Hence, slightly non-behaviour of load-deflection was formed with slightly reduced in beam stiffness and improvement in deflection. UW-BCO with ultimate-load capacity of 383.80 kN re-gained the beam strength approximately to 90.28 % as compared to CB. As for SS-BCO, with ultimate-load capacity of 239.26 kN re-gained the beam strength approximately to 56.28 % as compared to CB.

ii. Strengthened or Un-strengthened RC deep beam with large circular openings in the shear region had interrupted the degree of natural load path and reduced the area of beam specimens as compared to CB. Flexural cracks and diagonal shear cracks which propagated from the loading point towards circular openings and from circular opening to support were observed. Thus, NS-BCO reduced the beam strength approximately 51.20 % as compared to CB. Furthermore, RC deep beams strengthened using CFRP prevented the appeared of flexural cracks. Formation of diagonal shear cracks caused peeling off of concrete with CFRP which bring to sudden shear failure. Hence, UW-BCO increases the beam strength approximately 85.0 % and SS-BCO increases the beam strength approximately 15.32 % as compared to NS-BCO, respectively.

iii. The most effective strengthening configuration using CFRP in RC deep beams with openings was U-wrap. This strengthening method had the strength in resisted the propagation of diagonal shear cracks through CFRP with epoxy resin and the tension force. Thus, UW-BCO had the highest re-gained beam strength with ultimate-load capacity of 383.80 kN re-gained the beam strength approximately to 90.28 % as compared to CB.

5.3 RECOMMENDATIONS

In this experimental study, recommendations that listed below are for the future works to further this experimental study and to fill in the gaps for the experimental researches that have done before.

i. Dynamic loading test can be adopted instead of static loading test.
ii. Strengthening configuration of CFRP with two layer of U-wrap can be applied instead with one layer of U-wrap.

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APPENDIX A

CONCRETE CONMPRESSION TEST RESULTS

Sample Mark	Weight (kg)	Date of Mix	Date of Test	Sample Age (days)	Load (kN)	Compressive Strength (N/mm^2)	Type of Failure (S/U)
C1	7.80	19/1/2015	22/1/2015	3	663.683	29.497	S
C2	7.85	19/1/2015	22/1/2015	3	679.161	30.185	S
C3	7.75	19/1/2015	22/1/2015	3	640.979	28.488	S
				Total	**1983.823**	**88.170**	
				Average	**661.274**	**29.390**	
C4	8.05	19/1/2015	26/1/2015	7	831.323	36.948	S
C5	7.75	19/1/2015	26/1/2015	7	785.688	34.919	S
C6	7.90	19/1/2015	26/1/2015	7	915.101	40.671	S
				Total	**2532.112**	**112.538**	
				Average	**844.038**	**37.513**	
C7	7.90	19/1/2015	2/2/2015	14	980.365	43.572	S
C8	7.75	19/1/2015	2/2/2015	14	930.902	41.373	S
C9	7.85	19/1/2015	2/2/2015	14	959.233	42.633	S
				Total	**2870.500**	**127.578**	
				Average	**956.833**	**42.526**	
C10	7.85	19/1/2015	16/2/2015	28	975.129	43.339	S
C11	7.85	19/1/2015	16/2/2015	28	972.043	43.202	S
C12	7.95	19/1/2015	16/2/2015	28	991.585	44.070	S
				Total	**2938.757**	**130.611**	
				Average	**979.586**	**43.537**	

