CHAPTER 1

INTRODUCTION

1.1 Background

Design, construction and maintenance requirements of tall buildings and industrial complexes are very different from those applicable for normal building design and construction. For example, for conveying the services and other facilities such as water supply, electricity, air-conditioning and sewerage discharge; a complex network of system routing is provided, which usually align vertically and horizontally and spread throughout the floor area. This complex network is often obstructed by the structural components such as beams, columns and floors and requires penetrating through such obstruction, which is called the structural penetrations. The size, location and configuration of structural penetration are derived from the type of services, magnitude and speed of facility to be provided. The most prevalent location, size and configuration of structural penetration are always an issue between structural engineers and service or facilities design engineers. Penetration means the loss of concrete area, which results in the reduction of resistance in the term of strength and axial stiffness. The way penetration area is configured, the flexural or shear stiffness and deflection resistance of the beam is also affected.

In the past same efforts have been made to study the effects of opening in beams. Extensive experimental study considering openings of circular, rectangular, diamond, triangular, trapezoidal and even irregular shapes was carried by Prentzas in 1968. The most common openings constructed are circular and rectangular openings. Circular openings are constructed to accommodate service pipes, such as for plumbing and electrical supply whereas rectangular openings are constructed to accommodate rectangular air conditioning ducts. Rectangular opening has sharp edges or sharp corners where stress is concentrated. One of the ways to reduce this stress is by rounding off these sharp edges. This can improve the cracking behaviour of beams in service. Mansur and Hasnat (1979) have defined openings such as circular, square or nearly square as small openings. According to Somes and Corley (1974), large circular opening has its diameter exceeds 0.25 times the depth of the beam web. These are several researches carried out by different authors with different definition of openings.

In most of the previous studies, additional steel reinforcement bars have been introduced along the edges, to return the lost capacity of the member. However, this procedure was not always found very successful particularly under high cyclic loads. Since last few years, various types of polymer based composite materials have been introduced in the construction industry for repair and retrofitting of the damage structures. Such composites are carbon fiber reinforced polymer CFRP, glass fiber, GFRP and others. In Malaysia construction industry carbon fiber reinforced polymer, CFRP are commonly used. Therefore, such materials can be an alternative to strengthen the beams to regain the lost capacity in case of openings.

1.2 Problem Statement

As discussed in the earlier part of this chapter that structural penetrations in modern buildings are essential to accommodate the services and other M&E facilities. These structural penetrations have always become an issue between structural engineers and M&E engineers because:

- Size, shape and location of openings in structural components are restricted from structural performance point of view.
- In many instances, M&E engineer has to change the layout out of his/her system that may affect its efficiency in term of out-put and or energy consumption.

Therefore, there is a need of technique or design guidelines that can facilitate openings at the desired locations and enable M&E system to run at the maximum possible efficiency.

1.3 Objectives

In order to understand the behaviour of openings at any location (may be a critical one) and their mitigation using appropriate techniques; following objectives were set for this research study:-

- ❖ To investigate the effects of various shapes of openings on the structural capacity of RC beams subjected to static and cyclic loading.
- ❖ To investigate the effects of traditional strengthening method (i.e. additional reinforcement bars along the edges) on returning the lost capacity.
- ❖ To study the effects of strengthening of beams with openings using carbon fiber reinforced polymer, CFRP sheets.

1.4 Scope of Study

The scope of this research was divided into experimental or testing method and data analyzing that is described below:-

- Experimental method was carried out to test the effects of cyclic and static loading on RC beams with openings in the critical tensile zone. Experiments were further carried out to determine the effectiveness of using carbon fiber reinforced polymers, CFRP and additional reinforcement bars along the edges which ensure the return of the lost capacity subjected to cyclic and static load. The experiment was carried out for reinforced concrete beams with circular, rectangular, elliptical and square openings. Twenty RC concrete beams with concrete compressive strength, fcu of +/- 35Mpa were cast and were subjected to cyclic and static load to obtain the failure load and stiffness lost. This research only focuses on 4 types of different openings that are mostly constructed openings. The usage of carbon fiber reinforced polymer, CFRP in this research is due to its effectiveness as a mean of improving, upgrading and strengthening reinforced concrete beams. The additional reinforcement bars along the edges were used to investigate the traditional method of strengthening.

