SHEAR STRENGTHENING OF RC DEEP BEAMS WITH LARGE OPENINGS USING CARBON FIBER REINFORCED POLYMERS (CFRP)

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TONG FOO SHENG

Thesis submitted in fulfilment of the requirements
for the award of the degree of
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DEDICATION

It is our genuine gratefulness and warmest regards that I dedicate
this thesis to my sweet and loving parents:

Tong Han Chau and Law Poh Giok

Who introduced me to the Earth
Give me everything essential
And
Supported me in the fulfilment of success and academic goal

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ABSTRACT

This research deals with the experimental study of the behaviour of reinforced concrete deep beams with or without large rectangular openings as well as openings strengthened using externally bonded Carbon Fiber Reinforced Polymer (CFRP) composites in shear. The structural behaviour, including the load deflection, cracking patterns, failure mode, and effectiveness of the CFRP wraps were investigated. A total of four (4) specimens of beams with compressive strength of 35 MPa were tested to induce shear failure under 4 points loading test, which included one solid deep beam acted as a control beam (CB), one of which was tested without strengthening (US-BRO), and the remaining beams were strengthened with CFRP wraps in varying configurations around the opening (S-BRO-1, S-BRO-2). The beam had a cross section of 120 mm in width and 600 mm in depth as well as a length of 2400 mm. All the test specimens had a same geometry, main reinforcement arrangements and openings location. All the preparatory works of specimen materials were conducted in Laboratory FKASA. The examined parameter was the effect of configurations of the CFRP wraps used for the shear strengthening. The inclusion of un-strengthened large rectangular openings in the shear zone of a reinforced concrete deep beam leads to a reduction of ultimate beam strength by approximately 70%. The application of CFRP wraps with the presented strengthening configurations restricted the propagation of the diagonal crack and effectively increases ultimate load-carrying capacity as well as the ductility of the beam. The strength re-gains by U-shaped strengthening configuration around the openings was approximately 36% as compared to the beam with un-strengthened openings. However, the deep beam with U-shaped CFRP with horizontal fiber strengthened at the top and bottom chords of the openings were not capable to restore the control beam’s original structural strength remarkably. The beam only managed to re-gain about 41% of the control beam’s capacity.

ABSTRAK

Laporan kajian ini adalah mengenai kelakuan rasuk konkrit bertetulang yang mendalam dengan atau tanpa lubang segi empat tepat yang besar dalam ricih serta lubang diperkukuhkan dengan menggunakan terikat luaran Carbon Fiber Reinforced Polymer (CFRP) komposit. Kelakuan struktur mengandungi graf beban dan lenturan, corak retakan rasuk, mod kegagalan, serta keberkesanan balutan CFRP telah disiasat. Sebanyak empat (4) spesimen rasuk dengan kekuatan mampatan 35 MPa telah diuji untuk mendorong kegagalan ricih di bawah 4 titik ujian beban, termasuk satu rasuk dalam pepejal bertindak sebagai rasuk kawalan (CB), salah satu yang telah diuji tanpa pengukuhan (US-BRO), dan baki rasuk diperkuatkan dengan CFRP balutan dalam pelbagai konfigurasi sekelilingnya (S-BRO-1, S-BRO-2). Rasuk dengan ukuran keratan rentas 120 mm lebar dan 600 mm dalam dan panjang 2400 mm. Semua spesimen ujian mempunyai geometri yang sama, tetulang utama dan lubang lokasi. Semua kerja-kerja penyediaan bahan spesimen telah dijalankan di Makmal FKASA. Parameter diperiksa adalah kesan konfigurasi daripada balutan CFRP yang digunakan untuk pengukuhan ricih. Penggunaan lubang besar dalam bentuk segi empat tepat yang tanpa diperkukuhkan dalam zon ricih rasuk konkrit bertetulang yang mendalam telah menunjukkan pengurangan kekuatan rasuk sebanyak 70%. Penggunaan CFRP balutan dengan konfigurasi mengukuhkan dibentangkan dapat mengehadkan penyebaran retak pepenjuru dan berkesan meningkatkan keupayaan menanggung beban muktamad dan kemuluran rasuk. Kekuatan yang didapatkan semula dengan penggunaan CFRP terikat luaran balutan dalam konfigurasi berbentuk-U sekitar lubang adalah sebanyak 36% berbanding dengan rasuk mengandungi lubang yang tanpa diperkukuhkan. Walau bagaimanapun, rasuk dalam dengan CFRP berbentuk-U dengan gentian mendatar diperkukuhkan oleh CFRP terikat luaran balutan dalam konfigurasi-U berbentuk sekitar lubang di chords atas dan bawah lubang tidak mampu mengembalikan kekuatan asal kawalan rasuk struktur biasa. Rasuk hanya berjaya memerlukan memulihkan kekuatan rasuk sebanyak 41% daripada kapasiti rasuk kawalan itu.

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LIST OF SYMBOLS

%	Percentage
a/d	Shear span-to-depth ratio
d	Distance from the support (mm)
N/mm^2	Newton per millimetre square
l/h	Span-to-depth ratio
Kg	Kilogram
Kg/m^3	Kilogram per meter cube
N	Newton
℃	Degree Celsius
°	Degree
k	Kilo
g/m^2	Gram per meter square
mm^2	Millimetre square
Mm	Millimetre
µm	Micrometre
MPa	Mega Pascal

LIST OF ABBREVIATIONS

ACI	American concrete institute
AS	Australia standard
ASCE	American society civil engineer
BS	British Standard
C	Cube sample
CB	Control beam
CFRP	Carbon fiber reinforced polymer
CSA	Canadian standard association
EC	Egyptian Code
FRP	Fiber Reinforced Polymer
LVDT	Linear variable displacement transducer
MB	Mechanical expansion bolts anchoring system
S-BRO-1	Beam with u-shaped strengthened openings
S-BRO-2	Beam with surface strengthened openings
SG	Electrical resistance strain gauges
SGFRP	Sprayed glass fiber reinforced polymer
US-BRO	Beam with un-strengthened openings

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

The application of reinforced concrete (RC) deep beams is typically applied in high-rise building, foundation, and offshore gravity type structures. It can be seen normally at the lower floors or basement in multiple-story buildings, which used as transfer girders in order to avoid the columns and thus providing more free space for parking purposes. Reinforced concrete deep beams is very useful in supporting the high loading in a structure, the upper part load is transferred to others column through the transfer girders. Since the transfer girder is subjected high shear stress, thus the deeper depth is demanded. Due to their economic efficiency and convenience, this application has enhanced dramatically.

The fundamental requirement of constructing a modern building consists the networks of ducts and pipes so as to facilitate the necessary services such as electricity, telephone line, sewerage, computer network, ventilation system and so on. In the past practices, for the aesthetic viewpoints, these pipes and ducts were installed and hanged underneath the floors slab or beam soffits, then covered by the suspended ceiling where the dead space is formed. These dead space height in each floor gather up to the entire building height. Hence, the presence of the openings in web of RC beam is becoming an alternative solution and frequently used to accommodate those necessary services. In the meantime, it can be significantly eliminates overall height of the dead space, construction and material cost such as the length of the pipes and ducts, and results in more compact and economical design, but the saving is not much effective for smaller buildings (Ahmed et al., 2012; Hafiz et al., 2014; Mansur and Tan, 1999; Torunbalci, 2002).

There are several definitions regarding deep beam according to different country design codes. Generally, a reinforced concrete deep beam is defined as a structural member with large depths to span or has a span to depth ratio of less than 5. Instead, deep beam does not behave the same way like normal beam do, deep beams transmit the shear forces to support by way of compressive stresses rather than shear stresses. The flexural cracks and diagonal cracks are the cracks that typically germinate in RC deep beams (Farghaly & Benmokrane, 2013). Thus the typical assumptions cannot be taken for granted. As per New Zealand Code, deep beam is subjected to load on one face and supported on the opposite face thereby compression struts can be developed between the supports and loads as well as have either clear span equal to or less than 3.6 times the effective depth for continuous or simply supported beam, while clear span equal or less than 1.6 times the effective depth for cantilever beams.

According to American Concrete Institute (ACI 318R-08), the clear span of a deep beam are either equal to or less than 4 times of the overall depth. The EC 203-2006 has the same circumscription as ACI 318R-08, while the EuroCode defined deep beam as a member whose span is equal or less to 3 times the overall depth. ACI-ASCE Committee 426 also classifies a beam with shear span-to-depth ratio (a/d) less than 1.0 as deep beam and a beam with a/d exceeding 2.5 as an ordinary shallow beam. In addition, shear span is the defined as the zone where distance between a reaction and the nearest load point and shear force is constant. Other than that, as per IS-456 Clause 29, the ratio of the effective span of the overall depth of simply supported deep beam is less than 2 while the continuous beam is less than 2.5. The Canadian code (CSA-A23.3-2004) defined deep beam in the ratio of the clear span to the overall depth is less than the 1.25 and 2.5 for simply supported and continuous beam.

1.2 PROBLEM STATEMENT

Due to the architectural or mechanical requirement, the enlargement of the openings cannot be avoided and undoubtedly weakened the structural member's shear capacity significantly and then rendering severe safety hazard (El Maaddawy & Sherif, 2009). There have been numerous studies of experimental have been concluded that the increase in the height and depth of the opening lead to a significant reduction in the beam strength. The reduction in beam strength is more significant when the opening interrupted the load path (Mansur, 1998; Mansur *et al.*, 1999; Ashour and Rishi, 2000; El Maaddawy & El Ariss, 2012). In general, shear failure of concrete beams happened without advance warning prior to failure (Chin *et al.*, 2012).

The introduction of the large opening in reinforced concrete deep beam transformed the beam's behaviours into a more complicated state due to the sudden change of beam cross section (Ahmed *et al.*, 2012; Torunbalci, 2002; Mansur *et al.*, 1992; Mansur, 2006). The previous practical and experimental studies have reported that the inclusion of a transverse opening in the web of the reinforced concrete deep beam produced discontinuities in the normal flow stresses, increase in deflection, and deduction in shear capacity and stiffness of the beam at load services stage. Other than that, introducing the transverse opening resulted the opening corners subjected by high stress concentration, thus cause the early unacceptable excessive cracking frequently (inclined and vertical cracks adopt at the corners of the opening) (Ahmed et al., 2012; Chin et al., 2012). Even though the collapse load was decreased, but it won't alter the mode of failure (Abdalla et al., 2003; Hawileh et al., 2012; Torunbalci, 2000).

1.3 RESEARCH OBJECTIVES

i. To determine the behaviour of deep beams with openings in terms of load-deflection and cracking patterns.
ii. To determine the behaviour of deep beams with openings strengthened using CFRP wraps strengthened in terms of load-deflection behaviour and cracking patterns.
iii. To determine the effects of opening shape, size and location.
iv. To determine the effective strengthening configuration using CFRP wraps.

1.4 SCOPE OF STUDY

This test was conducted on reinforced concrete deep beams included the large rectangular opening in the shear region in the experimental program of this research. The RC deep beams were designed as an under reinforced section in accordance with

American Concrete Institute (ACI 318R-08). The shear span-to-depth ratio (a/d) of the beams was 0.83 that's designed to actuate the shear failure and develop the deep beam action. A total of 4 reinforced concrete deep beams undergoes the 4 points loading tests which including one solid deep beam acted as a control beam, one deep beam with un-strengthened openings and remaining deep beams with strengthened opening using CFRP wraps with varying arrangements and configurations. All the reinforced concrete deep beams had the same geometry with a cross section of 120 mm in width and 600 mm in depth as well as a length of 2400 mm. The beams were simply supported at its ends, which placed 300 mm from the end of the beam. Thus had an effective span of 1800 mm which giving a l/h ratio (span-to-depth ratio) of 3. In addition, two concentrated point loads are positioned 500 mm away from the support point as well as at a distance of 800 mm apart were applied to the top of the beam.

All the beams were cast simultaneously in a horizontal direction by using the high strength ready mixed concrete with a nominal designed for 28-days compressive strength of 35 MPa. All the specimens had two openings, one in each middle of the shear span except the control beam. The openings shape and size were created and maintained constant throughout the test which is a rectangular shape with a cross section of 600 mm in depth and 270 mm in width. The internal web reinforcement was not allowed to erect in the test region. The crack patterns and load-deflection behaviour were also determined in this experimental study.

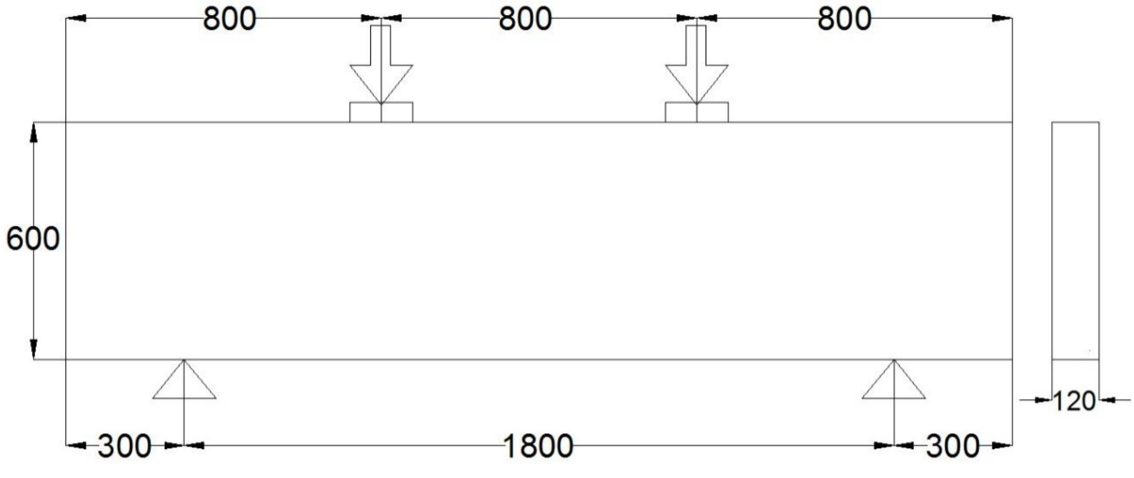

Figure 1.1: Illustration of solid deep beam (value in mm)

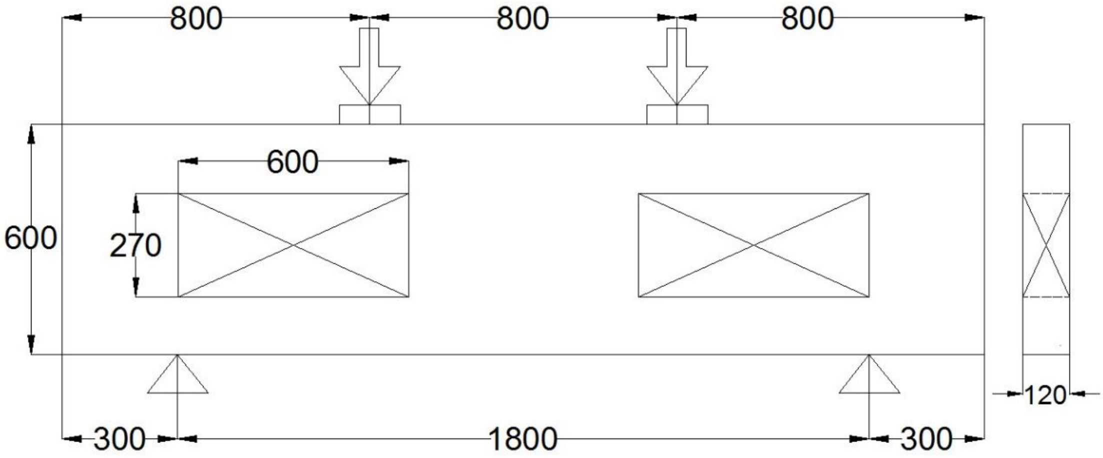

Figure 1.2: Illustration of deep beam with rectangular openings (value in mm)

1.5 RESEARCH SIGNIFICANCE

The present paper is intended to provide the experimental information about the load deflection behaviour, cracking pattern and ultimate load of RC deep beams with un-strengthened openings and strengthened openings using CFRP wraps in two different configurations. Hence, the important of this research contributed experimental result and evidences about the behaviour of RC deep beams with large rectangular opening.

The present research also intended to examine the potential use of this technique as a structural engineering solution to upgrade the RC deep beams with enlarged openings. The most effective CFRP configuration in enhancing the beam ultimate strength of RC deep beams with openings was also examined. Other than that, its purpose is to contribute the experimental evidences that would aid practicing engineers and researchers to better understand the interrelationship between the opening location, size, ultimate strength, load-deflection behaviour and failure mode of the RC deep beam with un-strengthened opening as well as the re-gains in term of ultimate capacity of RC deep beam with openings strengthened with CFRP wraps.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

A number of good deal of studies has been carried out on deep beam with openings in the last few decades. The previous research results deals with the experimental study of the behaviour of RC deep beams contained with large opening will be focused on this chapter.

2.2 OPENING CLASSIFICATIONS

The opening shape, size and location can be varied according to the design.

2.2.1 Shape

Prentzas (1968) considered rectangular, circular, trapezoidal, triangular, diamond and even irregular shapes in his extensive experimental study. Even though there is numerous shapes of transverse opening are available, but rectangular and circular opening shape are the most common one in practice. The circular opening generally uses to facilitate the service pipes such as the electrical supply and plumbing while the air-conditioning ducts are normally made in rectangular shape so they can pass through the rectangular openings of the beam.

2.2.2 Size

In 1974, Somes and Corley considered circular opening is large when its diameter larger 0.25 times than the beam web depth. Later in 1979, Mansur and Hasnat defined the square, circular or nearly square opening in shape as small opening or, in other words, less than the overall depth of beam about approximately 40%. According to Mansur and Tan (1999) have considered the essence to classify the opening either as large or small which lay in the structural reaction of the beam. An opening can be classified as a small opening if the normal beam theory is applicable or, in other words, the opening is small enough to allow the structure to behave like normal beam does. While an opening is considered as large when the normal beam-type behaviours are no longer applied due to the presence of the openings. As reported by Mansur and Tan (1999), the opening depth should not exceed than 50% of the overall depth of the beam. Many researchers have been dealing with the opening size, whether it is small or large opening, but currently there is without any clear-cut demarcation line or definition.

2.2.3 Location

The openings can be located at anywhere in the beam web either in horizontal or vertical directions in the region between the support and point load applied. It also can be within high moment or low shear zone. A web opening located in a high moment region has an influence on the loading capacity of the beam, due to the beam stiffness is weak in that area, and collapse load defined by this opening (Torunbalci, 2000, 2002). In 1969, Hanson tested a series of longitudinally RC T-beams with square and circular opening in the web and found that the inclusion of opening located adjacent to the centre stub (support) lead to zero strength reduction. The behaviour of 8 reinforced concrete continuous beams with large web openings was investigated by Mansur *et al.* (1991). They were discovered that the location of the opening has very insignificant effect in the term of cracking load, but placed the openings in a comparatively high moment region generate a large deflection and smaller collapse load. The collapse mode remains unaffected by the location of opening virtually.

In contrast, the researches of Kong and Sharp (1977) and Ashour and Rishi (2000) revealed that the strength of beam, stiffness and failure mode are primarily dependant upon the location and size of the opening. They disclosed the strength of the beam was reduced when the location of opening interrupted the natural load path of the beam. Other than that, the inclusion of opening in the interior shear span resulted the highest load capacity reduction occurred. The ultimate shear capacity and beam strength was cut down when the opening interrupted the natural load path of the beam or the stress field joining the loading and the reaction point were intercepted by the opening. (Ashour and Rishi, 2000; Campione & Minafò, 2012). In addition, Mansur and Tan (1999) also contributed the guidelines to select the location of web openings. They concluded the location of openings should not be placed closer than half of the beam's depth to the supports in order to prevent the crucial zone for the congestion of reinforcement and shear failure happen. In a similar way, an opening location should not nearer than 0.5D to any concentrated loads.

The spacing of the opening from the top and bottom of the beam also affects the load-carrying capacity of a beam. The eccentricity of the web openings is closest to the applied load is increased downward below the longitudinal beam axis. The domination of the tensile stressed in the region below the opening, and these stresses are compensated by the existing tension reinforcement. In the meantime, the axial compressive stress is compensated by the concrete at the part above the opening. When the opening is close to the support, the situation is reversed. When openings are above the longitudinal axis of the beam, better results are obtained. Hence the load carrying capacity of the beam depends on how much the openings interrupt the compression strut spanning from the support. As a result, opening should be placed below the axis of the beam in the middle of the span and above the axis near the support (Torunbalci, 2000). Javad and Morteza (2004) also concluded the first place to consider the location of the opening in reinforced concrete beam was the middle of the shear span. In order to achieve the ultimate strength of such beams, the opening location should locate near the support.

2.3 METHOD OF STRENGTHENING

There are 2 methods to strengthen the RC deep beams with opening which including internal strengthening and external strengthening. Internal strengthening used the different patterns and quantities of steel bar erected around the opening while external strengthening material by pasting the externally bonded composite materials around the opening in varying arrangement and configuration schemes.

2.3.1 Internal Strengthening Method

This method is favourable when the opening is pre-planned before the construction or during the design stage. The location and size of opening are known in advanced. The web reinforcement played an effective role in controlling the propagation of crack width, upgrading the ultimate shear strength, and deflection that due to stress concentration around the openings. The existence of longitudinal bars on the upper and lower of the opening are very effective in controlling the flexural strains and cracks around the opening. In order to increase the ultimate strength and decrease the deflection of the deep beams with opening, diagonal bars were installed for corner reinforcement as well as the small stirrups at the openings top and bottom (Javad and Morteze, 2004; Ahmed et al., 2012; Kong and Sharp, 1977). In 1990, Siao and Yap concluded that the beams failed by the sudden formation of a diagonal crack in the compression chord due to no additional reinforcement is erected in the members near the opening.

It's also shown that it is necessary to increase the amount of the internal web reinforcement around the opening in order to increase the shear capacity and ductility of RC beams with web openings (Yang *et al.*, 2006; Yang *et al.*, 2007; Yang and Ashour 2008). In additional, inclined web reinforcement is the most effective arrangement in resisting cracks of diagonal in solid deep beams as well as upgrading the ultimate shear strength of solid deep beams. Therefore, the beneficial effect of inclined web reinforcement is even more prominent in the deep beams with openings. (Tan *et al.*, 2004)

2.3.2 External Strengthening Method

In contrast, the second method is much beneficial when the opening is introduced after the construction which cannot meet any design consideration and analysis about the opening. The openings were drilled in an existing structure while the problem may arise during and after the process. This happened often due to the M&E engineers re-locate the opening location to simplify the arrangements of ducts and pipes in order to achieve the huge savings in term of costs, materials and time. Hence, strengthening by using externally bonded FRP system is very crucial. (Alsaeq, 2014; Chin *et al.*, 2011).