APPENDIX B

CONTROL BEAM (CB) DATA

Control Beam (CB)			
Load (kN)	**Deflection (mm)**	**Load (kN)**	**Deflection (mm)**
0	0	272.92	7.24
8.57	0.24	269.64	7.49
14.87	0.49	285.01	7.73
22.93	0.73	298.12	8.01
34.52	1.01	307.19	8.26
42.34	1.25	316.01	8.50
54.43	1.50	325.84	8.74
66.28	1.74	335.16	8.98
72.07	1.98	346.50	9.23
77.36	2.23	354.82	9.51
88.20	2.51	359.60	9.75
92.48	2.75	370.44	10.00
99.04	2.99	378.76	10.24
105.84	3.24	385.81	10.48
114.16	3.48	396.65	10.77
121.46	3.76	402.44	10.97
131.04	4.01	404.96	11.21
137.09	4.25	412.02	11.49
148.68	4.49	417.06	11.74
161.03	4.73	421.09	11.98
168.84	4.98	419.58	12.26
180.68	5.26	423.11	12.51
193.54	5.50	424.37	12.75
204.12	5.75	425.12	12.79
217.22	5.99	422.60	12.99
228.82	6.23	417.06	13.23
241.42	6.48	404.21	13.48
260.32	6.76	393.88	13.76
267.12	6.96	384.55	14.04

APPENDIX C

RC DEEP BEAM WITH CIRCUAR OPENINGS (NS-BCO) DATA

RC Deep Beam with Circular Openings (NS-BCO)	
Load (kN)	**Deflection (mm)**
0	0
41.73	1
77.59	2
107.11	3
125.55	4
150.53	5
174.20	6
196.37	7
207.47	8
161.14	11
108.05	13
109.16	13
109.31	13
109.28	13
109.26	13
109.26	13
109.30	13
109.31	13
109.24	13
109.27	13

APPENDIX D

RC DEEP BEAM WITH CIRCULAR OPENINGS STRENGTHENED USING U-WRAP (UW-BCO) DATA

RC Deep Beam with Circular Openings Strengthened Using CFRP (UW-BCO)			
Load (kN)	**Deflection (mm)**	**Load (kN)**	**Deflection (mm)**
0	0	163.55	7.77
3.02	0.24	171.86	8.01
4.03	0.49	179.17	8.22
6.55	0.77	185.22	8.50
8.32	1.01	192.28	8.74
11.09	1.25	200.34	8.98
14.36	1.50	213.70	9.27
15.12	1.74	225.79	9.51
20.66	1.98	233.10	9.75
23.44	2.23	241.16	10.00
28.73	2.51	246.96	10.28
32.26	2.75	254.77	10.48
34.78	2.99	263.09	10.77
37.80	3.24	271.40	11.01
42.08	3.48	280.48	11.21
46.87	3.76	289.04	11.49
55.69	4.01	296.10	11.74
60.73	4.25	305.17	11.98
62.75	4.49	312.98	12.26
68.80	4.73	320.54	12.51
78.62	4.98	327.85	12.75
86.18	5.26	336.67	13.03
91.48	5.50	344.48	13.23
95.26	5.75	351.79	13.48
104.33	5.99	358.09	13.76
108.86	6.23	365.65	14.00
116.68	6.48	372.96	14.25
128.27	6.76	381.02	14.53
133.31	7.00	383.80	14.73
141.88	7.24	381.02	14.89
151.20	7.49	379.26	14.93

APPENDIX E

RC DEEP BEAM WITH CIRCULAR OPENINGS STRENGTHENED USING SURFACE-WRAP (SS-BCO) DATA

RC Deep Beam with Circular Openings Strengthened Using CFRP (SS-BCO)			
Load (kN)	**Deflection (mm)**	**Load (kN)**	**Deflection (mm)**
0	0	160.64	6.01
6.26	0.25	165.15	6.26
12.67	0.50	171.30	6.50
17.12	0.75	174.48	6.78
20.07	1.01	179.54	7.04
24.15	1.27	180.32	7.38
25.57	1.50	192.27	7.50
29.39	1.77	201.16	7.74
29.84	2.00	209.85	8.00
32.98	2.25	218.95	8.25
54.15	2.50	221.83	8.50
64.48	2.76	228.42	8.75
78.65	3.00	228.69	9.01
85.42	3.24	230.81	9.25
93.53	3.51	232.28	9.50
99.25	3.76	234.08	9.76
103.79	4.02	234.15	10.00
107.93	4.25	235.17	10.01
113.04	4.56	235.31	10.03
115.03	4.76	235.72	10.04
132.84	5.00	236.24	10.07
138.56	5.25	238.03	10.08
149.68	5.51	239.26	10.09
154.66	5.76		