- For the data analysis section, the results were compared and discussed for the different types of openings with and without CFRP sheets and additional reinforcement bars along the edges. The results were further compared with beams with openings and beam without openings (reference beams). In this research beams subjected to cyclic and static load is compared and discussed based on ductility, yield strength, stiffness lost and rupture failure. Finally, this research will conclude whether CFRP sheets and additional reinforcement bars will help to strengthen the RC beams with and without openings based on the analysis.

1.5 Thesis Organization

The thesis is organized as follows:

Chapter 1 consists of the background study, problem statement, objectives, scope of study and thesis outline.

Chapter 2 discusses theoretical background to support the research objectives and addresses the role of carbon fibre reinforced polymer, CFRP in the structural engineering subjected to static and cyclic load. It discusses what other researchers have done in the field, and the issues and challenges faced.

Chapter 3 presents useful information about experimental work or testing method that was carried out to achieve the objectives of this research.

Chapter 4 contains the results and discussions. It highlights the comparative analysis on the effects of opening in RC beams subjected to static and cyclic load, pair-wise comparison of beams with opening pasted with CFRP sheets and added with additional reinforcement bars along the edges and justifications of the results.

Chapter 5 presents the main output from this research and describes the general recommendations for further work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The principal aim of this research study was to investigate the effects of opening in deep RC beams subjected to static and cyclic loads and determine the effective strengthening procedure. Therefore, the literature review was conducted to draw the issues and gaps in the available literature that can support the justification of the research objectives. There were two main part of this chapter. In the first part mechanics and effects of opening in RC members were studied, where as in the second part potential of CFRP are discussed.

2.2 Openings and Penetration in RC members

The structural engineers are often faced with the problems of providing convenient passage for environmental services in concrete beams used in parking garage, industrial and residential buildings, and sometimes bridges. The main function to penetrate RC members is to facilitate the passage of utility pipes and service ducts which results not only in a more systematic layout of pipes and ducts but it also translate into substantial economic savings in the construction of a multi-storey building. For small building, the savings achieved may be not significant, but for multi-storey buildings any saving in the storey height multiplied by the numbers of stories can represent a substantial saving in a total height, length of air-conditioning and electrical ducts, plumbing risers, walls and partition surfaces and overall load on the foundation. These pipes and ducts are placed underneath the beam soffit. These pipes and ducts are covered by a suspended ceiling for aesthetic reasons which creates a dead space and results in a more compact design. Changes in the sectional configuration due to opening corners which are subjected to high stress concentration may lead to cracking and this is unacceptable from aesthetic and durability viewpoints [Cheng, et al. (2009)].

Engineers permit the embedment of small pipes by providing some additional reinforcement which is used around the periphery of the opening. But when large openings are encountered, particularly in reinforced or prestressed concrete members, they show a general reluctance to deal with them because adequate technical information is not readily available. There is also a lack of specific guidelines in building codes of practice (ACI, 1995; BS 8110-97), although they contain detailed treatment of openings in floor slabs. Due to this the engineers has to design based on the intuition and may lead to disastrous consequences. There is at least one case on record, described by Merchant in 1967, in which the failure of a large building was averted when severe distress at a large opening in the stem of a beam was discovered and mitigated in time. There are three forms of pre-planned holes:

1. Holes that are cast at the point of construction of the element and are left open ready to receive services.

2. Services that are cast into element and remain in position.

3. Areas within a concrete element that are designed for holes to be cut retrospectively.

2.2.1 Why Openings are Needed?

In the construction of modern buildings, tall buildings and other industrial structures, pipes and ducts are installed to accommodate essential services such as water supply, sewerage, air conditioning, electricity, telephone and computer network. These openings in beam are necessary to allow the pipes and ducts to pass through in order to save the height of the room. These openings may be of different shapes and sizes [Cheng, et al. (2009)]. Most constructed openings are circular and rectangular openings although numerous shapes are possible.