2.4 EXTERNALLY BONDED COMPOSITE MATERIALS

Fiber Reinforced Polymer also known as Fiber Reinforced Plastic which is well known to strengthen, repair, upgrade and retrofit the reinforced concrete structural members in the construction industry around the worldwide. FRP composites provide excellent properties which are not available in the conventional construction materials such as good fatigue properties, non-corrosive characteristics, high strength-to-weight ratio, electromagnetic resistance and versatility dealing with different corners and sectional shapes. The ease of handling FRP wrap gives an advantages over the traditional strengthening techniques. (Abdalla *et al.*, 2003; Ban & Abduljalil, 2014). There are several kinds of FRP in the construction industry, most common type of FRP in practice is made by glass, aramid, or carbon fiber that generally in the form of strips, wraps, laminates and sheets. The amount and configuration of FRP laminates strongly influenced the increase in ductility and strength of reinforced concrete structures.

2.4.1 Amount

One of the factors to re-gain the shear strength relies on the number of the FRP layers. Increase the amount of the FRP sheets from one to two layers did increased the shear capacity, but the additional shear capacity gain was not proportional to the additional amount of the CFRP if debonding of CFRP controls the failure (Triantafillou and Antonopoulos, 2000; Chaallal *et al.* 2002). Bousselham and Chaallal (2006b) also revealed that increasing in the amount of the CFRP in deep beams had no noticeable result on the gain in the shear capacity in their experimental studied.

2.4.2 Orientation and Configuration Schemes

The configurations of strengthening system had a great impact on the beam strength and stiffness. It is very important for the CFRP wraps to intercept the potential shear crack, thus can provided effectively to the shear strength of the beam. Pimanmas (2010) found that placed the FRP rods around the opening simply was not much effective due to diagonal crack propagated through the beam with crack paths were migrated to avert make friends with the FRP rod. There are two methods to improve by the FRP rod, which are enclosing the opening and pasting it throughout the whole entire beam depth diagonally. The author also found that the use of inclined near-surface-mounted composite rods externally installed diagonally to the beam axis alongside the opening throughout the entire beam depth can fully recover the shear capacity of RC beams with web opening. When the FRP rods were applied throughout the entire beam depth, an impressive improvement in ductility and loading capacity was observed, which is quite similar with strengthening by internal steel reinforcement. Thus the mode of failure was recovered.

Other than that, Allam (2005) was conducted an experimental studied regarding the efficiency of strengthening beams externally with large shear opening. They employed both CFRP sheets and steel plates to strengthen the beams with opening as well as their configuration schemes. His experimental results showed that the efficiency of CFRP in strengthening the beams with opening when it was applied to both inside and outside opening edges. The improvement of strengthening the outside edges only was also discovered to be more remarkable. Moreover, the application of steel plates to strengthen the beam provided with opening was much more prompt than a case of CFRP sheets.

It was also found that orientated the fibers in perpendicular direction to the potential diagonal shear cracks more effective than others. Ashour and Rishi (2000) concluded that the vertical FRP reinforcement was enhanced the strength than placed it in horizontal. The Vertical FRP shear strengthening lead to an improvement of shear strength about 79% at 1.875 shear span-to-depth ratio, whereas only re-gained 46% shear strength at 1.25 shear span-to-depth ratio. The result showed the performances of the FRP system declined as the behaviour of a shallow beam changes to a deep beam.

2.5 Review of Previous Experimental Studies

Plenty of studies have been carried out by researchers on RC beams with openings to examine the load deflection response, cracking and ultimate behaviour of such beams in the last 4 decades. The major variables investigated included the location, shape and size of the opening, shear span-to-depth ratio, the presence and amount of steel reinforcement around the opening as well as the concrete compressive strength.

2.5.1 Behaviour of RC Deep Beams with Openings

Kong and Sharp (1977) found three types of failures in their extensive test. A total of 72 simply supported deep beams were tested, which included 16 normal weight concrete beams and 56 lightweight concrete beams. The test variable were the sizes and location openings along with different web reinforcement arrangements. Failure mode 1 indicated the same mode of failure that generally present in solid deep beam where when opening did not interfere the natural load path of the beam. Modes of failure 2 and 3 presented when the natural load path of the beam was intersected. A diagonal crack occurred from the inside edge of the support and propagated to the farther bottom corner of the opening for these failure modes. On the top of the opening, diagonal crack occurred between the top corner of the opening and outside edge of the load point.

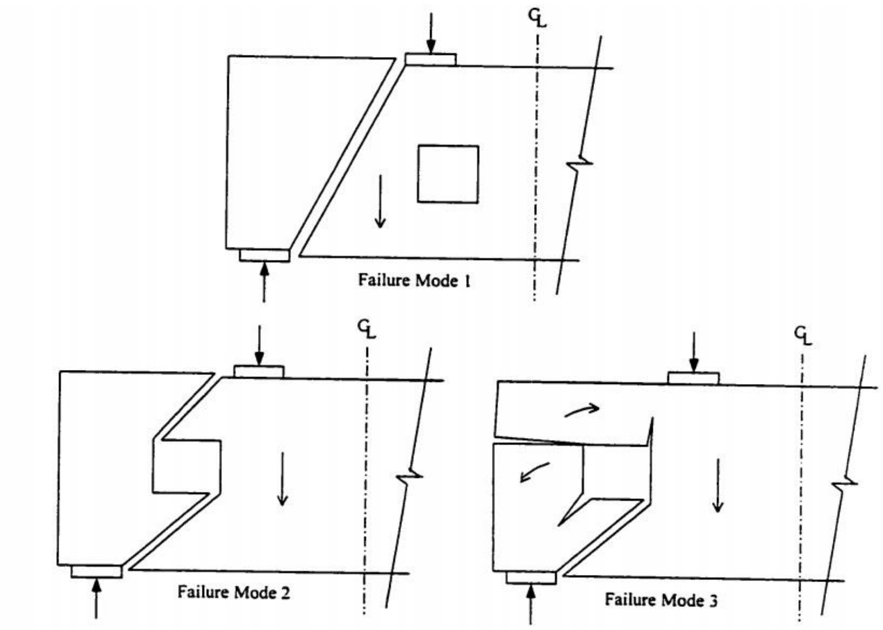

Figure 2.1: Failure modes observed by Kong and Sharp

Source: Ha (2002)

Then Kubik (1980) conducted further work on deep beams with opening at University of Cambridge. He tested 8 normal weight beams and 18 lightweight beams. The normal beam weight was approximately 2.5 times bigger than the beams were tested by Kong and Sharp. He found that the beam was deformed by the rotation of three major blocks when the opening is interrupted the natural load path of the beam. One block below the opening, one block was above the opening, and the third block was between the opening and the end of the beam. Furthermore, he also revealed another two modes of failure that were not seen by Kong and Sharp. These failures presented at a plane at the top outer corner of the web opening and at the bottom of the beam at either flexural crack or from the beam soffit. The crack patterns were similar to those found by Kong and Sharp, except for some splitting cracks in the web of the beam. These new cracks have shown in the Figure 2.2 (Ha, 2002)

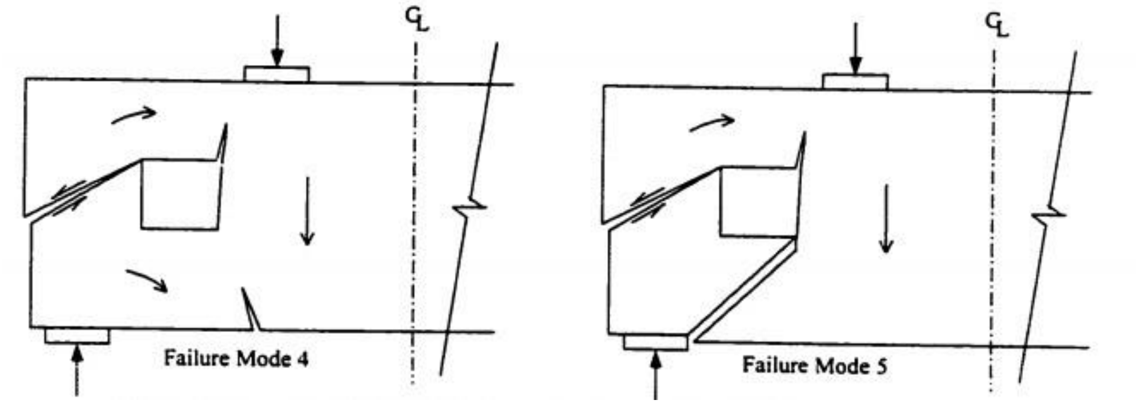

Figure 2.2: Additional failures mode observed by Kubik

Source: Ha (2002)

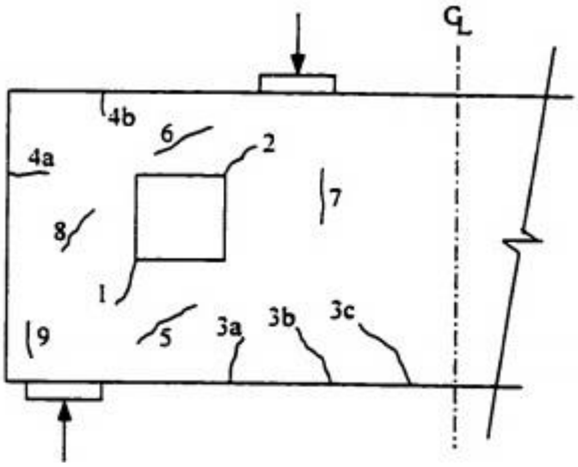

Figure 2.3: Crack patterns observed in testing by Kong, Sharp, and Kubik

Source: Ha (2002)

From the past practical and experimental results (Mansur, 1988; Abdalla and Kennedy, 1995) have shown that vertical and inclined crack develop at openings in reinforced concrete beams at 4 critical locations, which are at the opening corners close to the vertical loads due to the framing action of the opening chords; in the opening chords due to the flexural stresses resulting from the secondary moments in these chords; in the tension chord due to the normal tensile stress in that chord; and in the opening chords due to shear (The last type of cracking can spark the complete collapse of the beam).

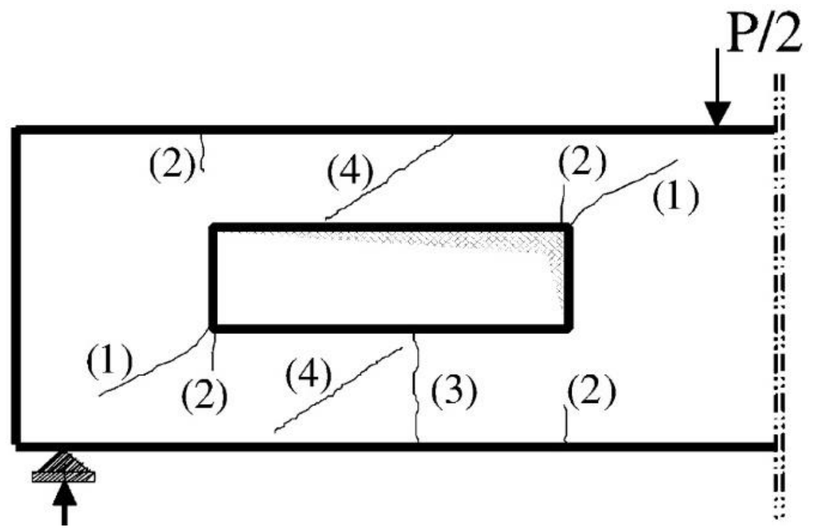

Figure 2.4: Crack pattern around the rectangular opening

Source: Abdalla (2003)

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The test data reported by Somes and Corley (1974) showed that the presence of a small opening (0.25 times the depth of the beam) in the web of a beam which is unreinforced in shear, the mode of failure remains essentially same as that of a solid beam. Later in 1985, Mansur *et al.* were tested 12 beams under one point loading test and subjected to shear force and bending. They also discovered that arise in the moment–shear ratio or size of opening (length and depth) increased both maximum deflection and crack width at the centre of the opening.

In 1991, Mansur *et al.* tested 8 RC continuous beams where each consists a large transverse opening and concluded an increase in depth of opening led to a decrease in collapse load. Later in 1998, Mansur investigated the influence of transverse opening on the behaviour and strength of RC beams under predominant shear and stated that opening represents a source of weakness and the failure plane always passes through the opening. *Tan et al.* (1996) tested 15 reinforced concrete T-beams with large web openings, each imitating either positive/negative moments. They revealed that the inclusion of web opening resulted reduced in both ultimate strength and cracking. They also discovered that the external shear distributed between chords in accordance with their stiffness of flexure based on either cracked transformed section or gross.

In 2005, Zainab *et al.* investigated 10 reinforced concrete T-beams under the static loading and simulated their negative moment regions. Of these beams, one had a solid web while nine were contained with large openings in the web. The effect of steel reinforcement around the opening, tension reinforcement area, shear span-to-depth ratio and concrete compressive strength of the strength of beams were examined. Both concrete compressive strength and shear span-to-depth ratio of such beams containing openings had a resolved influence on the load bearing capacity of the tested beams. Both the upper and lower chord member refused the shear force of beams contained openings independently from high compressive strength concrete. The predicted ultimate loads matched experimental ultimate loads with the shear span-to-depth ratio of 2. It was shown that the normal strength concrete beams included openings behaved quite distinct compared with the performance of high strength concrete beams contained openings.

Yang *et al.* (2006) tested 32 high strength RC deep beams contained with or without rectangular and square openings under two-point top loading tests. The specimens had different concrete strength (24, 50 and 80 MPa), and the size of the opening and the shear span-to-depth ratio ranged between 0.5 and 1.5. At the initial loading stages, the depth and width of the opening did not influence the mid-span deflection, but it affected the deflection significantly after the occurrence of first diagonal cracks. Their research results showed that the strengths at diagonal crack and peak were intently related to the angle of the inclined plane, joining the support and the corner of the web opening. The researchers also found that the effect of concrete compressive strength on the ultimate shear strength significantly decreased in deep beams with openings compared with solid deep beams. The strength of a compressive concrete strut in deep beams with openings increased at lower slowly with the increase in concrete strength.

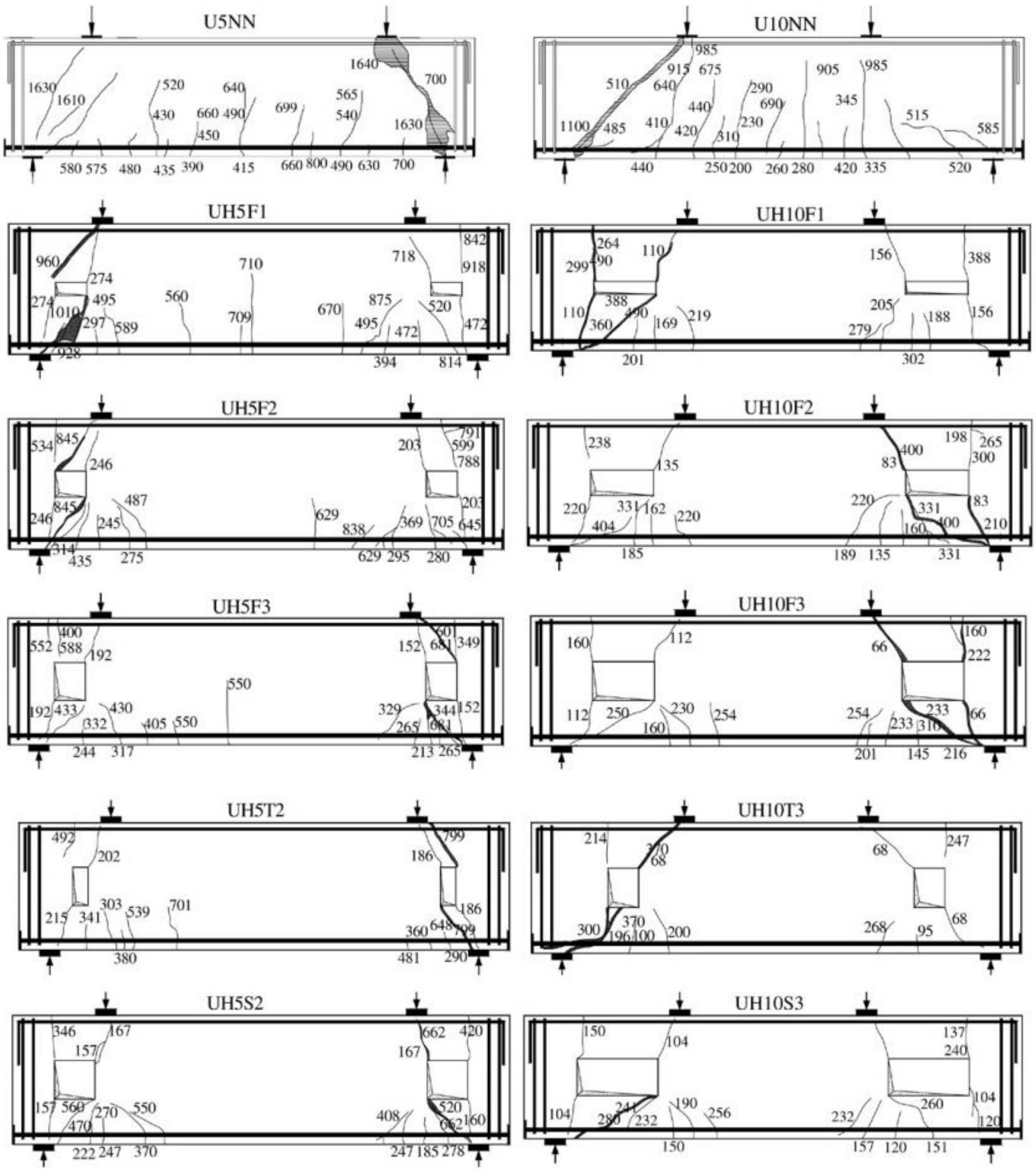


Figure 2.5: Crack pattern at failure observed by Yang

Source: Yang (2006)

The investigation carried out by Hu *et al*. in 2007 was focused on openings placed out of the shear span. They studied the influence of the trapezoidal web openings size, shear span-to-overall height ratio a/h ranged between 0.5 and 1.5 on the behaviour, and shear strength of high-strength RC deep beams. A total of six deep beams included four contained openings and without web reinforcement. The trapezoidal openings were placed in the mid-span or stretching from the mid-span to the shear span were tested to failure under two-point symmetric top loading. The compressive strengths of the specimens were in the range of 84 MPa – 103 MPa. Initially the flexural cracks were formed in RC deep beams with openings and the main failure cause was critical diagonal cracks, under the circumstances of the opening does not interrupt the transferring path of force or reduced the strut width. The presence of an opening in the mid-span modified the value of the first flexural cracking load and its size also influenced the diagonal crack width. The test outcomes expressed that the deep beam's ultimate strength was similar to that of the solid beam if the web opening did not interrupt the force path; different modes of failure were identified on the basis of the size of the opening and localized failure of concrete at the corners was observed for specimens with larger openings due to the trapezoidal shape. The mode of failure changed from shear to localized failure if the opening was large enough to reduce the strut width.

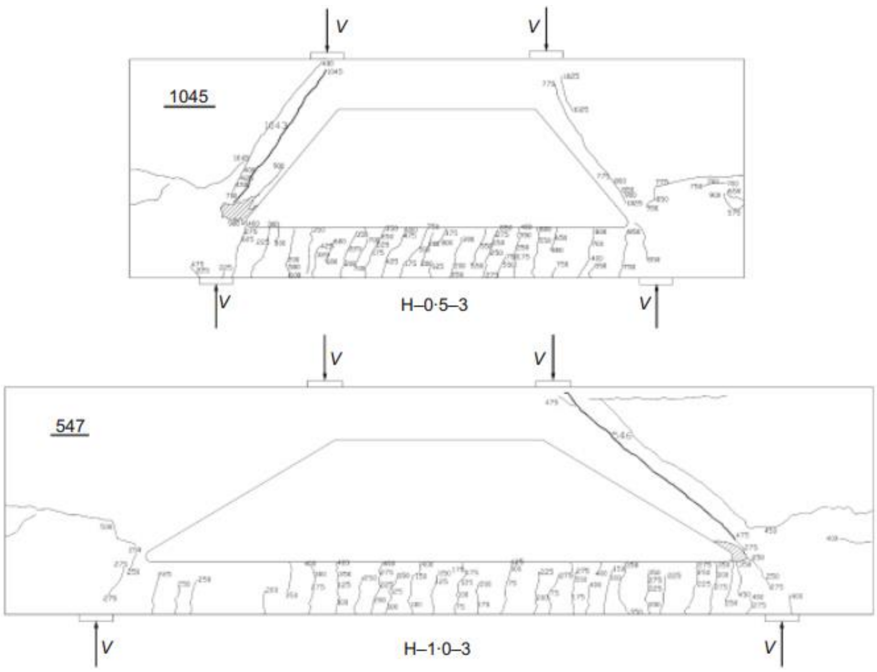


Figure 2.6: Crack pattern of beam at failure observed by Hu *et al*.

Source: Hu *et al*. (2007)

In 2012, Campione and Minafò had investigated the effect of circular openings in RC deep beams with low shear span-to-depth ratio, a/h equivalent to 0.27. They tested twenty (20) small-scale RC deep beams with or without circular openings in flexure under four-point loading test. The parameters in this studied were the amount and arrangements of reinforcement and location of openings. Four distinct arrangements of vertical and horizontal reinforcement as well as two different locations of the openings were premeditated. The cylindrical openings were stretched from the centre of the shear span to the middle span.

All the specimens were failed due to diagonal cracking or to concrete strut failure. Their studied result concluded that the first cracking load and failure mode primary depend on the location of the opening. The specimens without opening showed an initial flexural crack at about 25% of the maximum load in the mid-span section. The first visible diagonal crack appeared at an average load level of about 60% of the ultimate load. When the opening was placed in the mid-span section, it does zero effect on the behaviour of the RC deep beam; while a reduction of load-carrying capacity occurs in the range of 18-30% when the opening was placed within the shear span. The researchers also revealed that vertical stirrups enhanced the ultimate load about 15% in beams with an opening placed in the centre or solid deep beams. Other than that, the diffused horizontal stirrups were not efficient enough in RC deep beams with an opening placed in the centre of solid deep beams. The vertical stirrups are inefficient if the opening was located within the shear span, but only the presence of horizontal stirrups increased the load-carrying capacity by 20%.

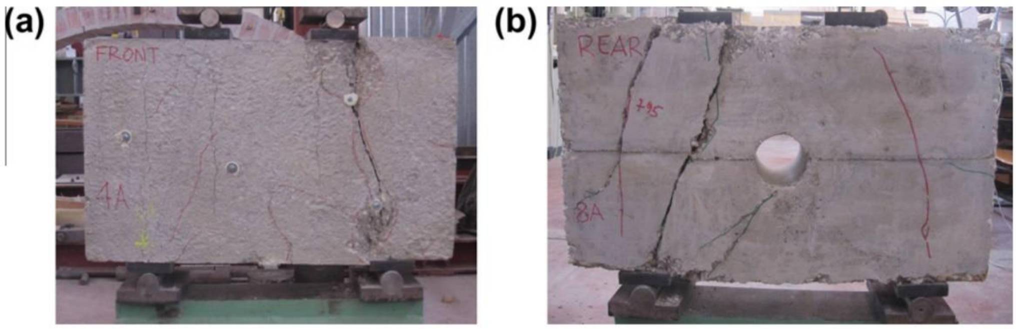


Figure 2.7: Specimens with and without openings in the mid-span after testing observed by Campione and Minaf ò

Source: Campione and Minaf ò (2012)

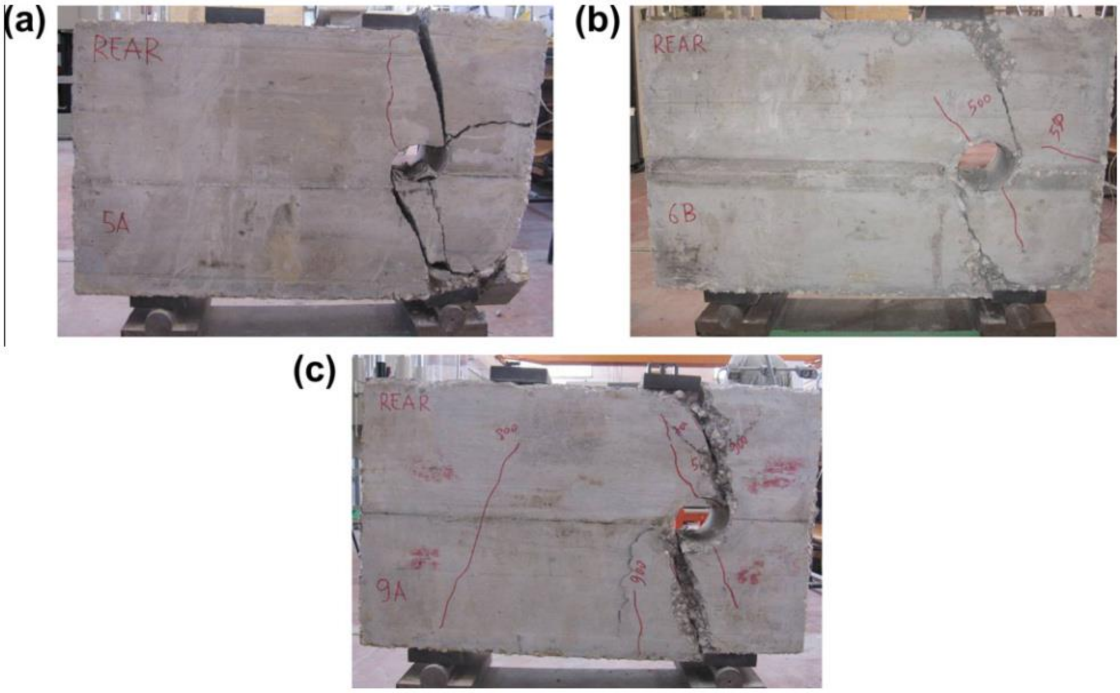


Figure 2.8: Specimens with openings in the shear-span after testing observed by Campione and Minafò

Source: Campione and Minafò (2012)

2.5.2 External Strengthening Around the Openings Using FRP Materials

A number of experimental studies have reported that externally FRP composite materials, remarkable improve the stiffness, load carrying capacity, flexural and shear capacities, controls the propagation of cracks, allocating confinement and ductility to compression structural members. The FRP materials system also did well in reducing the weakness caused by the presence of an opening in the web of RC beams. The viability of using externally bonded CFRP composite system to strengthen the shear capacity of shallow RC beams with opening has also been reported in the literature by researchers.

Abdalla *et al.* (2003) tested 10 RC beams where 4 of which were unstrengthening, 5 upgraded with CFRP sheets about the shear opening and the remaining beam was solid served as a control beam. This research considered several parameters which consisting the size of an opening, configurations and amount of the CFRP sheets paste around the opening. The rectangular shape of openings were implemented in all tested beams and placed 200 mm away from the support. They examined the efficiency of using CFRP sheets to confine the cracks surrounding the large transverse rectangular openings as well as to defy superfluous shear stress in the vicinity of the hole.

According to their result of this research, they revealed the inclusion of unstrengthen opening in a RC beam reduced its ultimate capacity significantly. The beam capacity was cut down approximately to 75% and 50% due to an unstrengthen opening contained the height of 0.6 and 0.4 of the beam depth. Increased the width of the opening for the same opening height has an insignificant effect on the deflection of beam especially before cracking. Hence, it can be seen that the height of the opening is the primary parameter influenced the load-deflection behaviour of beams with un-strengthened openings. The results proved that application of CFRP sheet in U-shaped obtained very ideals achievements. The increased in the load capacity ranged between 50% for opening size 300 x 10 mm to 200% for opening size 100 x 100 mm. It reduced the load-deflection of the beam, controlled the cracks around the opening, as well as improved the ultimate capacity of the beams. Thus an assumption has been made about abundant capacity of the beam with comparatively small opening can be retrieved by using FRP sheets. The failure of shear occurs at the strengthened openings chord caused by the association of bond failure between the FRP sheet and concrete as well as the shear cracking of concrete. It was proven that the application of CFRP is able to appraise the shear capacitance of reinforced concrete beams.

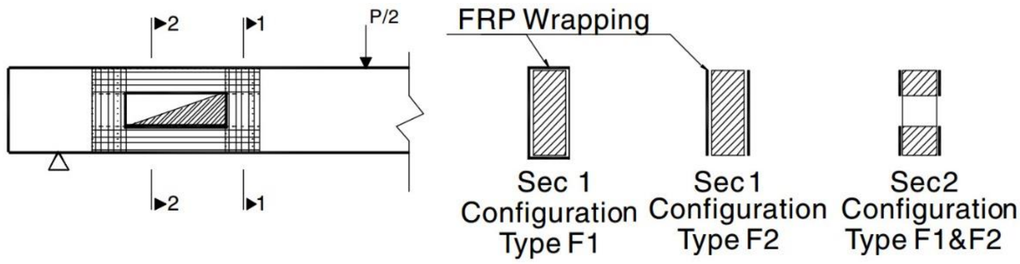
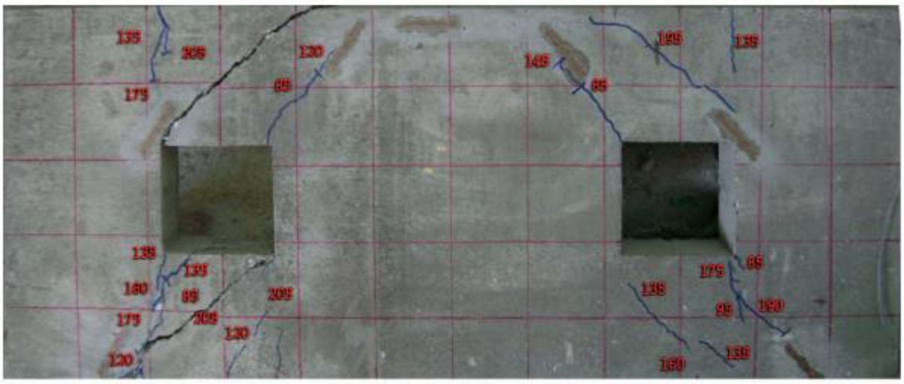


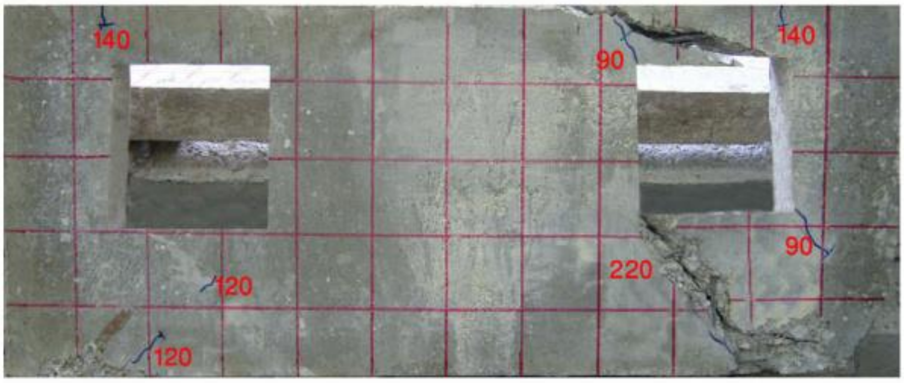
Figure 2.9: Types of external CFRP strengthening by Abdalla *et al.*

Source: Abdalla *et al.* (2003)

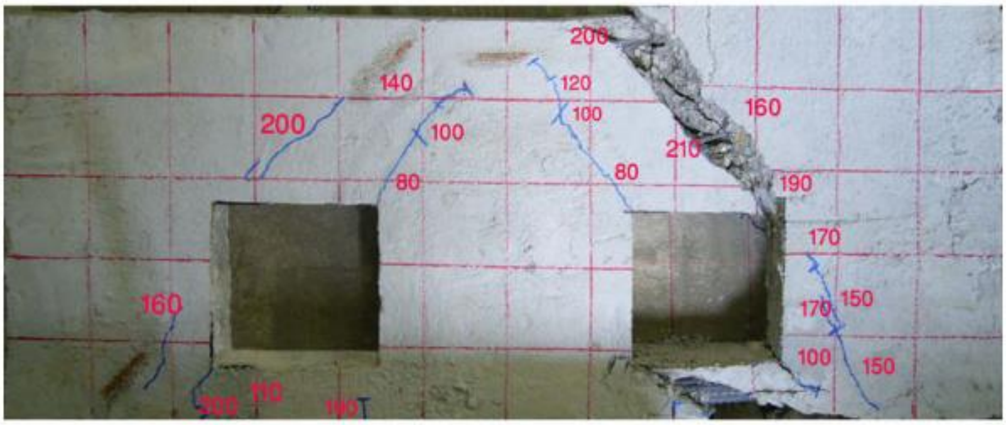
In 2009, El Maaddawy and Sherif tested 13 RC deep beams with large square openings. The test parameters included the opening size, location, and the presence of CFRP sheets. All the specimens consist two square openings, one in each shear span and placed about the midpoint of the beam symmetrically. The opening size was either 150 x 150 mm, 200 x 200 mm, or 250 x 250 mm which corresponded to opening height-to-depth (a/h) ratios of 0.3, 0.4, and 0.5 respectively. The web reinforcements were interrupted by the opening was cut prior to casting in order to resemble the case of the inclusion of an opening in an existing beam. The specimens were designed to induce failure of shear before to any flexural distress. They also revealed the opening size is the primary factor that affect the failure mode of un-strengthened RC deep beams with openings. The un-strengthened specimens experienced an average shear strength reduction in the range of 21 - 51 % of the opening size increased with a/h values by 0.3, 0.4 and 0.5 respectively. The un-strengthened beams exhibited 2 distinct failure modes, which were failure mode A or B. The specimens with an opening size less than 250 mm exhibited failure modes A where failure occurred by a formation of two independent diagonal cracks suddenly at the bottom and top chords of the opening, then splitting the beam into 2 independent sections. While the specimens exhibited failure mode B due to a relative rotation of three distinct in the shear span in the shear span of the beam when the opening size was 250 mm.



Specimen NS-150-C



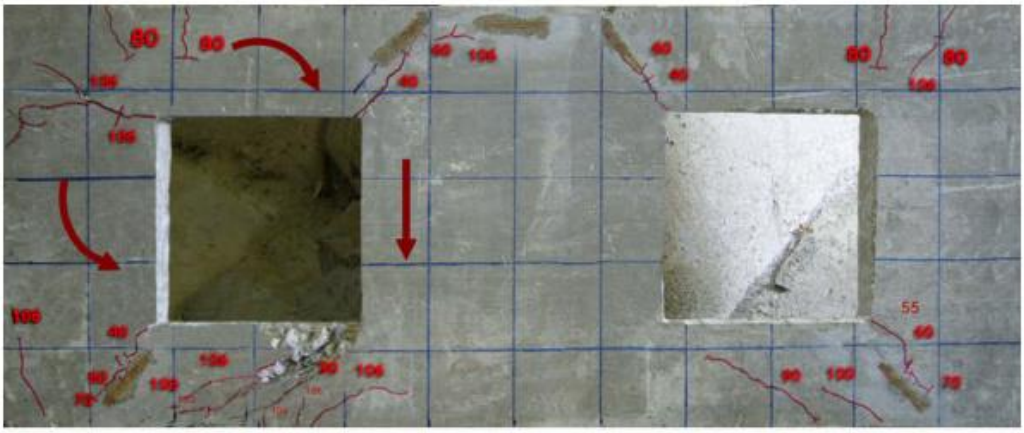
Specimen NS-200-T



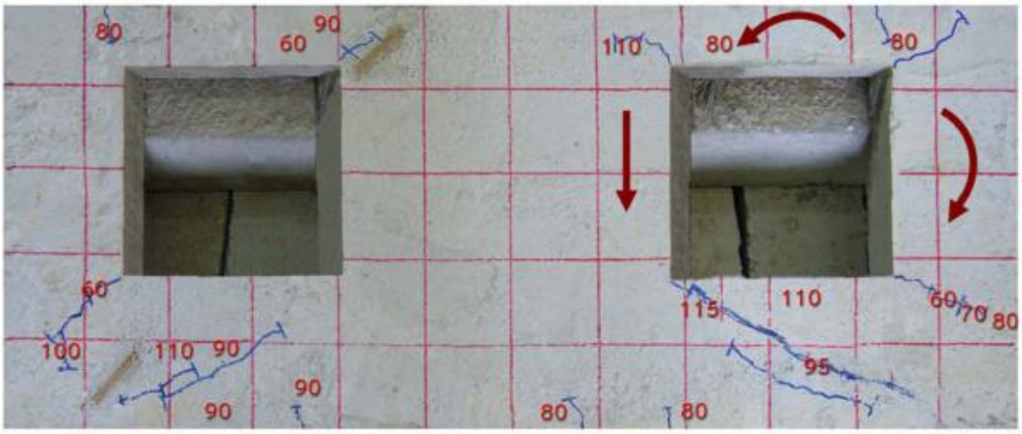
Specimen NS-200-B

Figure 2.10: Failure mode A (Unit in kN) observed by El Maaddawy and Sherif

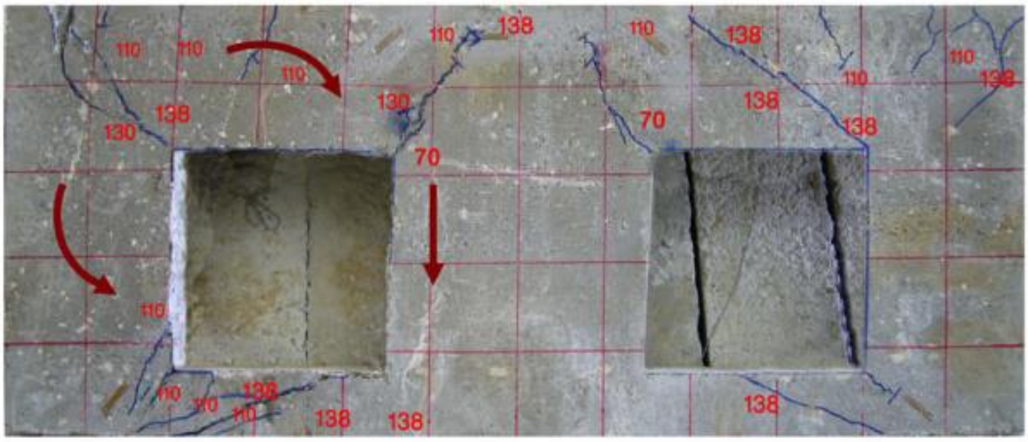
Source: El Maaddawy and Sherif (2009)



Specimen NS-250-C



Specimen NS-250-T



Specimen NS-250-B

Figure 2.11: Failure mode B (Unit in kN) observed by El Maaddawy and Sherif

Source: El Maaddawy and Sherif (2009)

The researchers also conclude that the externally bonded CFRP sheets in U-shaped was very effective in strengthening the opening. The shear strength re-gained in the range of 66-72% when the opening was located at the midpoint of the shear span. The maximum gain of shear strength was 72 % when the opening was located at the top of the beam because most of the shear force was transferred by the bottom chord which was fully wrapped with CFRP. While the beam with openings at the bottom only recorded the strength gain of 35% due to the shear force was carried by the top chord which had a U-shaped CFRP sheet.

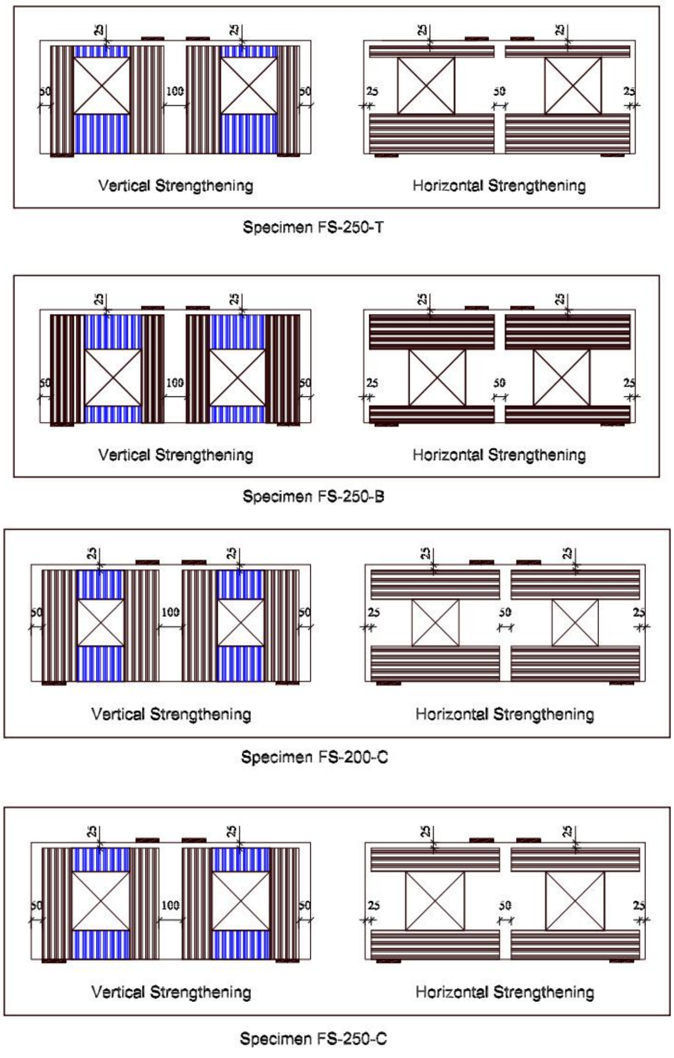


Figure 2.12: CFRP strengthening scheme by El Maaddawy and Sherif (unit in mm)

Source: El Maaddawy and Sherif (2009)

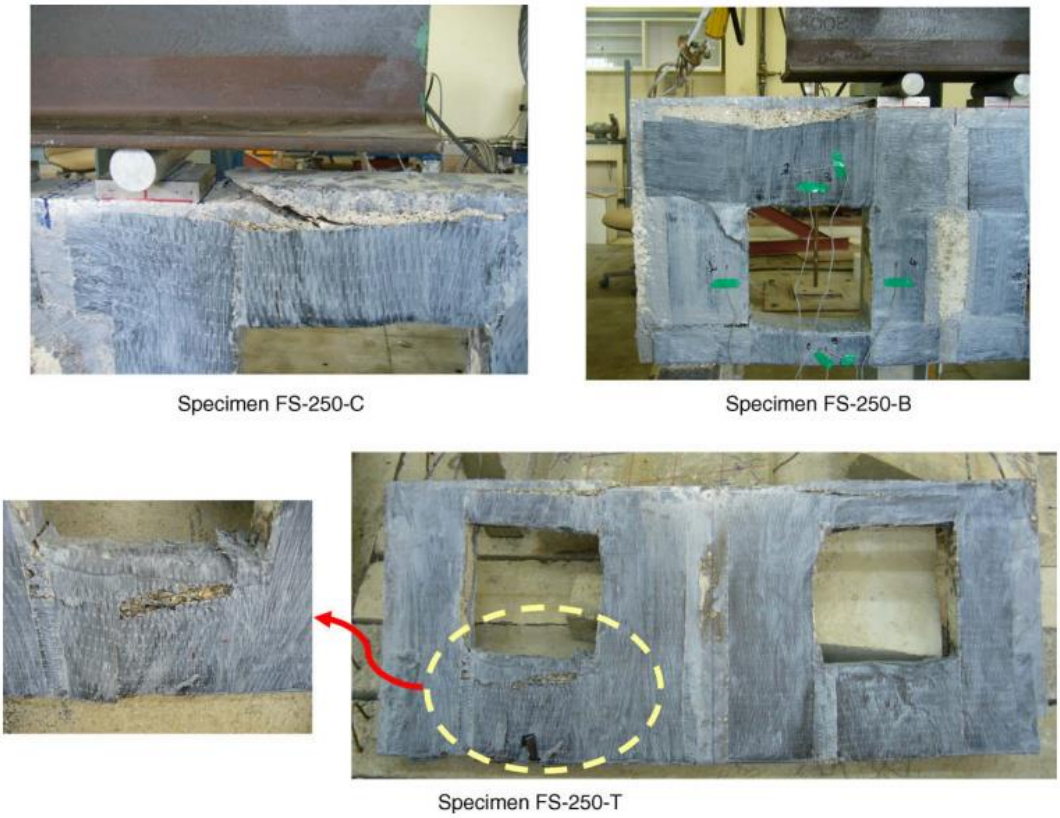
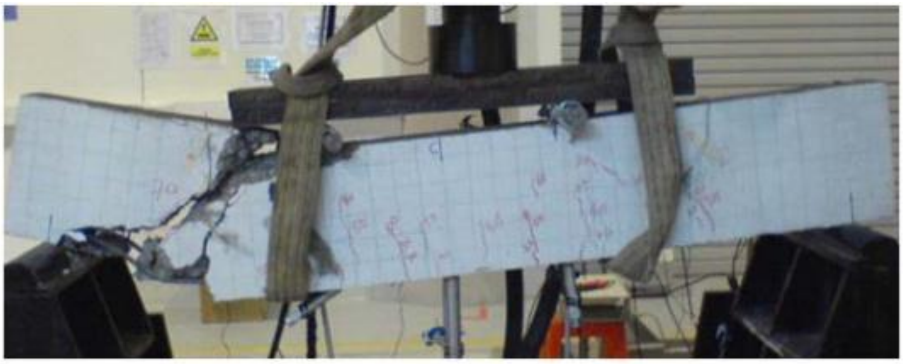


Figure 2.13: Failure modes of the CFRP-strengthened beams observed by El Maaddawy and Sherif

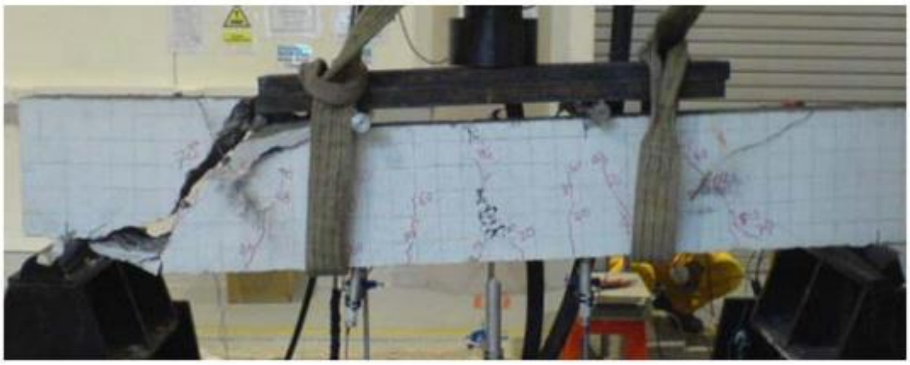
Source: El Maaddawy and Sherif (2009)

Pimanmas (2010) strengthened 13 RC beams with openings in square and circular shape by FRP rods. The cross section and reinforcement arrangements of all beams were constant. The inclusion of openings in RC beams obviously brought down the shear capacity of the beam. The failure mode changed from yielding of flexural to brittle shear failure. In his experimental studied, two performances of different configurations of strengthening were evaluated, one of which was placed the FRP rods enclosed the opening area while the rest was placed FRP rod diagonally throughout the entire beam depth. Since it was found that placed the FRP rods around the opening simply was not effective because a diagonal crack propagated through the beam with the path of crack diverted to abstain intersection with the FRP rod. A significant improvement in terms ductility of loading capacity was achieved when FRP rods were placed throughout the entire depth of beam, which is actually quite similar to the internal strengthening by reinforcement bars.