Circular openings are constructed to accommodate service pipes, such as for plumbing and rectangular openings are constructed to allow the passage for air conditioning ducts that are generally rectangular in shape. Services and structural engineers have to work hand in hand so that proper decision is made in advance to avoid any undesirable damage to the concrete beams [M.A. Mansur (2006)]. In general, the presence of web openings leads to a decrease in both cracking and ultimate strength, as well as the post cracking stiffness of continuous beams. Torsional strength and stiffness of a beam decreases with an increase in opening size. Circular holes are preferable as square and rectangular holes can induce stress concentrations around the corners, increasing the risk of cracking. There are no differences in casting openings in an element at the precast factory or formed in-situ. The main factors affecting the behaviour and performance of beams with web openings are:

- span to depth ratio;
- cross-sectional properties (i.e. rectangular section, Tee-section, etc.);
- amount and location of main longitudinal reinforcement;
- amount, type and location of web reinforcement;
- properties of concrete and reinforcements;
- shear span to depth ratio;
- type and position of loading;
- size, shape and location of web opening.

There are several advantages of openings in RC beams which are:

- Improved versatility in the design and use of a building with openings in the beam webs can often contribute to lower costs.
- If openings can be provided, it is simpler to design to accommodate mechanical and electrical systems.

- Provision of an adequate number of such openings often makes it possible to design concrete structures that are less expensive and, therefore, more competitive in price with steel or timber structures.

- Openings often make it possible to eliminate suspended ceilings. This permits reduction of ceiling heights or story heights in multi-storey buildings and again saves considerable amounts of materials.

- The presence of a considerable number of openings produces a significant reduction in dead load, which again contributes to savings in materials.

- Multiple openings in beams of office buildings offer maximum versatility for frequently needed relocations of electric wiring, plumbing, and heating and ventilating.

Among the two shapes of openings, the circular opening is found to be more effective in transmitting the load and the diagonal cracking is well-defined. Therefore, circular opening is always recommended for provision in the design. Maximum crack width at failure will be greater when the opening centre is located at the centre of the shear zone than at any other position. Opening at the centre of shear zone will definitely cause maximum damage to the web region. The opening should not be brought too close to the vertical edge and inner and outer soffits of the beam. This is due to the higher loads secondary cracks might appear and cause failure of the beam. The strength of the beam increases when the opening is located away from what can be called the loaded quadrant to the unloaded quadrant and vice-versa [M.A. Mansur, et al. (1999)]. Again, for openings located completely outside the shear region, the beam with a web opening may be assumed to be a solid web beam. The location of the web opening is therefore a major factor influencing the strength of the beam. It is interesting from the load-deflection characteristics that the flexibility of the beam decreases as the location of the opening is moved away from the support to the interior of the beam.

2.2.2 Effects of Shape, Size and Location of Openings

Prentzas in 1968 carried out his extensive experimental study, on considering openings of circular, rectangular, diamond, triangular, trapezoidal and even irregular shapes. Mansur and Hasnat in 1979 have defined small openings as those circular, square or nearly square in shape. Somes and Corley in 1974 has defined circular opening to be considered as large when its diameter exceeds 0.25 times the depth of the web because introduction of such openings reduces the strength of the beam. M. A. Mansur in 1998 however considers that classifying an opening either small or large lies in the structural response of the beam. When the opening is small enough to maintain the beam-type behaviour or, in other words, if the usual beam theory applies then the opening may be termed as small. When beam-type behaviour ceases to exist due to the provision of openings, then the opening may be classified as a large opening. According to the above criterion, the definition of an opening being small or large depends on the type of loading. For example, if the opening segment is subjected to pure bending, then the beam theory may be assumed applicable up to a length of the compression chord beyond which instability failure takes place. Similarly, for a beam subjected combined bending and shear, shown that beam type behaviour transforms into a vierendeel action as the size of opening is increased. Tests have shown that, for a single opening in a beam without web reinforcement, location of the opening with respect to the beam support determines the amount of reduction in shear capacity. An opening located at a distance from the end of about twice the beam depth causes the most severe reduction in strength. If the opening is located further from the support, there is little or no additional reduction in shear capacity. As would be expected, large openings cause a greater reduction in strength than do small ones [M.A. Mansur (2006)].

The introduction of a large opening in a reinforced concrete beam would normally reduce its load –carrying capacity considerably. However, it is possible to reinforce such beam and restoring its strength to a similar solid beam. This can be illustrated by comparing the behaviour under pure bending of a solid beam with a similar beam containing a web opening.

From the above summarization through various literature reviews, it is drawn that about the size of opening (large or small) there is not any empirical relationship presented. Every researcher gives his/her own interpretation based on his/her testing parameters, experimental setup and findings.

2.2.2.1 Beams with Rectangular Web Opening

The first visible inclined cracks normally appear in the support bearing regions and from the opening corners at load varying levels of about 36–55% of the ultimate loads. With incremental loads, these initial cracks of short lengths tend to propagate in their forward diagonal direction slowly. Some similar types of crack parallel to and alongside the initial ones also form for short lengths and these are not much active in the formation of critical diagonal crack. For the loading range of about 50–97% of the ultimate, typical diagonal cracks longer than the initial ones (resembling the phenomenon of a critical diagonal crack in a solid web deep beam) suddenly emerge with a harsh noise in the upper and lower shear zones above and below the openings but appreciably away from the openings and bearing points. These critical diagonal cracks instantaneously propagate both ways towards the bearing regions and opening corners, widen and announce the failure of the structure [M.A. Mansur, et al. (1999)].

2.2.2.2 Beams with Circular Web Opening

The first visible cracks normally appear at almost the same range of percentages of ultimate loads as in the case of rectangular openings. There are two main distinctive features.

i. The cracks that start at about the bottom-most diametrical position of openings in the shear zones propagate towards the support bearing regions and become established as the critical diagonal cracks in the course of the load increments. Some of these initial cracks may completely stop propagating towards the support bearing regions after a small length of advancement at a few incremental load stages and prove to be harmless, as in the case of rectangular openings.

ii. The cracks initiated at the mid-shear zones (but away from the regions of openings and bearings) progress both ways diagonally and tangentially to the curved contour of the openings on further incremental loading. Similar cracks suddenly arise at positions about diametrically opposite on the opening surface towards the bearings. Either of these crack patterns can be responsible for final failure of the beam [M.A. Mansur, et al. (1999)].

2.2.3 Tradition Methods or Techniques to Treat Openings

Traditional method is used to increase the strength of the concrete structure in tension zone. As is known that concrete is weak in tension and good in compression. Therefore, reinforcements are placed in concrete to overcome this problem. The main steel not only acts as tension reinforcement in flexure, but contributes substantially to the shear strength of beams. Furthermore, web reinforcement controls crack width and deflection. However, first cracking is generally not influenced by its provision. Among all types of web reinforcement, the inclined type placed perpendicular to the plane of rupture (critical diagonal crack) has been found to be the most effective arrangement to offer resistance to sliding [Ray (1980), a (1982), b (1983), (1984)]. The next practical and effective type is the horizontal web steel which with nominal vertical web steel may further increase the effectiveness of the beam and so its strength. It was observed [Ray (1980), a (1982), b (1983), (1984)] that in beams with web openings, horizontal web reinforcement distributed equally on either side of the opening location showed better results. In beams with unusually high web reinforcement, special attention should be paid to the detailing of anchorage and bearings at the load and support points. Otherwise, web steel must be limited to a certain amount. Failure will be gradual and slow in beams with web reinforcement, while it is sudden in beams without web reinforcement. It was further seen [Ray (1980), (1982)] that after cracking of the beams the steel strain rapidly increased at the location near the supports and the steel strain in the flexural zone remained almost constant (i.e. tension was uniform).