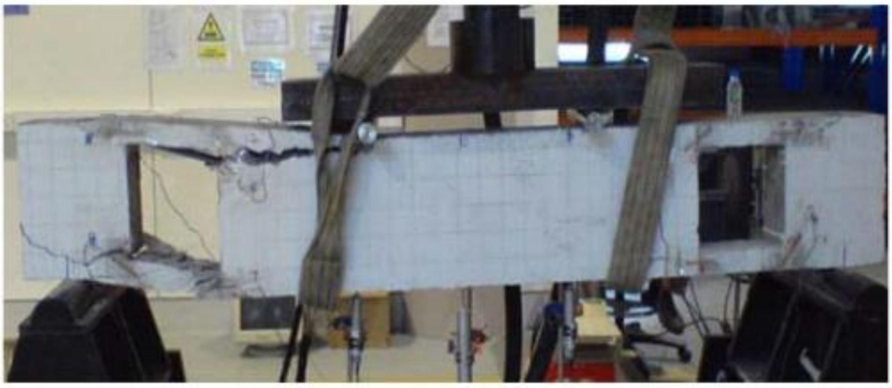
In 2012, Chin *et al.* tested 6 reinforced concrete beams with large square opening placed in the shear region, at a distance 0.5d and 0d away from the support, strengthened by CFRP laminates. The inclusion of openings in the shear region resulted a great reduced in the beam capacity, which approximately in the range of 69 – 74 %. The control beams were failed in shear mode as observed. The diagonal constituted at the corners of openings and leads to yielding reinforcement eventually as well as concrete cover crushed.



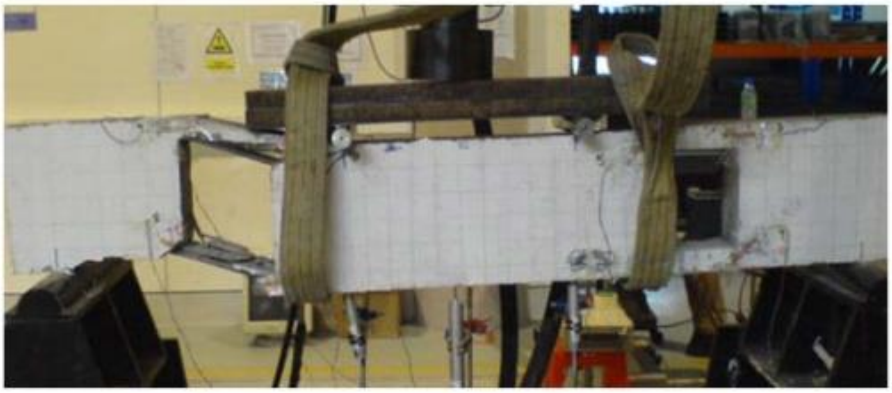
(a) B1



(b) B2



(c) B3



(d) B4

Figure 2.14: Crack pattern and failure mode of control beam and un-strengthened beams observed by Chin *et al.*

Source: Chin *et al.* (2012)

The implemented strengthening configurations were full wrapping system around the openings. The presence of CFRP laminates effectively disrupted the path of crack propagation which required a higher energy to distract the cracks into flexural cracks along the mid-span. The beam strength re-gain respectively to approximately 54% of the original structural capacity of beams.

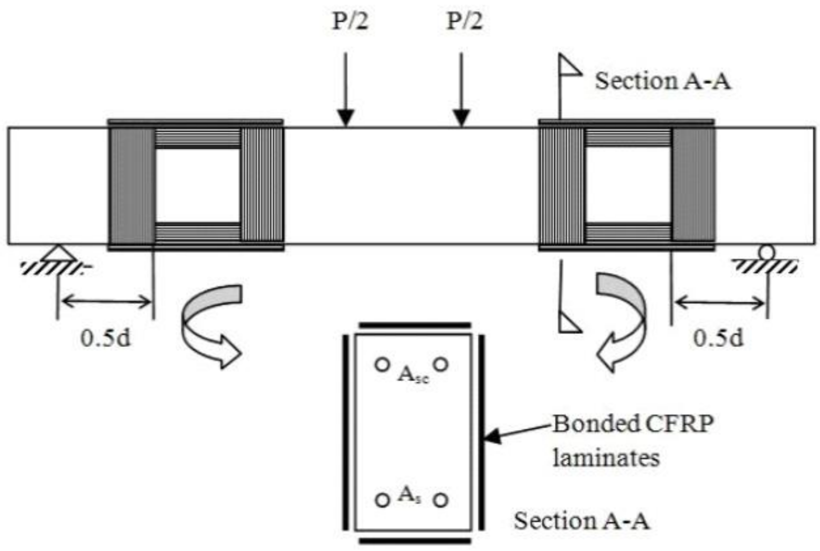
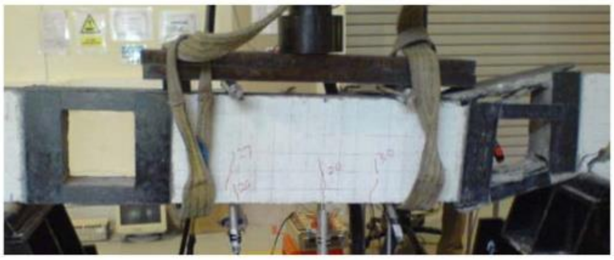
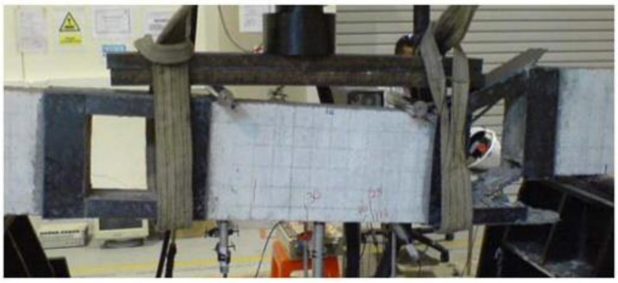


Figure 2.15: CFRP strengthening configuration by Chin *et al.*

Source: Chin *et al.* (2012)



(a) B5



(b) B6

Figure 2.16: Crack patterns and failure mode of strengthened beams by Chin *et al.*

Source: Chin *et al.* (2012)

El Maaddawy and El-Ariss (2012) tested 16 reinforced concrete beams with web opening strengthened in shear using externally bonded carbon fiber reinforced polymer (CFRP) composite sheets. This experimental studied focused on the shear behaviour of RC beams with shear span to beam depth ratio, a/h = 2. All the specimens had the same geometry as well as longitudinal top and bottom reinforcement. A square or rectangular opening was considered and took place in the middle of the short span. The web reinforcements were not allowed in order to resemble the case of the presence of an opening in an existing beam which would typically result in cutting the internal web reinforcement around the opening. The test parameters were the depth and width of the opening and the amount of the CFRP sheets used. The test results were indicated the presence of web openings greatly reduced the beam shear capacity and stiffness. The average reduction in the shear capacity of the beams was recorded for approximately 72% with a premature failure mode at the corners of the opening. While the shear capacity reduction was falling in the range of 44-58% for the beams with the shear failure mode in the chords.

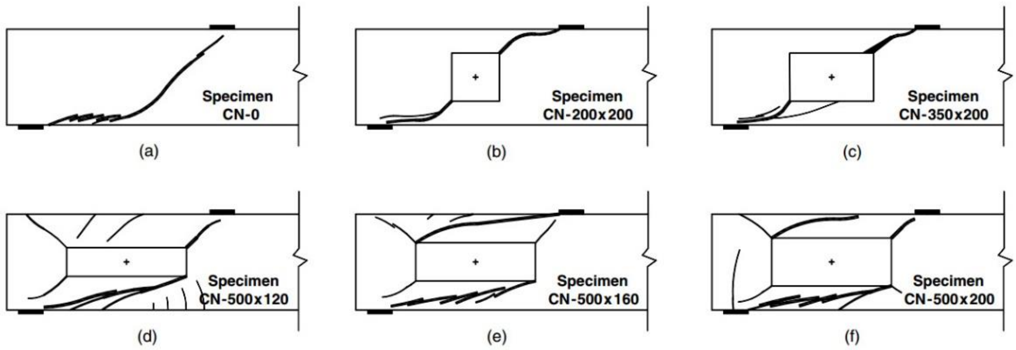


Figure 2.17: Crack pattern at failure for un-strengthened beams observed by El-maaddawy & El-ariss

Source: El-maaddawy & El-ariss (2012)

Two CFRP regimes were used for shear strengthening around the opening. Regime 1 included one layer of vertical strengthening with fibers oriented in a direction perpendicular to the longitudinal axis of the beam and horizontal strengthening with fibers oriented in a direction parallel to the longitudinal axis of the beam. While regime 2 is similar to Regime 1 but consisted two layers of vertical and one layer of horizontal CFRP strengthening. The U-shaped CFRP sheets were provided at the both sides, bottom and top chords of the opening. The vertical CFRP sheets were wrapped fully around the bottom chord below the opening with an overlap at the top face of the chord. Other than that, each side of the opening was wrapped with additional U-shaped CFRP sheets to limit the growth of any diagonal cracks that might originate at the corners of the opening. Increasing the opening size resulted reduction re-gains shear capacity caused by CFRP. The amount of the vertical CFRP sheets were doubling from one to two layers showed the enhancement of shear capacity, but the shear capacity gained was not in proportion to the added amount of CFRP. In additional, the horizontal CFRP sheets were not anticipated to contribute to the shear resistance of the chords significantly, but they were needed to assist in restriction of the growth and spreading of diagonal cracks at the corners of the opening. They were also acting as a flexural reinforcement for the chords which reducing flexural failure of the chords. The shear resistance was improved by pasting the vertical CFRP sheets in the chords.

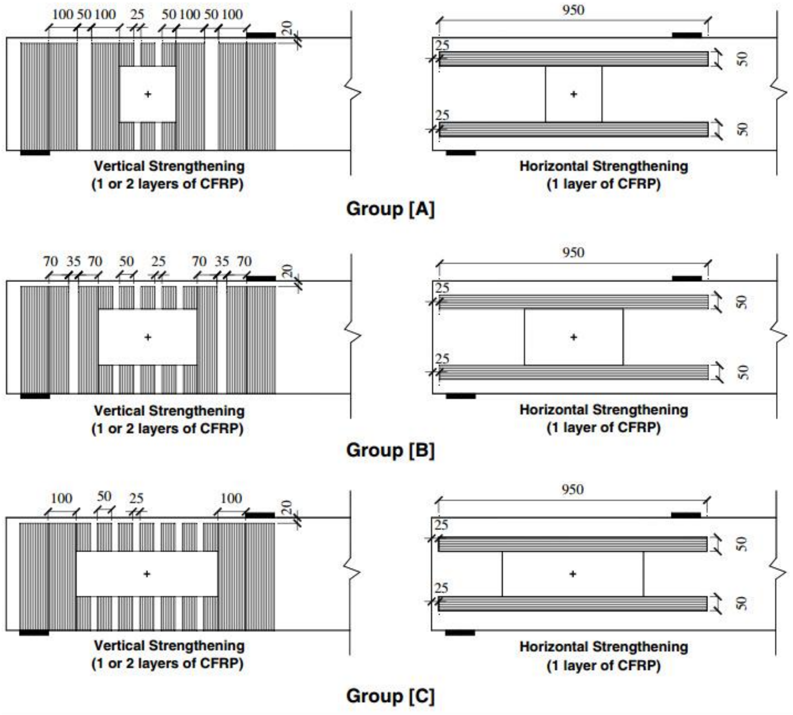


Figure 2.18: Layout of the CFRP-shear strengthening by El-maaddawy & El-ariss

Source: El-maaddawy & El-ariss (2012)

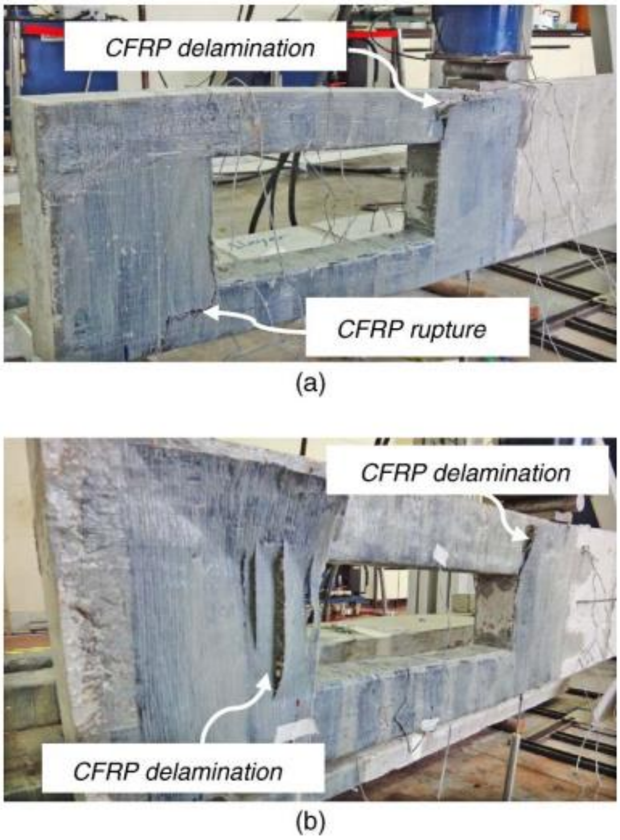


Figure 2.19: Photos of specimens strengthened with CFRP regime 1 at failure observed by El-maaddawy & El-ariss

Source: El-maaddawy & El-ariss (2012)

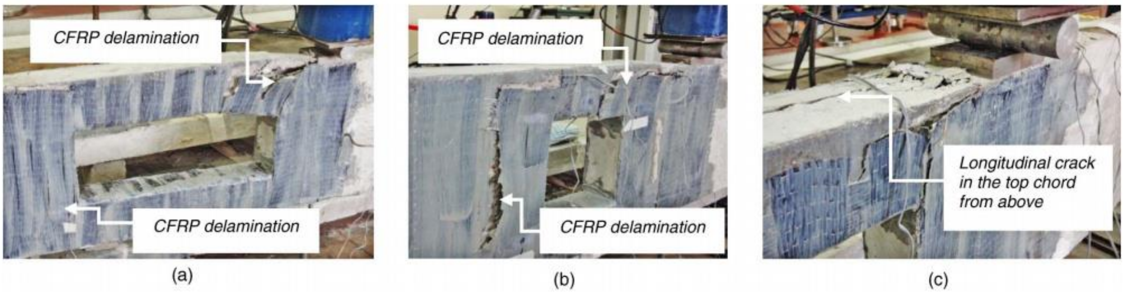


Figure 2.20: Photos of specimens strengthened with CFRP regime 2 at failure by El-maaddawy & El-ariss

Source: El-maaddawy & El-ariss (2012)

Lately, Ban & Abduljalil (2014) had investigated shear resistance of 8 RC deep beams with rectangular openings strengthened with CFRP strips. The test variables focused on this experimental studied were the effect of fiber orientation, either 90 °or 45 ° CFRP strips about the longitudinal axis of the beam, the influence of using vertical and longitudinal CFRP strips as well as the effect of anchoring the vertical CFRP strips. In order to avoid the failure of bonding and limited anchoring length available, the CFRP was wrapped or anchored. The applied load was directly transferred from loading nose to support nose along the load path for the solid deep beam. On the other hands, the deep beams with openings was interrupted the load path lead to reduction of shear carrying capacity.

Based on their experimental results, the RC deep beam included openings strengthened with 45 °CFRP strips contributed higher ultimate load and cracking load as compared to strengthened with 90 ° CFRP strips, the increase was approximately up to 25% and 18.8%. This is because the inclined web reinforcement in deep beam effectively prevented the growth of diagonal cracks, thus the failure of diagonal cracking could not exist. The combination of applying the longitudinal CFRP strips followed by 90 °CFRP strips lead to an increase in terms of cracking and ultimate load by 5% and 24.6% separately. On the other hands, combination of applying the longitudinal CFRP strips followed by 45 ° also recorded an additional increment in cracking load of 8% and ultimate load of 40.2% respectively. The strengthening scheme of 45 °CFRP strips with extra longitudinal CFRP strips is more efficient in improving the shear resistance as compared with 90 °CFRP strips with longitudinal strips in the RC deep beam.

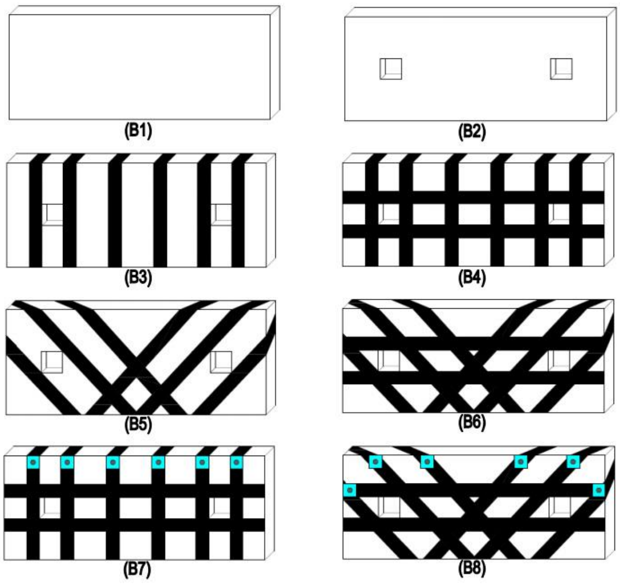


Figure 2.21: Strengthening scheme of the tested beams by Ban & Abduljalil

Source: Ban & Abduljalil (2014)

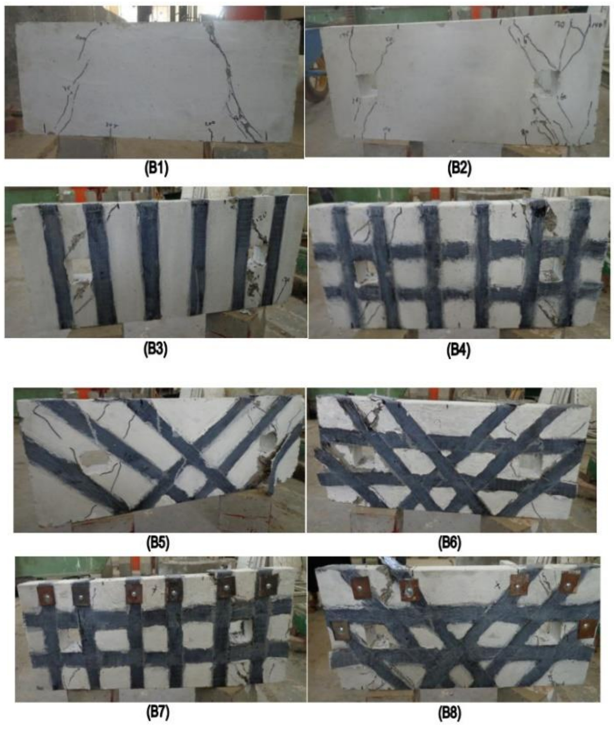


Figure 2.22: Modes of failure of the tested beams observed by Ban & Abduljalil

Source: Ban & Abduljalil (2014)

The arrangement of CFRP strips in longitudinal direction and wrapped with transverse CFRP strips (90 °or 45 °strips) significantly not only enhanced the strength of cracking, but increased both ultimate strength and post-cracking deflection as well as decreased the maximum crack width. The effect of anchoring CFRP strips on the behaviour of deep beams with opening was recorded an increment of the contribution to the ultimate shear resistance of deep beam with opening by 10.3 % for 45 °CFRP strips and 25.6 % for 90 ° CFRP strips. Hence, the experimental result concluded that the externally CFRP strips increased the ultimate shear capacity significantly, restrict the crack width of shear, and improved the stiffness of deep beams included openings.

Hussain and Pinanmas (2014) were conducted an extensive research about shear strengthening on RC deep beams included openings using externally Sprayed Glass Fiber Reinforced Polymer (SGFRP) composites. In contrast to typical externally bonded uni-directional FRPs, SGFRP considered as a new technique has been applied in this experimental studied to strengthen the structural member. The research parameters consisted shape, width and depth of the openings, varied thickness and configurations of SGFRP as well as concrete strength. Different sizes of square and circular openings were investigated. They had tested 29 RC deep beams with varied shapes and sizes of web openings under a three-point loading scheme.

According to the previous results of the experimental studied, RC deep beams improved by SGFRP may fail due to de-bonding of the fibers from the substrate surface. Hence, the mechanical anchoring system has been implemented to attach the SGFRP to the beam surface securely in order to avoid such failures. On the other hand, the combination of SGFRP technique and sufficient MB anchoring system was revealed to be an effective means to upgrade the shear strength of RC beams with openings. It was indicated by the failure mode was changed from de-bonding to inclined crack rupture in the fibers.

The beams were ungraded with three SGFRP thickness, which are 3 mm, 5 mm, 7 mm and three strengthening configurations. For strengthening configuration A, the SGFRP was pasted onto side faces of the specimen only; for strengthening configuration B, SGFRP was applied onto both side and bottom faces in the form of U-shaped.

Strengthening configuration C was similar to configuration A, except the SGFRP thickness was increased at the top and bottom edges and around the openings of beams. The performance of the U-shaped SGFRP strengthening bonds onto the bottom faces and side of the specimens was superior compared to strengthening on side faces only. Other than that, the effectiveness of SGFRP strengthening and the MB anchoring system found was lower in concrete with high strength beams than in concrete with low strength beams. The experimental results also showed the increased in the thickness of SGFRP lead to a higher increased in the shear strength and ultimate load of RC beams with opening.