The inclined cracks began to develop at higher loads. Reinforcement should be placed around the opening web area to increase the strength of the beam with web opening. This reinforcement will act to increase the strength of the beam in tension zone.

2.3 External Strengthening of RC Members using Composite Laminates

For several decades Fiber Reinforced Polymer (FRP) is a kind of polymer which is widely used in the aerospace industry. In 1950s FRP materials were first used in reinforced concrete structures. In 1950s fabrication techniques, construction methods and material properties were not that advance as compared to now. The significant use of FRP materials as external reinforcement in concrete bridge structure started in 1980s. The external retrofitting techniques were developed in Japan (sheet wrapping) and Europe (laminate bonding). In Japan currently more than a thousand concrete girder bridges have been strengthen with sheet bonding to the slabs. FRP materials have been applied to many structural elements including beams, columns, slabs and walls as well as many special applications such as chimneys, pipes and tanks. FRP materials is an attractive solution for post strengthening, repairing and retrofitting due to its reduce material cost, low to weight ratio, simpler installation, relatively unlimited material length available and immunity to corrosion. Increment in loading conditions or decrement in material behaviour can cause the concrete structure to be in unacceptable condition. This problem is solved by using FRP strengthening materials as external reinforcement to concrete structure. FRP materials will increase the lifetime of the concrete structure to an acceptable level. Flexural or shear strength is also increased by external application of high tensile strength materials [C.-T. T. Hsu, et al. (1977)].

2.3.1 Types and Classification of Composite Laminates Properties

Fiber Reinforced Polymer (FRP) composites is defined as a polymer (plastic) matrix, either thermo set or thermoplastic, that is reinforced with a fiber or other reinforcing material with a sufficient ratio (length to thickness) to provide discernable reinforcing function in one or more directions. High strength fibers are embedded in a polymer resin of FRP composites. The fibers are the main load-carrying element and have a wide range of strengths and stiffness that exhibit a linear stress-strain relationship until failure. There are several types of fibers used in the fabrication of FRP composition for construction such as carbon, glass and aramid. All this three fibers are commercially available as continuous filaments.

The purpose of resin surrounded and encapsulated the fibers are to bind them together, protect them from danger, maintain their alignment and to allow distribution of load among them. Polymers are available in two categories, thermosetting polymers (e.g. epoxy and polyester) and thermoplastic polymers (e.g. nylon). More details on the chemical compositions and mechanical properties of various types of fibers and polymers are given in many textbooks. The corrosion of steel plates, deterioration of bond between steel and concrete, installation difficulties because of employment heavy equipments have been identified as major drawback of bonding steel plate technique. FRP composites have become more popular and accepted by designers, contractors and owners due to combinations of their unique characteristics.

Recently FRP is becoming popular in the construction industry for strengthening purpose. There are many advantages of FRP as a strengthening tool that is listed below [C.-T. T. Hsu, et al. (1977)].

- Low volume to weight ratio: Density of FRP materials is about one fifth of the density of the steel. Therefore, it is easier to transport without any need of special equipment.

- Immunity to corrosion: FRP materials are non-corrosive, non-magnetic and have excellent resistant to chemical attack whereas steel is a corrosive material when expose to chemical processes due to aggressive environmental conditions (chloride).

- Unlimited delivery length (in sheet form): FRP are available in very long length while steel are generally limited to 6m length. Therefore, there is no need for joints.

- High strength and stiffness retention: FRP has high strength and stiffness retention. Therefore, the ultimate strength is 8 to 10 times higher than steel.

- Easy installation: FRP can be installed and handled easily by using man-access platform rather than full scaffolding platform that are used for steel.

- Time saving: FRP can be installed in a very short time compared with the time taken for installing steel plates. This is because FRP is applied externally to the reinforced concrete structure.

- Labour saving: It has a low weight which reduces transportation expenses and allows for some prefabrication that consequently reduces time at the job site. Besides that, simple installation and limited construction time result in decreasing the cost of labour.