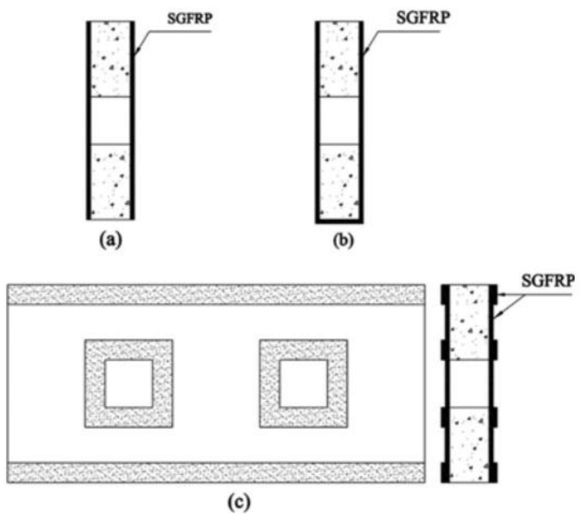


Figure 2.23: SGFRP strengthening configurations by Ban & Abduljalil

Source: Ban & Abduljalil (2014)

Figure 2.24: Failure mode of SGFRP strengthened beam specimen observed by Ban & Abduljalil

Source: Ban & Abduljalil (2014)

2.6 SUMMARY

By reviewing the detail of the past researches, gaps have been identified. To date, rarely research has looked into the large openings in rectangular shape implemented at 0d as well as lack of the information on openings erected in the latter case. Even though there are numerous extensive theoretical studies and experimental studies have been done regarding RC beams with rectangular openings at shear region. But there is still scarce of clear and proper design requirements and most of the codes such as Euro code and ACI318-08 do not provide solid guidance regarding the shear strength prediction of RC deep beams with openings and updated with CFRP wraps. There is also short of specific guidelines for the shear strength prediction of RC deep beams with openings strengthened with CFRP wraps.

Therefore, this opportunity has been taken to contribute the guideline for structural engineers to apply in problems with structural strengthening and rehabilitation of RC deep beams with large openings especially at shear region.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

In order to achieve the objectives of this research, the experimental works of research were conducted and presented in chapter. The experimental procedures included the preparation of specimens, casting and curing process, preparation and application of Carbon Fiber Reinforced Polymer (CFRP). All the details were elaborated in the following sections. Figure 3.1 presents the flowchart of the overall experimental works in this study.

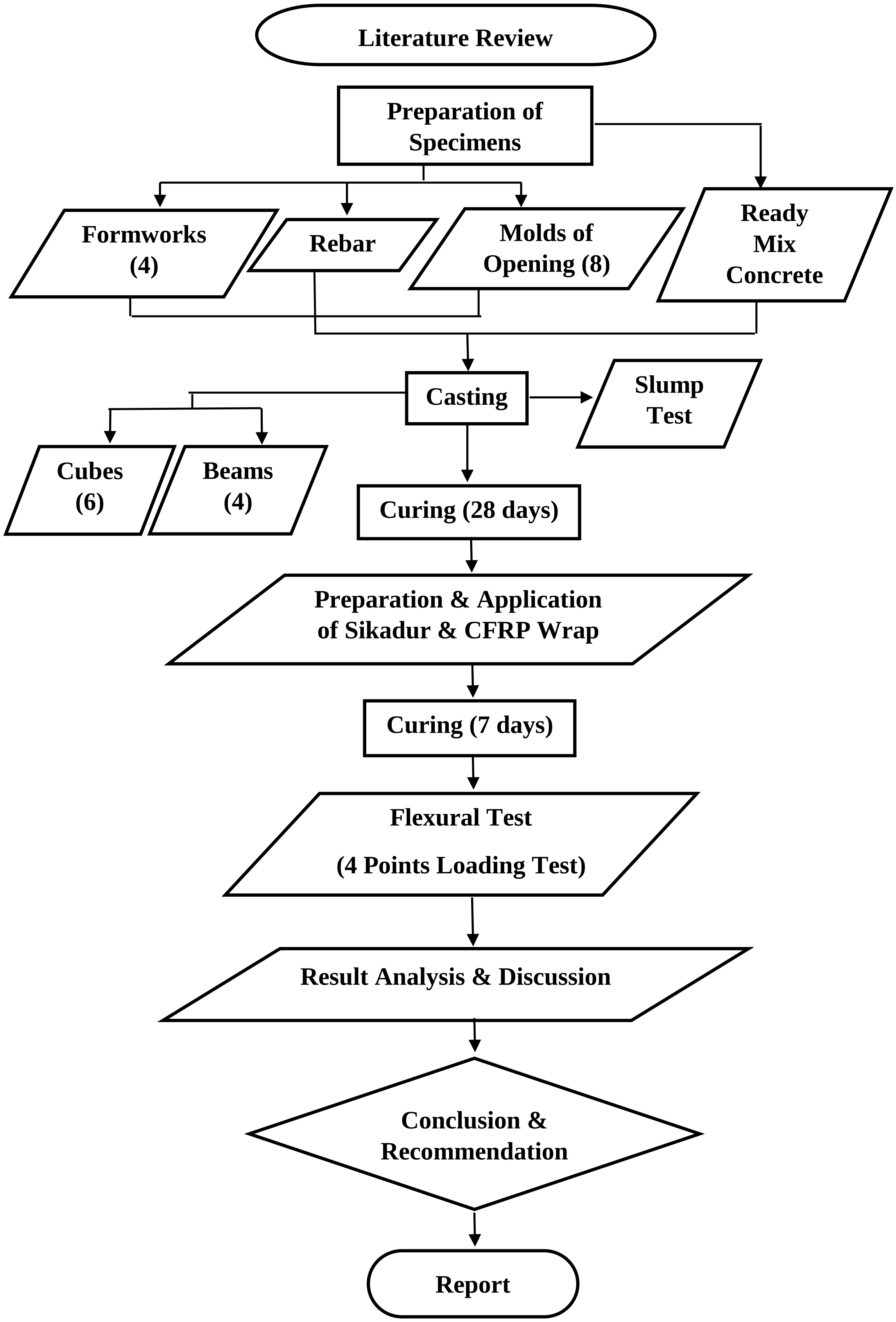


Figure 3.1: Flow chart

3.2 PREPARATION OF SPECIMENS

All the preparatory works of specimen materials were conducted in Laboratory of FKASA.

3.2.1 Formwork

The traditional timber formwork was chosen by considering the economic criteria, lightweight and available sources in the FKASA laboratory. The main function of the formwork is allowing the reinforcement bar to fit in and withstand the weight of fresh concrete. The formworks are made by a combination of plywood act as concrete shuttering panels and wooden planks as an outside shutter. The quality of the plywood and wooden planks always been checked before cut into required shape and dimensions in order to prevent the formation of rough concrete surface and unwanted wastage. All the beams were cast simultaneously, a total of 4 timber formworks were assembled horizontally with an approximately constant length of 2530 mm and a rectangular section of 730 x 120 mm. The release agent (mould oil) was applied on the inner surface of the formwork in order to prevent the adhesion of concrete after hardened and ease for the formwork to be disassemble.

Figure 3.2: Formwork of beam specimen

3.2.2 Reinforcement

The reinforcement bars consist in this experimental study were ribbed steel bars and ligatures. The longitudinal steel reinforcement was deformed steel bar with nominal yield strength of 410 MPa while the web reinforcement was mild steel with nominal yield strength of 275 MPa. All the RC deep beams had the same compression and tension steel reinforcement. The compression steel reinforcement was made up by two 10 mm of diameter, each having a nominal cross section area of A = 78.6 mm^2. While the tension steel reinforcement consisted two 16 mm of diameter ribbed steel bars, each having a nominal cross section area of A = 201 mm^2. Only the solid beam consists both longitudinal and horizontal steel stirrups of 6 mm diameter with spacing 150 mm centre to centre along the beam length and depth. Ligatures were used to form footing cages and provide shear reinforcement in concrete beams. While no web reinforcement in longitudinal and vertical direction were provided in the test zone to resemble for the case of the inclusion of openings in existing RC deep beams.

The badly corroded or damaged steel is not allowed to use for reinforcement work because it may lead to structural failure. The number of bars were cut and bent into required dimension and shape by using the bending and cutting machine according to the length and shape which are specified in the draft prior tying. Individual reinforcing bars were tied together at the intersection between link and rebar to form the reinforcement cage by using tying wire. Additionally, the clear cover of 20 mm was maintained at the bottom, top and vertical sides of the beam. The spacer blocks were cast in advanced according to the required dimension so that can provide a sufficient distance for the reinforcement bar to prevent the steel rust. The adequate number of spacer blocks were inserted at the proper position to support the weight of reinforcement bar and fresh concrete loads without any breaking.

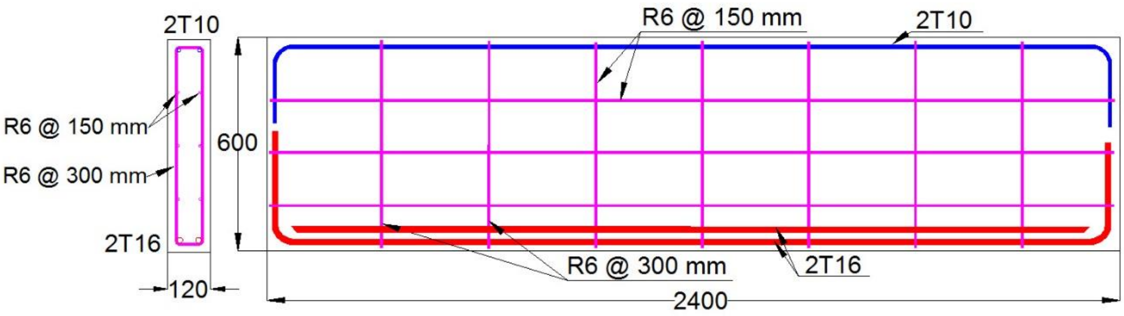


Figure 3.3: Arrangement of reinforcement bar of solid deep beam

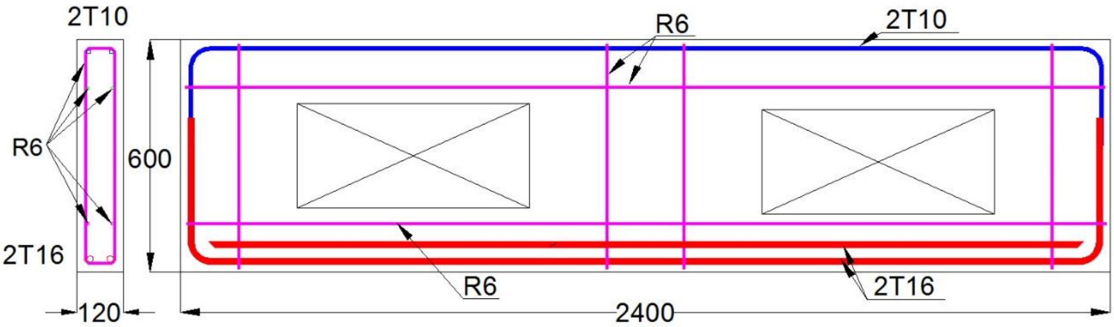


Figure 3.4: Arrangement of reinforcement bar of deep beam with openings

3.2.3 Concrete

The concrete used was high strength ready mixed concrete designed for 28 days with compressive strength of 35 N/mm^2. Ready mixed concrete ordered and supplied from the Hanson Building Materials Malaysia. The water cement ratio was 0.54. The coarse aggregate was 20 mm granite crushed aggregates. Fine sand as fine aggregate was used. Before the concreting is proceeding, the proposed design mix of 35MPa grades of concrete was submitted by the concrete supplier for approval in advanced.

3.2.4 Mould of Opening

Polystyrene sheets served as the materials to create and hold the opening area. They were cut into demanded size and shape. One of the advantages of using polystyrene to create an opening is it offered zero bonding with concrete surfaces during curing. Hence, it can be removed easily compared with the timber mould.

Figure 3.5: Mould of opening

3.3 CASTING AND CURING

Before the concrete placement took place, all the necessary inspections of the formwork and reinforcement have been done without any comments. The stability and rigidity of the formwork are to ensure to withstand the weight of fresh concrete, vibration of the vibrator and prevent the concrete wastage. The formworks were also cleaned to ensure free from and debris. Besides that, all the relevant equipment and tools for handling concrete placement were concerned. The grade and amount of the concrete which stated in delivery order has been checked when the concrete is arrived. The slump test and sampling of the 12 cubes with the standard dimension mould of 150 mm x 150 mm x 150 mm has been done in advanced.

Figure 3.6: Sampling of cubes and slump test

All the beams were cast flatwise simultaneously. The concrete started to be placed at the corner of the formwork first. After that, concrete vibrating took place immediately as the concrete was placed on the formworks. Vibrators were inserted and withdrawn vertically within 5 seconds up to 30 seconds in order to avoid the over vibrating. The head of the vibrator was penetrated through the top layer and partially through the layer underneath. Over vibrating will force the finer aggregates move to the top and drives the larger aggregates toward the bottom which led to the segregation, but under-consolidation is more common. In order to achieve the smooth surface and great concrete strength, the contact between the formwork and vibrator was avoided as it may loosen the formworks and cause the honeycomb. Other than that, the contact between the vibrator and reinforcement bar was avoided too so that the bond between the bar and concrete is not broken.

After the concrete has been poured on the formwork, it was cured properly to develop the good final properties. The formworks of 4 beams were unmoulded after 24 hours of pouring. The surfaces of concretes were wrapped by wet gunny bags which was wetted periodically. This process was repeated continuously for 28 days in order to achieve its ultimate strength. After 28 days of moist curing, the beams were washed and smoothing on surface before the application of CFRP wraps. The 9 concrete cubes were also unmoulded after 24 hours of pouring before put into the water tank.

Figure 3.7: Curing process

3.4 CFRP STRENGTHENING SYSTEM

3.4.1 Sikadur® 330 Epoxy Laminating Resin

Sikadur®-330 was implemented in this experimental study to provide structural adhesive for bonding between CFRP wraps and concrete even surfaces. Sikadur®-330 were supplied by the factory proportioned units comprising the proper amount. According to the product data sheet that provided by Sika, Sikadur®-330 is a combination of 2 part thixotropic epoxy based impregnating resin or adhesive. It offers an excellent characteristics such as contribute a strong adhesion, high mechanical properties and required no separated primer. Other than that, It is easy to mix and apply by using a trowel and impregnation roller.

Sikadur®-330 has categorized into two parts, which is resin part A of white in colour and hardener part B in grey colour. Part A and B each consist 24 kg pails and 6 kg pails. Both of the packages were stored properly in original unopened, unseal and undamaged in dry conditions at temperatures between +5 ℃ and +25 ℃. The process of mixing Sikadur®-330 Comp A and Sikadur®-330 Comp B were conducted in accordance to Material Safety Data Sheets and product data sheet which provided by Sika.

Table 3.1: Mechanical properties of Sikadur®-330 epoxy laminating resin

Sikadur®-330 Mechanical Property	Value
Tensile Strength	30 N/mm^2 (7 days at +23 ℃)
Flexural Modulus of Elasticity	3800 N/mm^2 (7 days at +23 ℃)
Tensile Modulus of Elasticity	4500 N/mm^2 (7 days at +23 ℃)
Elongation at break	0.9% (7 days at +23 ℃)

Figure 3.8: Sikadur®-330 Comp A and Sikadur®-330 Comp B

3.4.2 Sikawrap-231C Carbon Fiber Fabric

Sikawrap-231C were used as the externally bonded composite material of strengthening the shear openings of RC deep beams. It is a unidirectional (0 °) woven carbon fiber fabric for the both dry and wet application process. The CFRP wraps were shaped in the form of roll in width and length of 500 mm and 1000 mm. The mechanical properties of the CFRP wraps were illustrated in Table 1.

Table 3.2: Mechanical properties of Sikawrap-231C carbon fiber fabric

Properties	Value
Weight	230 $g/m^2 \pm 12 \ g/m^2$
Wrap Design Thickness	0.127 mm
Tensile Strength	4900 N/mm^2
Tensile Modulus of Elasticity	230 000 N/mm^2
Elongation at break	2.1 %

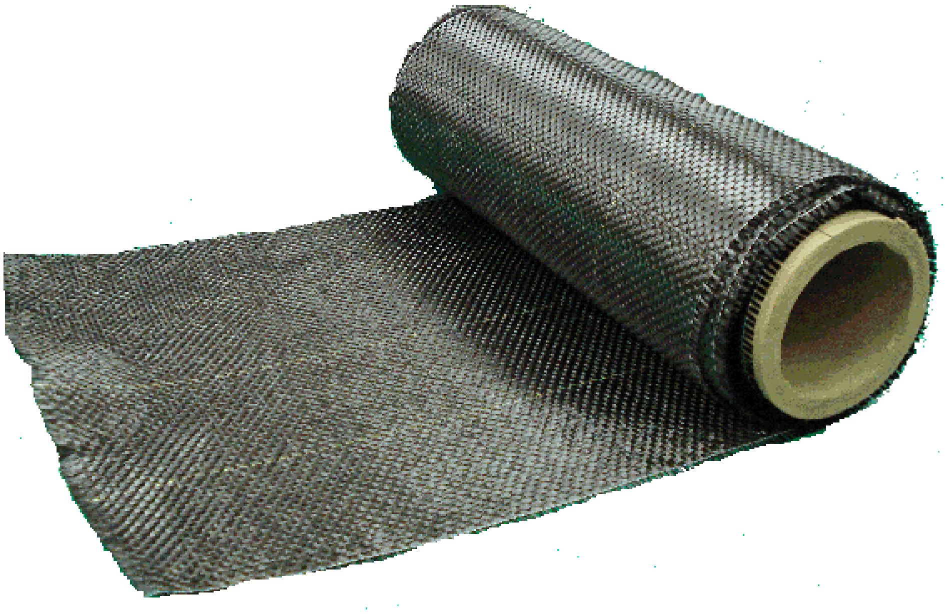


Figure 3.9: Sikawrap-231C carbon fiber fabric

3.4.3 Strengthening Configurations

The CFRP scheme used as external shear strengthening is shown schematically in Figure 3.10. It is essential for the CFRP wraps to intercept the potential shear crack, thus they can effectively dedicate to the shear strength of the beam. The longitudinal CFRP wraps were pasted to the concrete surfaces, at the top and bottom chords of the openings, in which the CFRP fibers were oriented parallel to the beam longitudinal axis. Two different CFRP configurations were installed for shear strengthening around the openings. The CFRP configuration 1 consists of one layer of 900 mm horizontal strengthening bonded at the top and bottom chords of the opening in one side with fibers oriented parallel to the beam longitudinal axis. While the CFRP configuration 2 is similar to CFRP configuration 1 but both sides of the beam were applied with the horizontal strengthening at the top and bottom chords of the openings as well as bottom soffit bonded to CFRP wraps which form a U-shaped CFRP system.

Table 3.3: Details of beam specimens

<table>
<tr><th rowspan="2">Beam</th><th colspan="3">Opening</th><th rowspan="2" colspan="2">Strengthening Method</th></tr>
<tr><th>Shape</th><th>Size (mm)</th><th>Location</th></tr>
<tr><td>CB</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>US-BRO</td><td rowspan="3">Rectangular</td><td rowspan="3">270 x 600</td><td rowspan="3">Middle of shear span</td><td>-</td><td>-</td></tr>
<tr><td>S-BRO-1</td><td colspan="2">U-shaped wrapping</td></tr>
<tr><td>S-BRO-2</td><td colspan="2">Surface wrapping</td></tr>
</table>

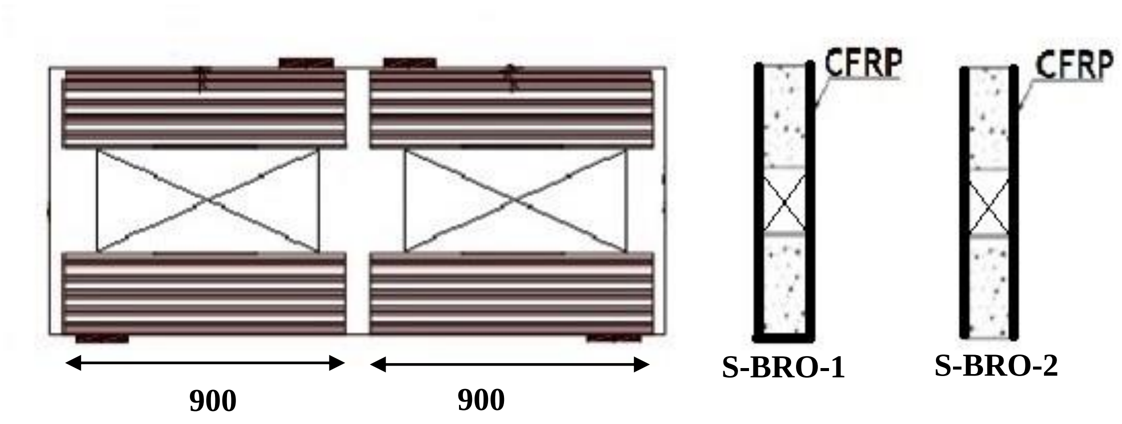


Figure 3.10: Details of CFRP strengthening configuration (value in mm)

3.4.4 CFRP Strengthening Procedure

The procedure of strengthening of CFRP wrap:

i. The CFRP wraps ware cut into demand size by using a razor knife and scissors.
ii. The concrete substrates were levelled and polished using a grinder and polish machine.
iii. The dust, loose particles and laitance, and any other contaminants were cleaned using wet clothes afterward.
iv. The resin part A and hardener part B were mixed with a ratio of 4:1 according to the required weight accurately.
v. Parts A+B were mixed together manually for approximately 3 minutes until the material became smooth in consistency and a uniform grey colour was appeared.
vi. The well mixed Sikadur®-330 were directly applied to the prepared substrate and CFRP wraps.
vii. The CFRP wraps, which pre-cut to the desired dimensions, were then placed onto the resin coating in the assigned orientation and location.
viii. Pressure was applied with plastic roller until the resin was squeezed out evenly from the CFRP wraps.

ix. The specimens were stored properly for curing and bonding at least 7 days before the testing.

Figure 3.11: Polishing concrete surfaces using polish machine

Figure 3.12: Weighing and mixing resin part A and hardener part B with a ratio of 4:1 according to the required weight

Figure 3.13: CFRP wraps strengthening of RC deep beam with openings

3.5 LABORATORY TESTING

All the laboratory testing were conducted at 2 different places. The fresh and hardened concrete were undergoes slump and compression test in the FKASA Laboratory. The beam with un-strengthened openings and CFRP surface wrapping were undergoes 4-point loading test using Magnus Frame at FKASA laboratory as well. While only the RC solid deep beam and beam with U-shaped CFRP wrapping were conducted at UITM Sham Alam Concrete and Structure Laboratory due the technical error and malfunction of Magnus Frame afterward.

3.5.1 Slump Test

The slump test was conducted and observed during concrete pouring in accordance to reference standard, BS 1881: Part 102 (1983). The workability and consistency of the fresh concrete were determined and measured in this laboratory testing. The relevant instrument are slump cone, base plate and tamping rod.

3.5.2 Compression Test

The concrete compression test as known as cube test was conducted in accordance to the reference standard, BS 1881: Part 116 (1983). The compressive strength test machine is the only instrument that was used to check the quality and specified design characteristics compressive strength and ultimate strength of concrete mix supplied.

3.5.3 Flexural Test

The concrete flexural tests were conducted in order to examine the flexural strength of the beam specimens. The load-deflection curve and cracking pattern were determined throughout this destructive test.

3.5.3.1 Four Point Loading Test

The flexural strength test was conducted by using a Magnus Frame with a capacity in the range of 300 kN and 500 kN after 28-days the RC deep beams were fabricated. This test was conducted in accordance to the reference standard, BS EN 12390-5:2000. The flexural machine, Magnus frame comprises 2 support noses and 2 loading noses. The loading points were equally distant to the line of centres. A spreader beam was used to deliver the load to the beam specimens through two loading points 800 mm apart. The loads were applied monotonically in a direction of vertical downward till the failure and beam specimens could no longer bear additional load. A linear variable displacement transducer (LVDT) was mounted at the at the bottom soffit of the beam mid-span to determine the beam deflection. Besides that, two electrical resistance strain gauges (SG) were used to measure the strain of unstrengthen and solid beams throughout the test. Each of it were pasted in the middle of the top chord of the opening and load points, which oriented perpendicular to the predicted propagation of cracks. The strain gauges and LVDT that attached to the tested beams were connected to data logger to obtain concrete strains and deflection respectively at during the entire testing period. The propagation and development of cracks were marked whereas the failure mode was recorded.

Figure 3.14: Beam testing setup

CHAPTER 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

During the tests, the crack patterns and width were observed, as well as the applied loads and deflection, were recorded along with the strain gauges and linear variable displacement transducer at proposed locations at each increment of loading up to the failure. The results of the RC solid deep beam are compared to the beams with un-strengthened or strengthened openings for the comparison purposes. The observation of the beam specimens during and after the tests as well as the detailed discussions are presented in this chapter.

4.2 SLUMP

From the observation of Figure 4.1, the slump result obtained was as a true slump, which recorded at a height of 80 mm. A true slump is an indication of high workability mixes. Hence the concrete quality is acceptable.

Figure 4.1: Slump test

4.3 COMPRESSION STRENGTH

The 12 cubes were divided equally and tested in 4 different days, which are 3, 4, 7, 14 and 28 days. The main focus of this test is to examine the compressive strength of concrete cubes at 7 and 28 days after it has been cast. The minimum compressive strength need to be achieved for a concrete grade of 35 N/mm^2 at 7 days is 23.5 N/mm^2. According to the results obtained that shown in Table 4.1, in all the cases, it can be concluded that the mean compressive strength of the cubes was achieved after 7 days at 37.513 N/mm^2. In addition, the mean compressive strength is over-achieved at days 14 and 28 days are recorded at 45.256 N/mm^2 and 45.537 N/mm^2 respectively.

Figure 4.2: Compression test

Table 4.1: Result of compressive strength test

Sample	Weight (kg)	Sample Age (days)	Load (kN)	Compressive Strength (N/mm^2)	Average Compressive Strength (N/mm^2)
C1	7.80	3	663.683	29.497	
C2	7.85	3	679.161	30.185	29.390
C3	7.75	3	640.979	28.488	
C4	8.05	7	831.323	36.948	
C5	7.75	7	785.688	34.919	37.513
C6	7.90	7	915.101	40.671	
C7	7.90	14	980.365	43.572	
C8	7.75	14	930.902	41.373	45.256
C9	7.85	14	959.233	42.633	
C10	7.85	28	975.129	43.339	
C11	7.85	28	972.043	43.202	43.537
C12	7.95	28	991.585	44.070	

The Figure 4.3 illustrated the development of average compressive strength versus sample age for 12 cubes. In the first 4 days, the graph shows a steep slope which indicated that the compressive strength of the cubes achieved high early strength. The rate of strength gain started to slow down after 4 days and the difference in terms of the strength gain between 7 and 28 days was about 6.024 N/mm^2 or approximately to 16%. The compressive strength reached a peak of 45.537 N/mm^2 at 28 days.

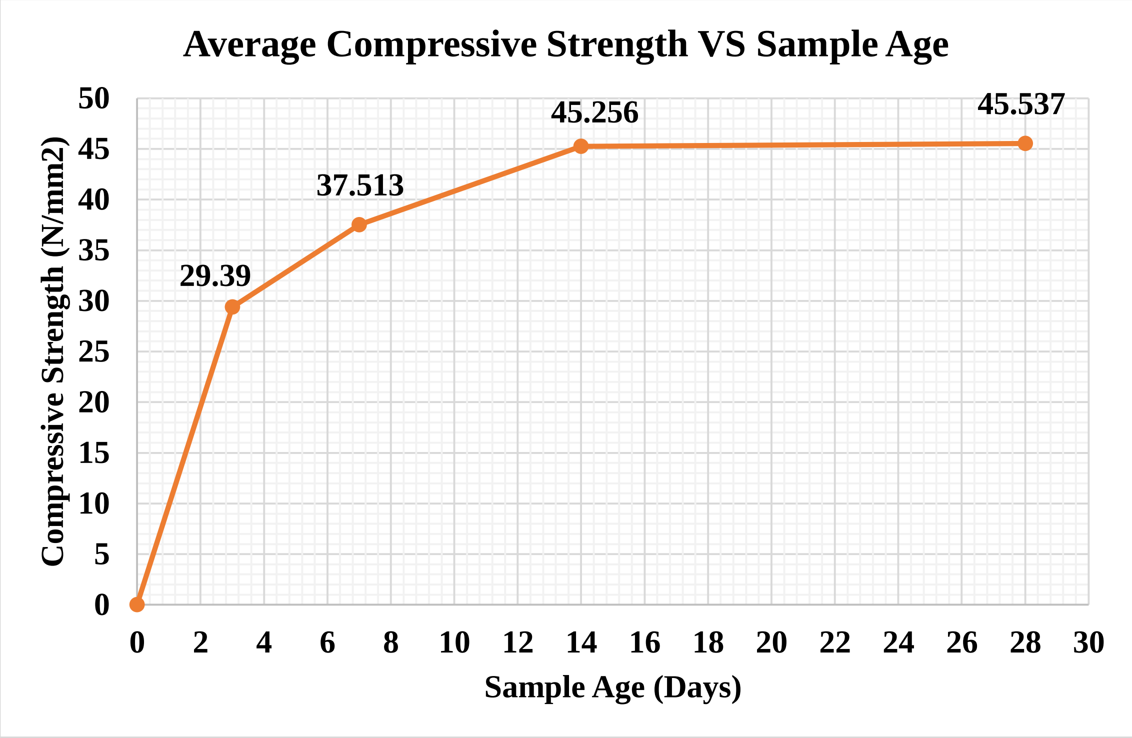


Figure 4.3: Graph of compressive strength versus days

4.4 LOAD AND DEFLECTION RESPONSE

The deflections were measured at the mid-span of the bottom of the beam specimens.

4.4.1 Control Beam (CB)

As can be seen in Figure 4.4, at the early stage, the graph showed a steady upward trend in both load and deflection. When yielding has ended at a load level of 269.89 kN with a deflection of 7.08 mm, the applied load increased slightly, resulting in a curve that rises continuously until it reached the ultimate load at 425.12 kN with a deflection of 12.87 mm. Up to the ultimate load, the applied load was dropped quickly with the slowly increment of deflection in the strain hardening phase.

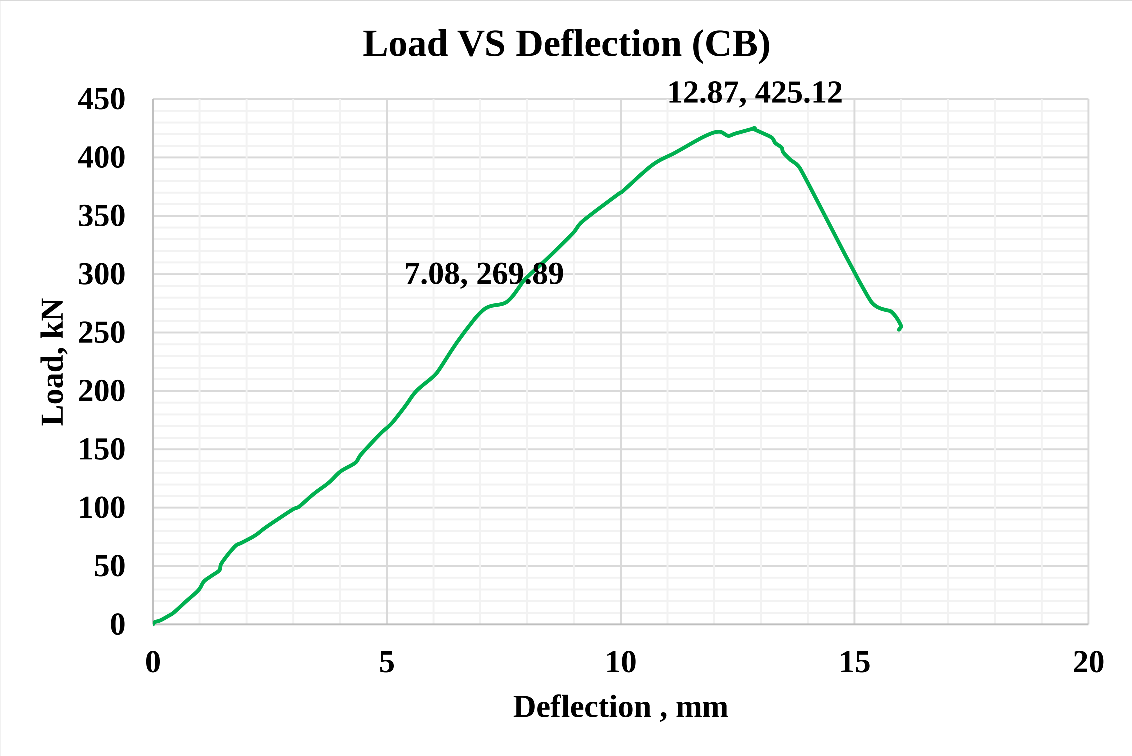


Figure 4.4: Load-deflection curve of beam CB

4.4.2 Beam with Un-strengthened Openings (US-BRO)

The load versus deflection graph of the beam is plotted in Figure 4.5. At the initial linear part of the graph, the curve has a very steep slope, which accords to the zero crack appeared in this region. The deflection is directly proportional to the applied load and the entire concrete section is considered in resisting the loads effectively. The end point of this linear part of the curve indicated the starting point of cracking in the beam at the load of 50.5 kN along with the deflection of 2 mm. After the yielding point, the graph shows a steady upward trend on both load and deflection which indicated that the deflection rate per unit load is much higher after the beam has cracked. This is also an indication of the stiffness reduction of the beam. The beam failed at the peak load of 128.69 kN along with a deflection of 10 mm. Beyond the ultimate load, the deflection of the beam was increasing appreciably with the load declined dramatically.

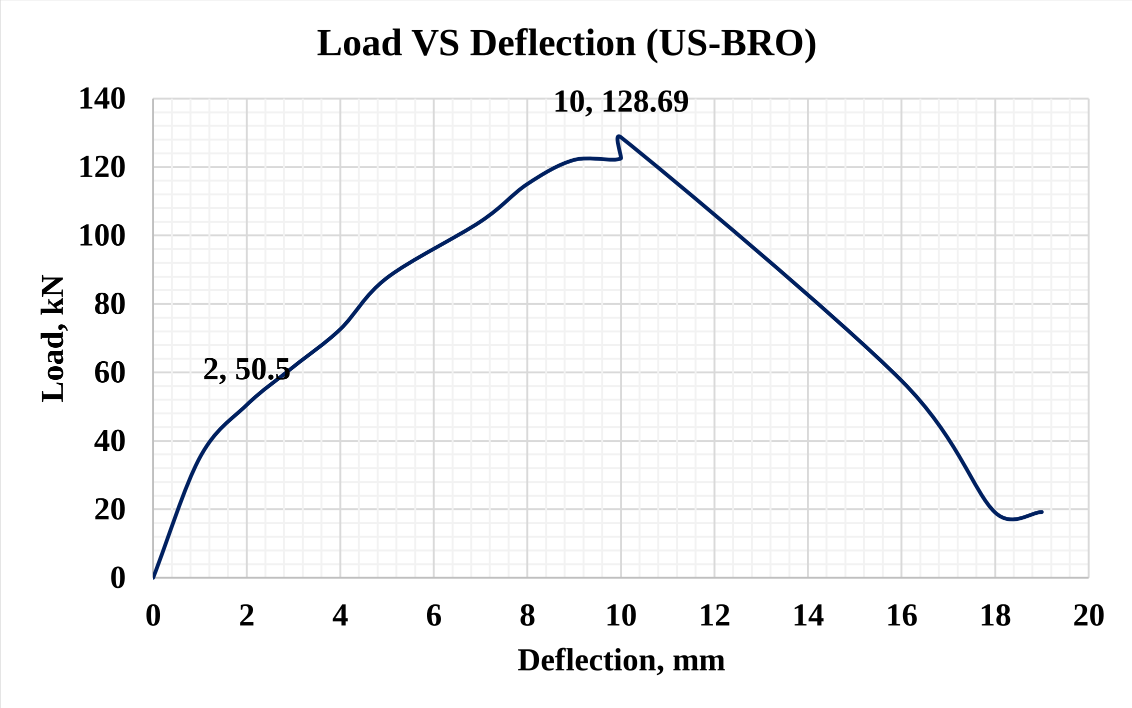


Figure 4.5: Load-deflection curve of beam US-BRO

4.4.3 Beam with U-shaped Strengthened Openings (S-BRO-1)

Figure 4.6 depicts a linear straight line in the very initial phase of testing. The load and deflection of the beam S-BRO-1 were linearly increased up to the yielding point at 28.48 kN with a deflection of 2.79 mm prior to the ultimate load of 174.38 kN after which, a non-linear behaviour was observed and continued until the failure. The mid-span deflection at the ultimate load was 14 mm. The load dropped gradually after the peak due to the delamination and peeling of the CFRP wraps. The loads were mainly carried by the flexural reinforcement individually after the bonding between the CFRP and the concrete has been reduced. The beam was, however, still able to undergo significant deflection without further increased in the load up to failure due to the confinement effect caused by the CFRP wraps. It can be also observed that after the ultimate loads drop to a certain level, the beams still remaining in a steady load reserve while the deflections continues increase, which indicated that the beams still maintain a certain degree of ductility even after the beams have already failed in shear. The slope of load-deflection curve fell slightly after the delamination and rupture of the CFRP wraps at the several opening corners and bottom chord of the opening.

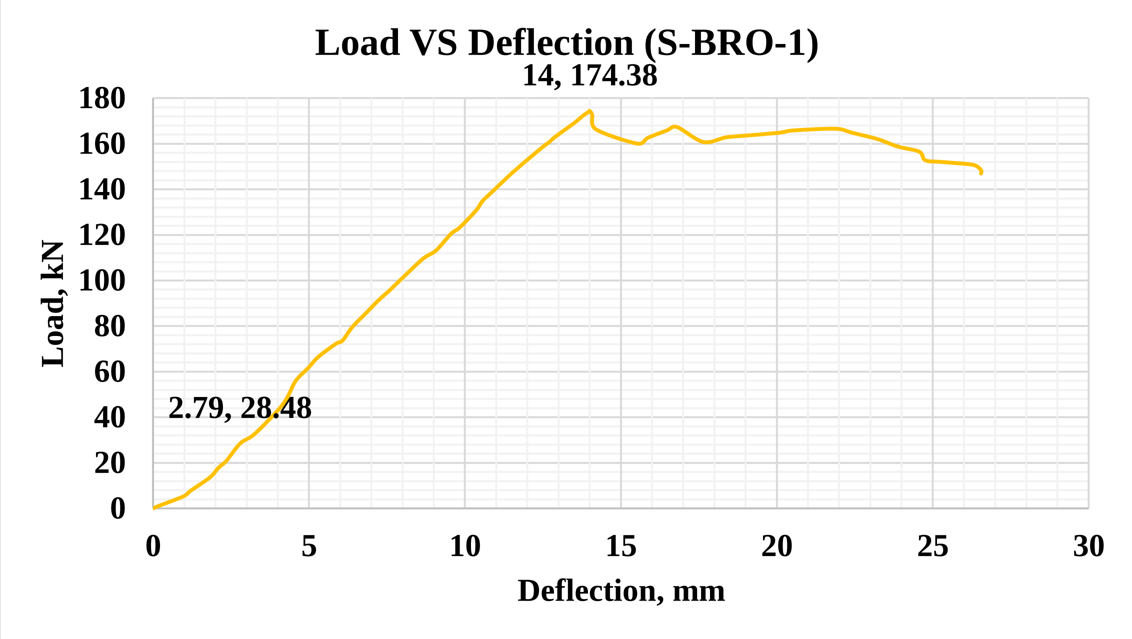


Figure 4.6: Load-deflection curve of beam S-BRO-1

4.4.4 Comparison

The response of the RC solid deep beam was included for the purpose of comparison. The control beam (CB) and beam with openings strengthened by CFRP U-shaped wraps (S-BRO-1) are compared with the beam to un-strengthened openings (US-BRO). In addition, the control beam (CB) also compared to the beam with openings strengthened by CFRP U-shaped wraps (S-BRO-1). Figure 4.7 shows the comparison graph of load versus deflection curves for beam CB, US-BRO and S-BRO-1.

(a) Comparison between beam CB and US-BRO

The results present that the presence of the large rectangular openings in the shear region reduced the ultimate load-carrying capacity of the RC deep beam significantly. The beam US-BRO exhibited the reduction in first cracking and ultimate load approximately of 81% and 70 % respectively. This is because the beam failed unexpectedly due to the debonding happened between the concrete and longitudinal steel reinforcement after the initiation and rapid progression of the shear cracks developed at the sharp corners of the opening. The sharp edges of the opening corners enhanced more cracks and high deflection rate at the failure point eventually. In addition, the web reinforcement of the beam CB also restricted the development of diagonal cracks effectively. Beam CB exhibited a higher value of deflection at yield point and ultimate load as compared to the beam US-BRO. It also can be seen in Figure 4.7 that the solid beam deformed more elastically rather than plastically deformed whereas beams with opening deformed more plastically instead of elastically. The slopes of the descending branch of both curves were fairly similar.

(b) Comparison between beam US-BRO and S-BRO-1

By comparing the results, it can be seen that the beams with the large rectangular openings strengthened by externally bonded CFRP wraps in horizontal U-shaped configuration were improved the ultimate load-carrying capacity. The beam S-BRO-1 bottom was able to withstand a larger load as compared to the beam US-BRO. The shear zone was reinforced by the CFRP wraps become stiffer than the original area, therefore affecting the entire beam behaviour. The ultimate load-carrying capacity of the beam S-BRO-1 was 174.38 kN which showed that CFRP wraps was able to restore the original capacity of the beam US-BRO and added a strength of 35.5 % or 1.35 times of the ultimate load-carrying capacity of the beam with un-strengthened openings. The stiffness of the beam pasted with CFRP wraps is higher caused by the low elastic modulus of CFRP wraps. Beam S-BRO-1 have a significant improvement in both post-cracking deflection and ductility as compared to the beam US-BRO. Furthermore, with the highest failure loads of the beam, the deflection was also elevated accordingly by 4 mm or 40%.

(c) Comparison between beam CB and S-BRO-1

The beam S-BRO-1 did not have a remarkable influence on the initial slope of the load-deflection curve as compared to the beam CB. Test results revealed that the strengthening using horizontal CFRP wraps were enhanced the cracking strength to an unsatisfactory level. It can be seen that first cracking load of the beam S-BRO-1 is lower as compared to the beam CB. Figure 4.7 also indicates that the U-shaped CFRP wrapping around the opening was not capable to restore the load-carrying capacity of the solid reference beam. The beam S-BRO-1 still requires about 58.98% increment in load in order to restore the original beam capacity completely.

Table 4.2 lists the yield load and ultimate load with the corresponding deflection for the beam CB, US-BRO and S-BRO-1.

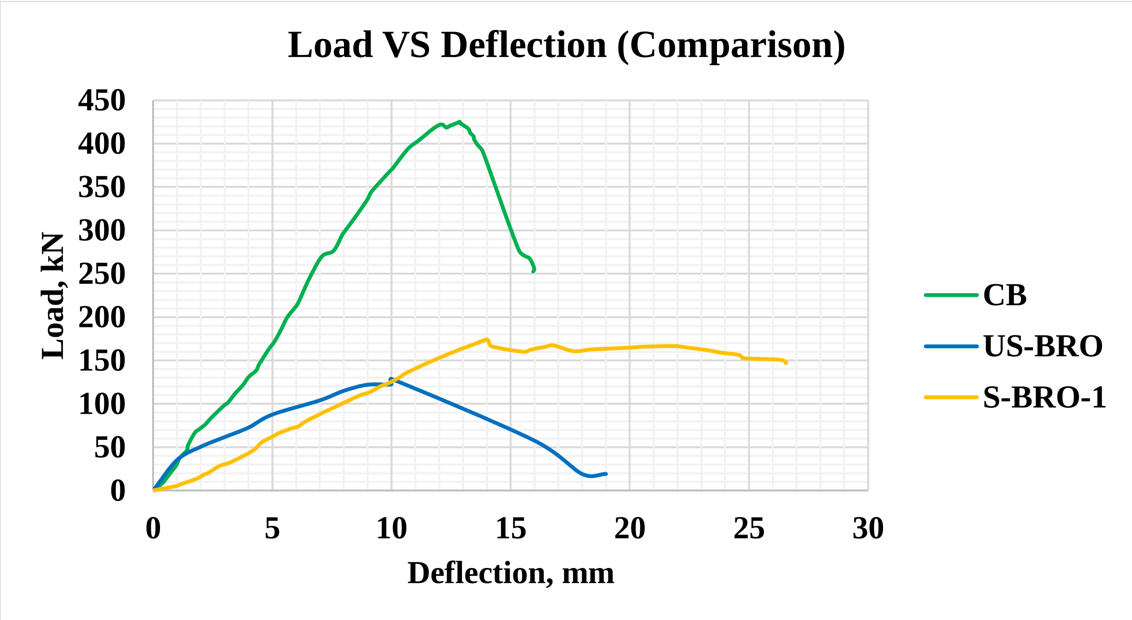


Figure 4.7: Comparison of load-deflection curve of beams

Table 4.2: Experimental test results

Beam	**Yield Load (kN)**	**Deflection (mm)**	**Ultimate Load (kN)**	**Deflection (mm)**
CB	269.89	7.08	425.12	12.87
US-BRO	50.50	2.00	128.69	10.00
S-BRO-1	28.48	2.78	174.38	14.00

4.5 CRACK PATTERN AND FAILURE MODE

The RC solid deep beams with and without strengthened openings were painted in a white colour on the smooth sides as well as grid lines were drawn in perpendicular and parallel to the beam longitudinal axis with the objective of the observation of crack development and propagation during and after testing. All the beams failed in shear due to the diagonal cracking formed in the shear span. The failure mode of the beam with openings was mainly influenced by the presence of openings in terms of size, shape and location. The load was paused periodically during the tests for the purpose of observing the cracks. The value marked beside the crack lines indicated that the applied load at which the crack was found in units of kN.