- High elastic modulus: FRP is has high elastic modulus and strength in both tension and compression.

- Durability factor: FRP do no need any maintenance that may cause traffic disruption and access cost.

- Flexibility: FRP solves the shortcoming of steel which have their own shape and non-negligible flexural stiffness. This is because FRP come in very thin layers with negligible flexural stiffness and can easily follow a curved profile without any pre-shaping.

There are also several other benefits of FRP. FRP is used repair damaged concrete structures. FRP is also used to strength undamaged concrete structures that require greater load capacity due to functional change, additional load or other reasons [C.-T. T. Hsu, et al. (1977)]. The use of FRP composites is accomplishes by utilizing the tensile strength and stiffness of the composite and the strain compatibility of the composite to the existing member. The design must include proper selection of the adhesive used to bond the FRP reinforcement to the surface of the concrete to be strengthened.

The type of composite, the number of layers, the orientation of fibers, and the preliminary work and surface preparation, all depends on the design goals and type of structural element as determined by the project. FRP have few disadvantages such as FRP materials have risks of fire and accidental damage. A particular concern for bridges over roads is the risk of soffit reinforcement being ripped off by over height vehicles. Even though the FRP materials are expensive but the extra cost of the material is balanced by the reduction in labour cost. More research has to be carried out because it is difficult to find contractor with the appropriate expertise for the application of FRP. By doing research on FRP, it will enhance FRP application in the country.

There are a few types of fibers. The selection depends on the type of fiber to be used for a particular application. This depends on the factors such as type of structure, expected loading and the environmental conditions. The common fibers used for strengthening and upgrading are:

- Carbon fiber
- Glass fiber
- Aramid fiber

2.3.1.1 Carbon Fiber (CFRP)

Fibers have a crystalline structure similar to graphite which is hexagonal, with carbon atoms arranged in planes held together by Van Der Waals forces. Atoms in each plane are held together by covalent bonds, much stronger than Van Der Waals forces, causing in high strength and stiffness in any direction within the plane. Carbon fibers are characterized by their high value of strength and stiffness.

Carbon fibers are used for the fabrication of high performance composites. Carbon fibers fail in brittle mode with low energy absorption [M.R. Islam, et al. (2005)]. CFRP is not very sensitive to creep and fatigue. These fibers are made of pure carbon in form of graphite and the fibers are low in density. These fibers also have a negative coefficient of longitudinal thermal expansion.

These carbon fibers are very expensive and can give galvanic corrosion in contact with metals. Therefore, they are generally used together with epoxy where high strength and stiffness is required. CFRP is an expensive material as compared to steel but the total rehabilitation project costs could be about 20% lower by using CFRP than steel. This is due to the savings in construction expenses. CFRP bonding leads to a slower critical diagonal cracks and enhances the load-carrying capacity of the beam. It will enhance the load carrying capacity up to a level that is sufficient to meet most of the practical upgrading requirements. Carbon fiber-reinforced polymers (CFRP) used has a combination of high strength unidirectional fibers with an epoxy matrix which can be cured at temperatures ranging from 5°C to 30°C [C.-T. T. Hsu, et al. (1977)].

Generally, there are eight possible failure modes in CFRP strengthened reinforced concrete beams. Not all of this eight failure modes were observed in pervious researches or applications. For a simply supported reinforced concrete beam strengthened by CFRP, the following four modes will most likely occur [C.-T. T. Hsu, et al. (2003)].