4.5.1 Control Beam (CB)

Initially, the flexural cracks were observed in the mid-span prior to the appearance of the diagonal cracks. These cracks were predominantly vertical and approximately perpendicular to the longitudinal axis of the beam. The crack lines appeared in the tension region and penetrated vertically up to the neutral axis of the beam, but did not penetrate into the compression zone. No significant growth crack in width was observed. The beam failed at concrete struts by exhibited one principal diagonal crack at an angle of approximately 45° with respect to the beam longitudinal axis, which joining the supporting and loading point at one side of the beam as shown in Figure 4.8. The failure of the control beam was brittle, which identified as diagonal shear failure, followed by concrete crushing on one of the support.

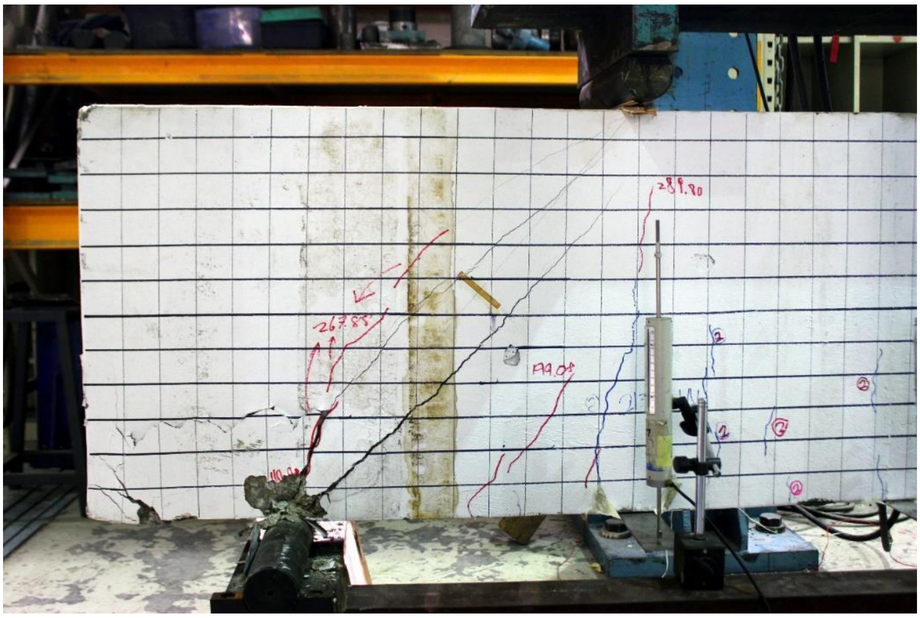


Figure 4.8: Crack pattern after failure for beam CB

4.5.2 Beam Un-strengthened Openings (US-BRO)

The beam US-BRO was failed by shear over the openings due to the location and size of the openings interrupted the natural load path of the beam. This specimen exhibited diagonal cracks as the first shear cracks at the lower opening corner closest to the support and inclined towards to the support point due to the concentration of stress initially. These shear cracks over openings began at approximately 31.97% of the ultimate load. The shear cracks were the major failure planes of the beam. The flexural cracks were seen developed at the top and bottom chords below and above the openings. The vertical and diagonal cracks appeared at the top chord near the opening corners were slowly propagated towards the loading point. Eventually, when the applied load was increased, new diagonal cracks which approximately parallel to initial crack were appeared at the bottom chord of openings. The crack width increased at the top right corner of the opening and penetrated to the loading point. Meanwhile, cracks were also widened at the bottom chord between bottom left corners and the support. The failure occurred abruptly by a formation of two independent diagonal cracks at the top and bottom chords below and above the openings thereby, the beam splitted into 2 separate segments on one side of the beam as shown in Figure 4.10. The maximum crack width value of failure mode was recorded as 63 mm.

Figure 4.9: Crack pattern after failure for beam US-BRO

Figure 4.10: Formation of diagonal cracks at the top and bottom chords below and above the openings

4.5.3 Beam with U-shaped Strengthened Openings (S-BRO-1)

Figure 4.11 shows the beam with U-shaped strengthened openings after failure. The top and bottom chords of the openings shared the most of the shear force. The bottom chord of the openings was fully wrapped by CFRP which restricted the shear deformation and eliminated any premature debonding of the CFRP wraps. The crack patterns and load were not be observed due to the CFRP wraps covered the shear span surface on the beam's web, making it very difficult to observe visually of the cracks appearance. However, the failure of the beam was initiated by the delamination and rupture of the CFRP wrap below and above the opening due to the higher stress concentration as shown in Figure 4.12. The delamination of the CFRP wraps is the dominant failure mode. Based on the test observations, the peeled off of the CFRP wraps were begun at 90 - 95% of the peak load at the several corners of opening on both sides of the concrete surface. The beam was observed to fail very quickly after the CFRP wraps started to peel off. The mechanism of the beam was changed with the application of U-shaped strengthened configuration pasted around the openings. The beam exhibited diagonal crack and crushed in different location on one side of the opening (outer corner of the opening) due to the U-shaped horizontal CFRP wraps were restricted the propagation of cracks or diagonal crack successfully as can be seen in Figure 4.13.

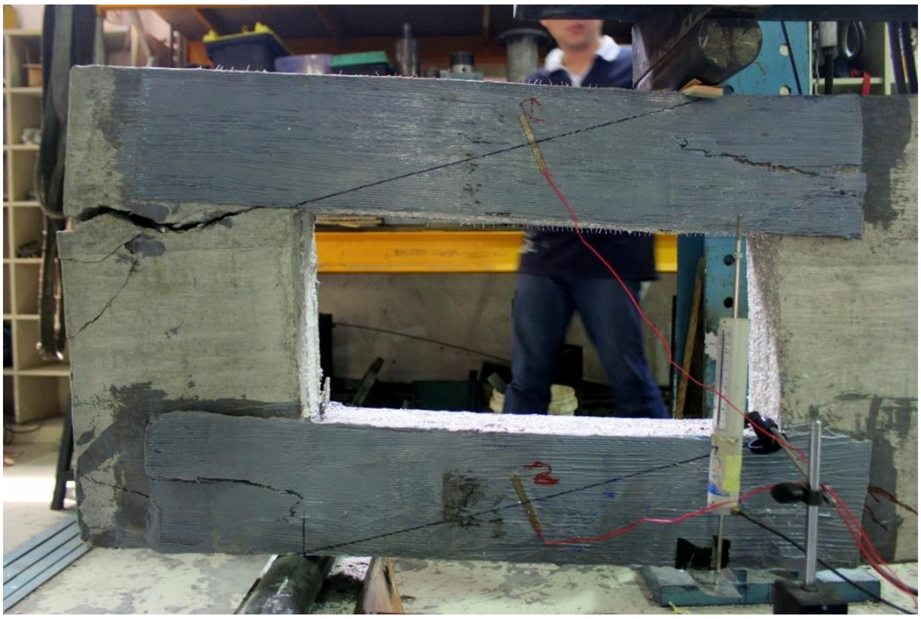


Figure 4.11: Failure modes of the beam S-BRO-1

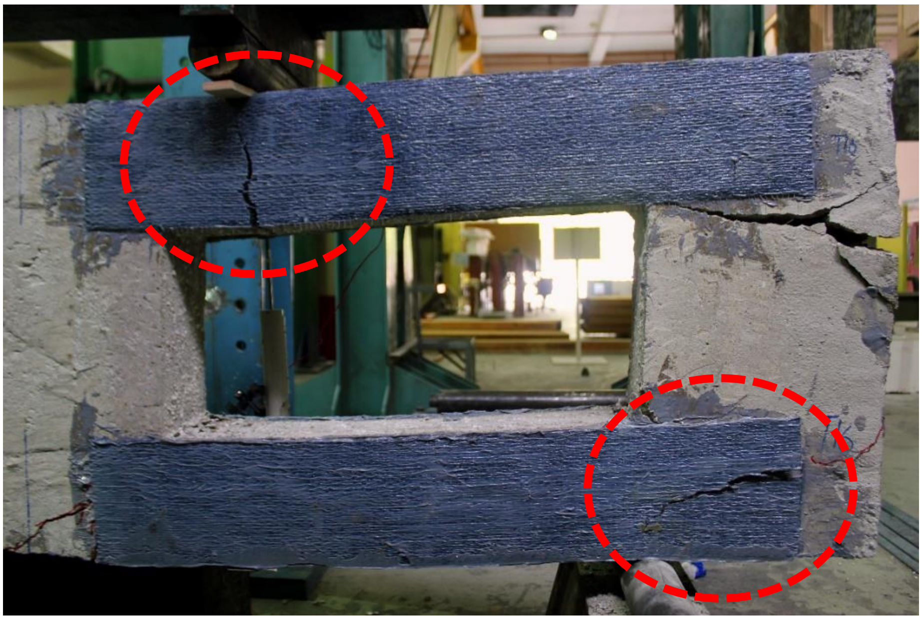


Figure 4.12: Rupture and delamination of the CFRP wrap above the opening

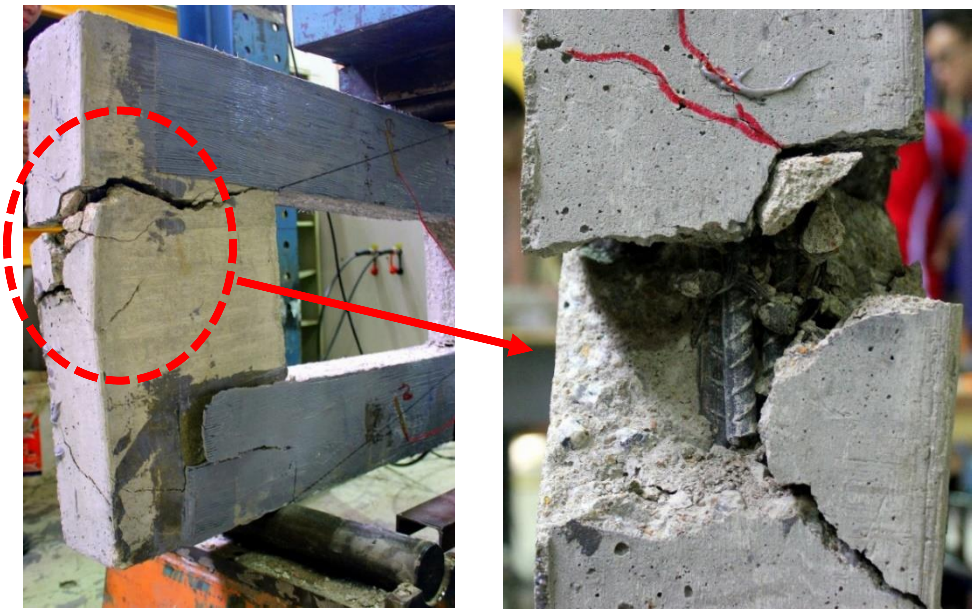


Figure 4.13: Crushing at the outer corner of the opening

4.6 LOAD AND STRAIN RESPONSE

4.6.1 Beam with U-shaped Strengthened Openings (S-BRO-1)

The load versus strain graph of strain gauges for the beam S-BRO-1 is illustrated in Figure 4.14. A total of four strain gauges were pasted on one face of the concrete surface. SG 1 and SG 3 each were applied above the opening region while SG 2 and SG4 were pasted below the opening in order to intersect the diagonal shear crack between the loading and supporting point. SG-1, SG-3 and SG-4 featured approximately the same strain pattern. The CFRP strain in SG-1, SG-3 and SG-4 increase at approximately constant rate as the applied load increased linearly up to the delamination of the CFRP wraps occurred at the opening corners near to the supporting and loading point. After the delamination of the CFRP wraps, the strain continued to increase with a slightly drop in applied loads until failure. The curve indicated that the strain on the CFRP wraps were very small before the initiation of the diagonal shear cracks and increased quickly after the appearance of the shear cracks.

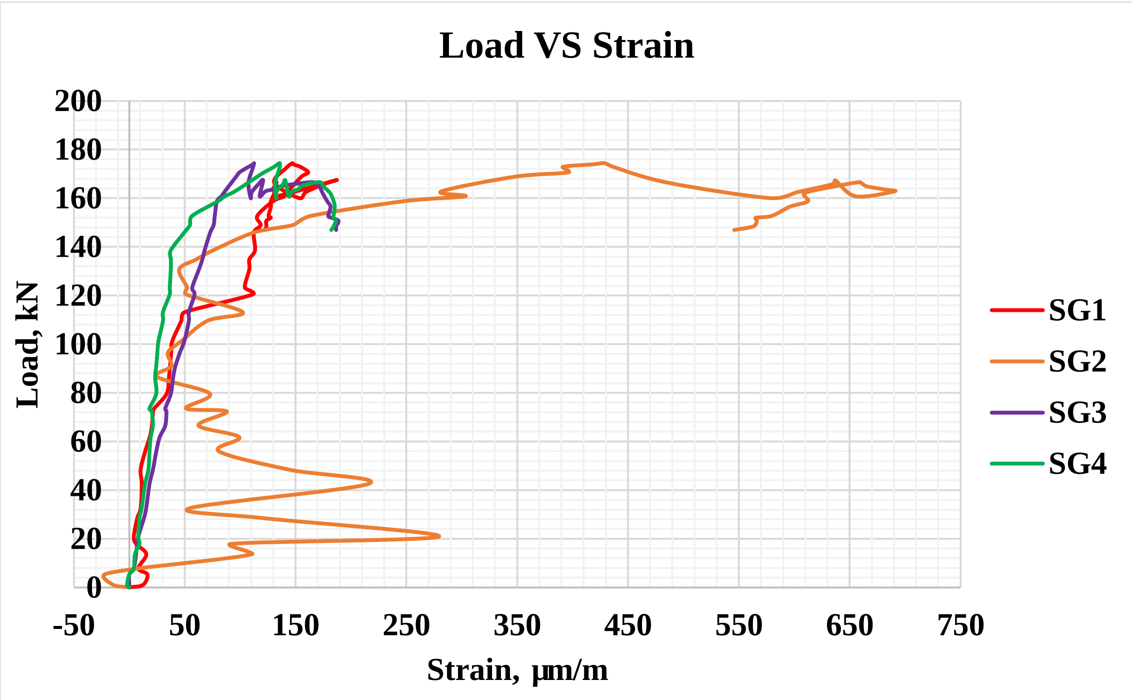


Figure 4.14: Load-strain curve of strain gauges in beam S-BRO-1

4.7 BEAM WITH SURFACE STRENGTHENED OPENINGS (S-BRO-2)

4.7.1 Load Deflection Response

The load and deflection curve of the beam S-BRO-2 is shown in Figure 4.15. The curve shows a steady rise in applied load and deflection up to the yielding point at a load level of 22.79 kN with a deflection of 0.94 mm. After the yield point, the load remains constant and continue increased linearly until reached its ultimate load. The beam failed at a lowest ultimate load among the others beams, which was 120.97 kN with a deflection of 9.36 mm. Beyond the ultimate load, there was a downward trend, the deflection of the beam was increased gently with the declined in load steeply.

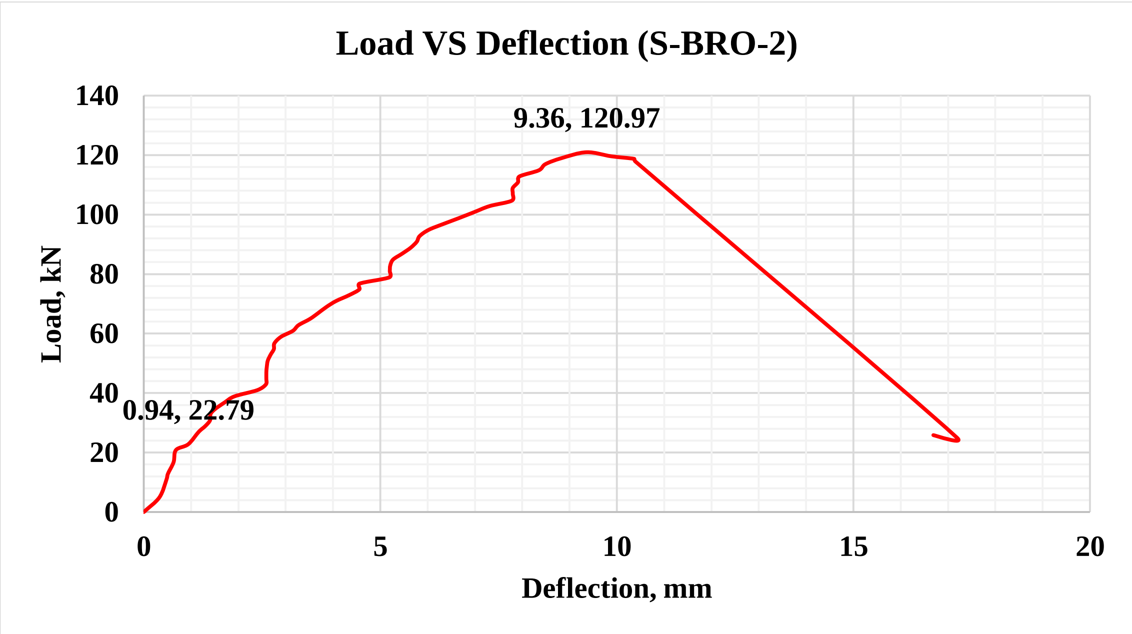


Figure 4.15: Load-deflection curve of beam S-BRO-2

4.7.2 Crack Pattern and Failure Mode

Beam S-BRO-2 were exhibited a similar mode of failure with the beam US-BRO which is also failed by shear over the one side opening as shown in Figure 4.16 and 4.17. The crack patterns and load were also not be observed and recorded due to the CFRP wraps were covered the shear span surface of the beam's web, making it very hard to observe visually of the cracks appearance. The delamination of the CFRP did not exist prior to the failure mode. The failure of the beam was arose suddenly by tearing the CFRP wraps fibers at the top and bottom chords below and above the openings. The two independent diagonal cracks below and above the openings teared the CFRP wraps on concrete surface and splitted the beam into 2 separate segments on one side of the beam opening can be seen in Figure 4.18. This was happened due to the technical problem of the Magnus Frame in the FKASA Laboratory.

Figure 4.16: Front view of beam S-BRO-2 after failure

Figure 4.17: Rear view of beam S-BRO-2 after failure

Figure 4.18: CFRP wraps torn at the top and bottom chords below and above the opening

4.8 Summary

The contribution of the CFRP wraps varies depending upon the CFRP configurations. The Beam S-BRO-1, which is reinforced by 0 °CFRP wraps with respect to the beam axis, gained an additional strength by exactly 45.69 kN or precisely 35.5% increase in load carrying capacity as compared with the only un-strengthened beam US-BRO. While the application of CFRP surface wrapping does not contribute to any strength re-gained on the Beam S-BRO-2 due to the malfunction of Magnus Frame during the testing stages. Thus, U-shaped CFRP wrapping can be considered as the most effective shear strengthening configuration throughout this research. In addition, beams S-BRO-1 also gave the largest deflection at ultimate load, which are 14 mm among others beams. This demonstrates that CFRP gives not only an increase in shear strength, but also an increase in ductility as well.

Besides that, the CFRP strengthening configuration also played a critical role in terms of re-gaining the loss in beam strength due to the openings. The horizontal CFRP fibers mainly assisting in restriction of the growth and spreading of diagonal cracks at the corners of the opening. They were also acting as a flexural reinforcement for the chords which reducing flexural failure of the chords. However, the horizontal CFRP fibers were not anticipated to contribute to the beam strength significantly. Although the U-shaped CFRP wraps were capable to upgrade the ultimate load-carrying capacity to a higher level as compared to the beam with un-strengthened openings, but unable to restore the beam capacity and ductility of the RC solid deep beam effectively. Therefore, the CFRP fibers should be arranged around the opening in the principal direction of the fibers perpendicular rather than parallel to the crack propagation direction is more effective.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 INTRODUCTION

This experimental studies on the behaviour of reinforced concrete deep beams with and without large rectangular openings at 0d away from the support in terms of load-deflection and cracking patterns. The conclusion in the following section is made based on the objectives stated in Chapter 1.

5.2 CONCLUSION

Out of the presented experimental results, several conclusions can be drawn:

i. The slope of load-deflection curve is steeper in the solid deep beam as compared to the beam with openings. The inclusion of large rectangular openings in the shear region of the RC deep beam which resulted an impactful reduction of the beam strength by approximately 71% compared to the control beam. The specimens exhibited diagonal cracks as the first shear cracks at the lower openings corners closest to the support and inclined towards to the support points initially. The failure of shear over opening occurred abruptly by a formation of two independent diagonal cracks in the below and above the openings thereby, the beam splitted into 2 separate segments on one side of the beam. The maximum crack width along the major inclined crack in the shear span occurred almost at the mid-depth of the beam and propagated toward the loading and support point was recorded as 63 mm.

ii. It is evident that the application of CFRP composite system contributed appreciable enhancement in both ultimate load-carrying capacity and cracking pattern of the beam with strengthened openings. The CFRP wrapping also greatly improved both post-cracking deflection and ductility of the beam with large rectangular openings. The shear failure occurred unexpectedly on one side of the strengthened opening corners due to the combination of high stress concentration and peeling of CFRP wraps at the corners of the opening. However, there is no remarkable reduction of beam deflection were observed. The rupture of the CFRP warps began at 90-95% of the peak load at the several corners of opening on both sides of the concrete surface. The U-shaped horizontal CFRP wraps were restricted the propagation of the diagonal crack at openings corners successfully.

iii. The beam strength and failure mode are primarily dependent upon the location, shape and size of the opening. The enlargement of the opening size and location reduced the beam’s ultimate load-carrying capacity due to the opening location and size are large enough to interrupt the natural load path of the beam. The sharp corners of the rectangular openings were subjected to a higher stress concentration which lead to a great reduction of beam strength.

iv. Based on the contribution of U-shaped CFRP wraps around the large rectangular openings in shear zone, it was found to be the most effective strengthening configurations throughout this experimental study. The U-shaped CFRP wrapping scheme slightly improved the ultimate load-carrying capacity of the beam by approximately 36 % or 1.35 times as compared to the beam with un-strengthened openings. In contrast, the U-shaped horizontal CFRP wrap was unable to restore the original capacity of the solid deep beam remarkably.