:i) CFRP rupture in tension zone

ii) Concrete crush in compression

iii) Delamination between CFRP and concrete

iv) CFRP peeling off in curtail zone resulting from a combination of shear and tensile stresses in the plane of the longitudinal steel bars

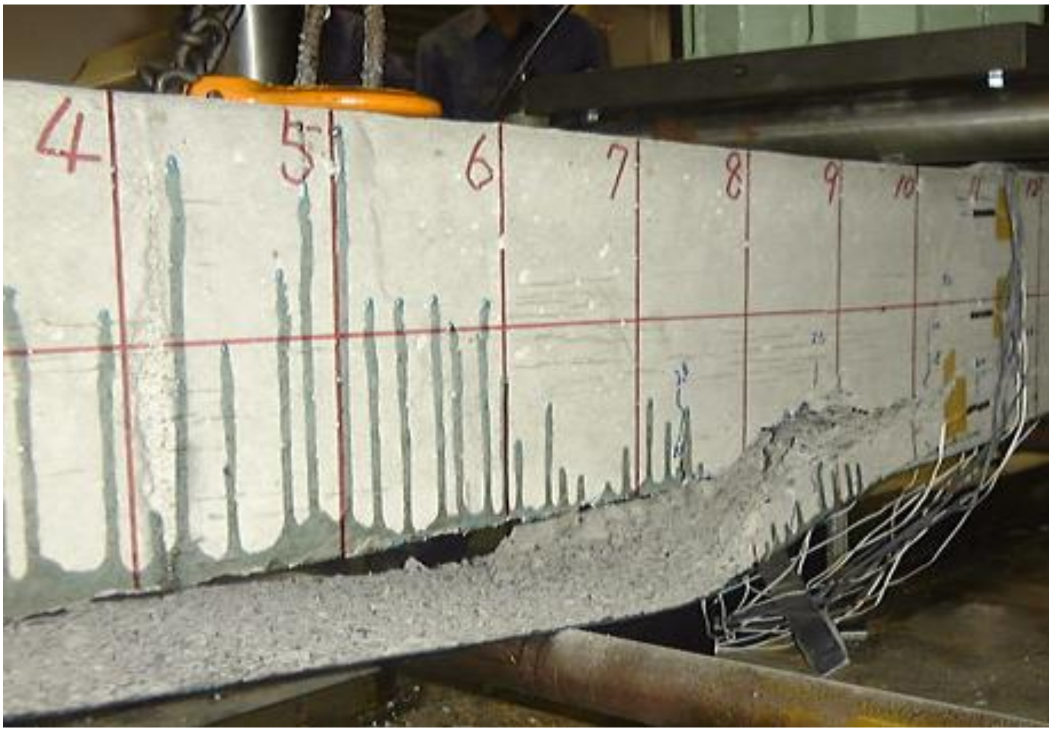

Fig. 2.1 Peeling of CFRP Sheet

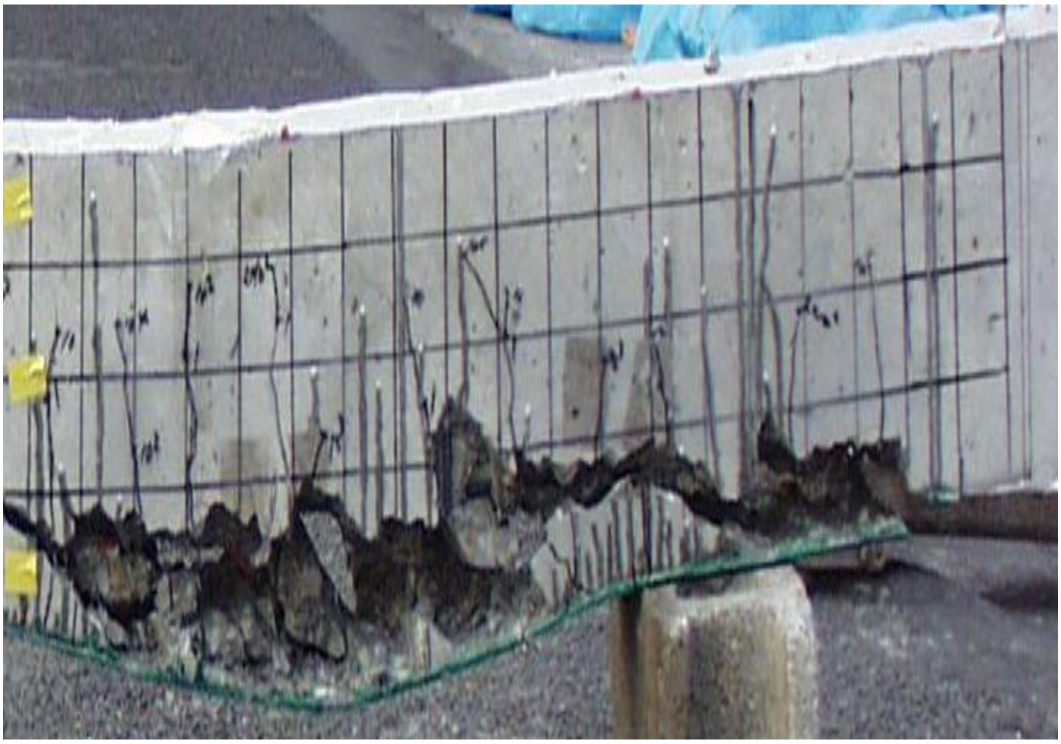

Fig. 2.2 Delamination between CFRP Sheet and Concrete

2.3.1.2 Aramid Fiber (AFRP)

AFRP are organic fibers made of aromatic polyamides in an extremely oriented form. These fibers are distinguishes for their high tenacity and resistance to manipulation. AFRP strength and stiffness is usually in the middle of the glass and carbons fibers. Compressive strength is usually about 1/8 of the tensile strength. This is due to the anisotropy of the structure of the fiber. AFRP fiber has compression loads that enhance the localized yielding and buckling which resulted in the formation of kinks. AFRP fibers can decompose under sunlight that can cause lost of strength of up to 50% and also sensitive to moisture, exhibit creep and sensitive to fatigue.