5.3 RECOMMENDATIONS

i. More research is demanded to be carried out in order to explore the effectiveness of the CFRP strengthening configurations on the beams with sharp opening corners further.

ii. Future studies should consider different types of loading and beam geometry such as continuous beams, multiple load points, different beam dimension, as well as opening location, size and shape.

iii. The orientation of the fibers should be arranged in perpendicular direction to the potential diagonal shear cracks. The horizontal CFRP fibers were not anticipated to contribute to the beam strength significantly, but they were needed to assist in restriction of the growth and spreading of diagonal cracks at the corners of the opening.

REFERENCES

Abdalla HA, Kennedy JB. Design against cracking at openings inprestressed concrete beams. PCI J, Precast/Prestressed Concrete Inst 1995;40(6):60–75.

Abdalla, H. ., Torkey, a. ., Haggag, H. ., & Abu-Amira, a. . (2003). Design against cracking at openings in reinforced concrete beams strengthened with composite sheets. *Composite Structures*, *60*(2), 197–204. doi:10.1016/S0263-8223(02)00305-7

Abdel Hafez LM, Alaa Eldin, Abou-Elezz YK. Static behavior of repaired RC beams having web circular openings in shear zone by using GFRP sheets. In: Proceedings of the 9th international conference on structural and geotechnical engineering. Cairo, Egypt: Ain Shams University; 2002.

ACI Committee 318. Building code requirements for structural concrete (ACI 318-08), and commentary (ACI 318R-08). American Concrete Institute, Detroit, Michigan; 2008. 430 pp.

Ahmed, a., Fayyadh, M. M., Naganathan, S., & Nasharuddin, K. (2012). Reinforced concrete beams with web openings: A state of the art review. *Materials & Design*, *40*, 90–102. doi:10.1016/j.matdes.2012.03.001

Allam SM. Strengthening of RC beams with large openings in the shear zone. Alex Eng J 2005; 44 (1):59–78.

Alsaeq, H. M. (2014). Enhancing the Structural Behavior of R . C . Deep Abstract :, (2).

Al-Zaid, R. Z., Al-Negheimish, A. I., Al-Saawani, M. a., & El-Sayed, A. K. (2012). Analytical study on RC beams strengthened for flexure with externally bonded FRP reinforcement. *Composites Part B: Engineering*, *43*(2), 129–141. doi:10.1016/j.compositesb.2011.11.015

Ashour AF, Rishi G. Test of reinforced concrete continuous deep beams with web openings. ACI Struct J 2000;97(3):418–26.

Ban, L., & Abduljalil, S. (2014). With Opening Strengthened By CFRP Strips Abstract : فـايلأ ن وبراكلا ةيريميلوبلا ةمواقم صقلا تابتعلل ةيناسرخلا ةحلسملا ةقيمعلا ت اذ تاحتفلا ةاوقملا حئارشب, *18*(1), 14–32.

Bousselham, A., and Chaallal, O. (2006b). “Effect of transverse steel and shear span on the performance of RC beams strengthened in shear with CFRP.”Composites: Part B, 37(1), 37–46.

Campione, G., & Minafò, G. (2012). Behaviour of concrete deep beams with openings and low shear span-to-depth ratio. *Engineering Structures*, *41*, 294–306. doi:10.1016/j.engstruct.2012.03.055

CANADIAN CODE (CSA-A23.3-2004)(CANADIAN STANDARD ASSOCIATION Design of Concrete Structures)

Chaallal, O., Shahawy, M., and Hassan, M. (2002).“Performance of reinforced concrete T-girders strengthened in shear with carbon fiber-reinforced polymer fabric.”ACI Struct. J., 99(3), 335–343.

Chin, S. C., Shafiq, N., & Nuruddin, M. F. (2011). Strengthening of RC Beams Containing Large Opening at Flexure with CFRP laminates, 1350–1356.

Chin, S. C., Shafiq, N., & Nuruddin, M. F. (2012). Strengthening of RC Beams with Large Openings in Shear by CFRP Laminates : Experiment and 2D Nonlinear Finite Element Analysis, *4*(9), 1172–1180.

Data, P. (2010). SikaWrap ® -231 C, 1–3.

Data, T., & Properties, M. (2014). *Sikadur ® 330 US*.

EC, Egyptian Code for the Design and Construction of Concrete Structures (203-2006).

El Maaddawy, T., & Sherif, S. (2009). FRP composites for shear strengthening of reinforced concrete deep beams with openings. *Composite Structures*, *89*(1), 60–69. doi:10.1016/j.compstruct.2008.06.022

El-maaddawy, T., & El-ariss, B. (2012). Behavior of Concrete Beams with Short Shear Span and Web Opening Strengthened in Shear with CFRP Composites, (February), 47–59. doi:10.1061/(ASCE)CC.1943-5614.0000237.

Farghaly, A. S., & Benmokrane, B. (2013). Shear Behavior of FRP-Reinforced Concrete Deep Beams without Web Reinforcement. *Journal of Composites for Construction*, *17*(6), 04013015. doi:10.1061/(ASCE)CC.1943-5614.0000385

Hafiz, R. B., Ahmed, S., Barua, S., & Chowdhury, S. R. (2014). Effects of Opening on the Behavior of Reinforced Concrete Beam. *IOSR Journal of Mechanical and Civil Engineering*, *11*(2), 52–61. doi:10.9790/1684-11275261

Ha, S. T. (2002). *Design of concrete deep beams with openings and carbon fiber laminate repair*.

Hanson, J.M., Square openings in webs of continuous joists, Portland Cement Association, 1969, pp: l-14.

Hawileh, R. a., El-Maaddawy, T. a., & Naser, M. Z. (2012). Nonlinear finite element modeling of concrete deep beams with openings strengthened with externally-bonded composites. *Materials & Design*, *42*, 378–387. doi:10.1016/j.matdes.2012.06.004

Hu OE, Tan KH, Liu XH. Behaviour and strut-and-tie predictions of high strength concrete deep beams with trapezoidal web openings. Mag Concr Res 2007; 59(7):529–41.

Hussain, Q., & Pimanmas, A. (2015). Shear strengthening of RC deep beams with openings using Sprayed Glass Fiber Reinforced Polymer Composites (SGFRP) : Part 1. Experimental study. *KSCE Journal of Civil Engineering*, *00*(0000), 1–13. doi:10.1007/s12205-015-0243-1

Indian Standard Code of Practice Plain and Reinforced Concrete" IS 456:2000-. Bureau of Indian Standards, Manak Bhavan, New Delhi, India.

Javad VA, Morteza HA. Effect of small circular opening on the shear and flexural behavior and ultimate strength of reinforced concrete beams using normal and high strength concrete. In: Proceedings of the 13th world conference on earthquake engineering. Vancouver. Canada. Paper No. 3239; 2004

Kong,F.K., Sharp, G.R.,"Structural Idealization for Deep Beams with Web Openings", Magazine ofOCncrete Research, Vol. 29. NO. 99, June 1977, pp. 81 – 91.

Kubik, L.A., "Predicting the Strength of Reinforced Concrete Deep Beams With Web Openings," Proceddings of the Instistution of Civil Engineers, Part 1 – Design & Construction, Vol. 69, No. 2. December 1980, pp. 939-958.

Lu XZ, Ye LP, Teng JG, Huang YL, Tan Z, Zhang ZX. Recent research on interfacial behavior of FRP sheets externally bonded to RC structures. Proc of the 2nd international conference on FRP composites in civil engineering. Berlin: Springer; 2004. p. 389–98.

Mansur MA. Effect of openings on the behavior and strength of RC beams in shear. Cement Concr Compos 1998;20(6):477–86.

Mansur MA. Ultimate strength design of beams with large openings. Int J Struct 1988;8(2):107–25.

Mansur MA, Tan KH. Concrete beams with openings: analysis and design. Boca Raton, Florida, USA: CRC Press LLC; 1999. p. 220.

Mansur MA, Tan KH, Lee YF, Lee SL. Piecewise linear behaviour of RC beams with openings. ASCE J Struct Eng 1991;117(6):1607–21.

Mansur MA, Tan KH, Lee ST: Design method for reinforced concrete beams with large openings. ACI Journal, Vol 82, No.4, 1985, 99. 517-524.

Mau ST, Hsu TTC. Shear strength prediction for deep beams with web reinforcement. Struct J Am Concr Inst 1987; 84(6):513–23.

NEWZEALAND CODE (NZS-3101-2006)New Zealand Standard CONCRETE STRUCTURES STANDARD Part-1 The Design Of Concrete Structures.

Pimanmas A. Strengthening R/C beams with opening by externally installed FRP rods: behavior and analysis. Compos Struct 2010; 92:1957–76.

Prentzas EG. Behavior and reinforcement of concrete beams with large rectangular apertures. PhD Thesis, University of Sheffield, UK; 1968. p. 230.

Rosenboom O, Rizkalla S. Experimental study of intermediate crack debonding in fiber-reinforced polymer strengthened beams. ACI Struct J 2008;105(1):41–50.

Sdn, S. K., Estate, N. I., Negeri, N. M.-, & Dk, S. (2010a). *Risalah Data Keselamatan Kima*.

Sdn, S. K., Estate, N. I., Negeri, N. M.-, & Dk, S. (2010b). *Risalah Data Keselamatan Kima* (pp. 1–11).

Sheet, P. D. (2014). *Sikadur ® -330* (pp. 1–5).

Sheet, T. D., & Data, T. (2003). *SikaDur 330 ®*.

Siao, W.B. and S.F. Yap, Ultimate behavior of unstrengthen large openings made in existing concrete beams, Journal of the Institution of Engineers, 30(3), 1990, 51-57.

Somes NF, Corley WG. Circular openings in webs of continuous beams. Shear in Reinforced Concrete. Special Publication SP-42. Detroit: American Concrete Institute; 1974; 359–98.

Standard, B. (2003). British Standard Testing hardened concrete Ð Part 5 : Flexural strength of test specimens.

Tan, K. H., Tang, C. Y., & Tong, K. (2004). Shear strength predictions of pierced deep beams with inclined web reinforcement. *Magazine of Concrete Research*, *56*(8), 443–452. doi:10.1680/macr.2004.56.8.443

Tan KH, Mansur MA, Huang LM. Reinforced concrete T-beams with large web openings in positive and negative moment regions. ACI Struct J 1996;93 (3):277–89.

Teng JG, Chen JF, Smith ST, Lam L. Behavior and strength of FRP-strengthened RC structures: a state-of-the-art review. Proc Inst Civil Eng – Struct Build 2003;156(1):51 62.

Teng JG, Chen JF, Smith ST, Lam L. FRP strengthened RC structures. John Wiley & Sons; 2002.

Triantafillou, T., and Antonopoulos, C. (2000).“Design of concrete flexural members strengthened in shear with FRP.”J. Compos. Constr., 4(4), 198–205.

Torunbalci, N. (2000). Behaviour and Design of Small Square Openings in Reinforced Concrete Beams. *Architectural Science Review*, *43*(4), 201–210. doi:10.1080/00038628.2000.9696908

Torunbalci, N. (2002). Behaviour and Design of Large Rectangular Openings in Reinforced Concrete Beams. *Architectural Science Review*, *45*(2), 91–96. doi:10.1080/00038628.2002.9697497

Yang, K., and Ashour, A. (2008).“Effectiveness of web reinforcement around openings in continuous concrete deep beams.”ACI Struct. J., 105(4), 414–424.

Yang, K., Chung, H., and Ashour, A. (2007).“Influence of inclined web reinforcement on reinforced concrete deep beams with openings.” ACI Struct. J., 104(5), 580–589.

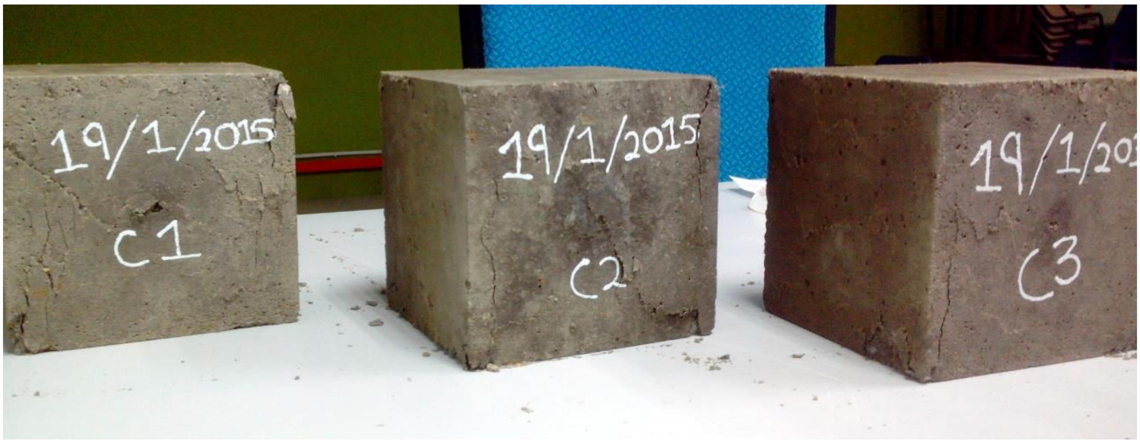
Yang, K., Eun, H., and Chung, H. (2006). “The influence of web openings on the structural behavior of reinforced high-strength concrete deep beams.”Eng. Struct., 28(13), 1825–1834.

Zainab EM, Ahmed M, Hassanean YA (2005). Some parameters influencing the static behaviour of rectangular web perforated high strength RC T-beams. 11th ICSGE. 17-19 May 2005. Ain Shams University. Cairo. Egypt.

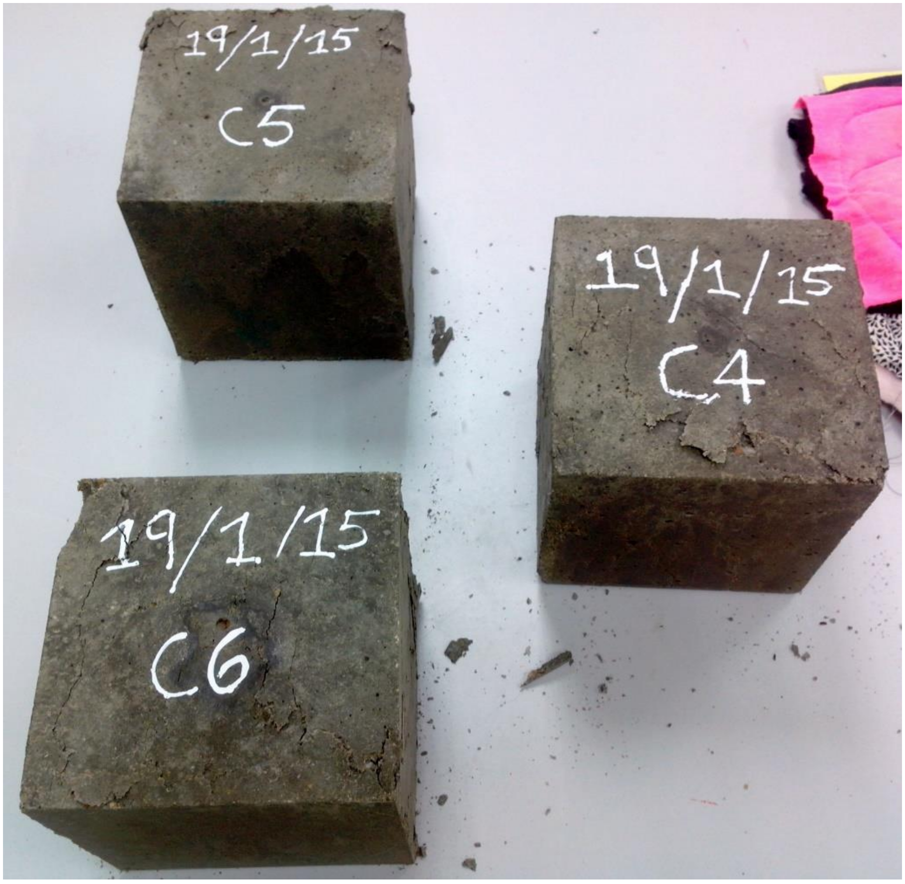
Zhang, Z., Hsu, C. T., Asce, F., & Moren, J. (2004). Shear Strengthening of Reinforced Concrete Deep Beams Using Carbon Fiber Reinforced Polymer Laminates, (October), 403–414.

APPENDIX A

PHOTOGRAPHS OF CUBE AFTER TESTING



Cube samples after testing at day 3



Cube samples after testing at day 7

Cube samples after testing at day 28

APPENDIX B

CONTROL BEAM RAW DATA

Load, kN	Deflection, mm
0	0
2.02	0.04
3.53	0.16
7.06	0.32
10.33	0.45
19.15	0.69
29.23	0.97
36.79	1.09
41.58	1.25
46.37	1.42
51.91	1.46
60.73	1.62
67.79	1.78
70.06	1.90
76.36	2.19
83.66	2.43
98.53	2.99
100.80	3.12
111.89	3.44
121.46	3.76
131.04	4.01
138.60	4.33
145.66	4.45
163.30	4.86
172.12	5.10
186.23	5.38
199.84	5.63
212.18	5.99
217.73	6.11
244.94	6.56
269.89	7.08
276.44	7.57
294.59	7.93
299.38	8.05
314.5	8.46
335.16	8.98
345.49	9.19
368.93	9.96
370.94	10.04
393.62	10.68
404.21	11.17
417.82	11.78
422.10	12.10
418.57	12.30
420.59	12.46
425.12	12.87
424.87	12.83
423.86	12.87
418.82	13.15
417.06	13.23
415.04	13.27
412.27	13.31
408.49	13.44
404.21	13.48
397.66	13.64
390.35	13.84
277.45	15.34
268.13	15.78
256.28	15.99
252.50	15.95

APPENDIX B

BEAM WITH UN-STRENGTHENED OPENINGS RAW DATA

Load, kN	Deflection, mm
0	0
35.17	1
50.50	2
61.64	3
72.60	4
87.62	5
104.06	7
115.02	8
122.06	9
122.5	10
128.69	10
57.59	16
19.10	18
19.22	19

APPENDIX C

BEAM WITH SURFACE STRENGTHENED OPENINGS RAW DATA

Load, kN	Deflection, mm
0	0
4.93	0.33
10.93	0.48
12.86	0.51
16.77	0.63
20.85	0.68
22.79	0.94
26.94	1.16
28.91	1.30
30.83	1.40
32.89	1.41
34.53	1.50
36.86	1.71
38.91	1.92
40.99	2.40
42.89	2.58
44.76	2.59
46.91	2.59
48.79	2.6
50.85	2.62
52.89	2.68
54.79	2.75
56.70	2.76
58.91	2.90
60.91	3.15
62.82	3.27
64.90	3.51
66.82	3.68
68.95	3.86
70.91	4.06
72.92	4.34
74.91	4.56
76.79	4.56
78.90	5.19
80.97	5.20
82.92	5.21
84.89	5.27
86.86	5.46
88.85	5.64
90.87	5.77
92.77	5.83
94.86	6.02
96.78	6.32
98.82	6.66
100.81	6.98
102.86	7.31
104.69	7.78
106.97	7.80
108.95	7.80
110.88	7.91
112.83	7.94
114.90	8.35
116.97	8.49
118.99	8.83
120.97	9.36
119.61	9.88
118.73	10.37
117.88	10.39
24.99	17.19
25.85	16.69

APPENDIX E

BEAM WITH U-SHAPED STRENGTHNED OPENINGS RAW DATA

Load, kN	Deflection, mm	Strain, µm/m			
		1	2	3	4
0	0	0	0	0	0
0.16	1.01	12.26	-14.328	0	-2.02
0.97	5.29	16.35	-22.515	0	0
1.21	7.81	8.17	8.187	4.06	4.05
1.82	13.61	15.33	110.542	6.08	5.06
2.1	17.89	6.13	92.117	7.1	9.11
2.35	20.92	4.09	279.473	8.11	8.1
2.79	28.48	7.15	120.778	13.18	9.11
3.24	32.51	10.22	54.244	15.21	11.14
3.97	42.59	11.24	215.989	18.25	14.18
4.29	48.38	10.22	144.323	21.3	17.21
4.57	55.94	14.3	80.856	24.34	18.23
4.98	61.74	18.39	99.282	27.38	19.24
5.3	66.53	20.43	62.433	32.45	21.26
5.87	72.32	21.46	88.021	33.47	20.25
6.07	73.58	22.48	51.174	32.45	18.23
6.39	79.63	33.71	72.668	37.52	24.3
6.88	86.44	35.76	25.586	39.55	23.29
7.2	90.97	36.78	37.868	41.58	24.3
7.65	96.52	37.8	34.797	45.64	25.31
8.01	101.3	38.82	47.08	49.7	26.33
8.66	109.62	47	70.621	53.75	30.38
9.07	113.15	50.06	102.353	53.75	30.38
9.55	120.46	111.37	51.174	58.82	36.45
9.83	123.23	104.22	52.197	56.8	36.45
10.36	130.79	108.3	45.033	62.88	37.47

Load, kN	Deflection, mm	Strain, µm/m			
		1	2	3	4
10.56	134.82	108.3	60.386	65.92	37.47
10.85	138.6	113.41	75.739	67.95	37.47
11.41	145.91	112.39	112.589	73.02	49.62
11.66	148.93	118.52	147.395	76.07	54.68
11.98	152.71	115.46	163.774	77.08	56.71
12.51	158.76	129.76	247.729	79.11	80
12.71	160.78	139.98	303.024	83.17	86.07
12.87	162.79	143.05	281.52	86.21	95.19
13.48	168.84	155.31	348.084	96.35	115.44
13.64	170.6	161.44	396.221	99.4	121.52
13.84	172.87	154.29	391.1	107.51	130.64
13.96	173.88	148.16	417.729	111.57	133.67
14	174.38	147.13	428.997	112.58	135.7
14.08	172.62	142.03	438.216	111.57	135.7
14.2	166.32	130.78	486.36	107.51	131.65
15.54	160.02	153.27	578.566	109.54	132.66
15.86	162.54	159.4	603.156	110.55	132.66
16.47	165.82	175.75	634.922	116.64	138.74
16.8	167.33	185.97	636.972	120.7	140.76
17.64	160.78	132.83	655.417	117.66	143.8
18.37	162.79	130.78	690.259	122.73	146.84
18.98	163.55	129.76	682.061	128.81	151.91
20.07	164.81	130.78	665.665	135.91	154.94
20.52	165.82	131.81	661.564	149.1	161.02
21.89	166.57	132.83	658.491	166.35	172.16
22.42	164.81	131.81	635.946	171.42	175.2
23.23	162.04	130.78	609.306	174.46	181.28
23.88	158.76	127.72	612.379	178.52	184.32
24.57	156.49	127.72	595.984	181.56	185.33

Load, kN	Deflection, mm	Strain, µm/m			
		1	2	3	4
24.77	152.71	125.68	579.59	179.54	184.32
25.33	151.96	127.72	565.246	182.58	184.32
26.31	150.7	123.63	566.27	188.67	186.34
26.55	148.43	123.63	563.197	186.64	184.32
26.55	146.92	122.61	545.78	186.64	182.29