2.3.1.3 Glass Fiber (GFRP)

GFRP fibers are widely used in the naval industry for the fabrication of composites with medium to high performance. They are characterized by high strength. Glass is mainly made of silica (SIO2) in the tetrahedral structure. Aluminium and other metal oxides are added in different proportions to simplify processing or modify some properties. GFRP fibers exhibit non-negligible creep and fatigue sensitive. A comparison among CFRP, AFRP and GFRP sheets (Nanni et al 1993) and reinforcing steel in terms of stress strain relationship is illustrated in Fig. 2.1.

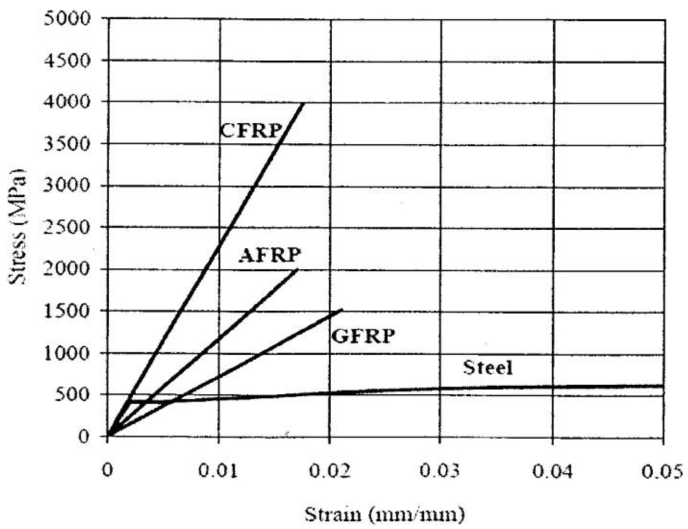

Fig. 2.3 Comparison among CFRP, AFRP and GFRP Sheets and Steel

Table 2.1 Major Characteristic and Application of FRP Composites

Description	Pre-cured (Pre-fabric)	Cured in situ (Wet lay-up)
Shape	Strip or laminates	Sheet or fabric
Thickness	About 1-1.5mm	About 0.1-0.5mm
Use	Simple bonding of factory made element with adhesive	Bonding and impregnation of sheet or fabric with resin (shaped and cured in situ)
Typical applications aspect	- If not pre-shaped only for that surface - Thixotropic adhesive or bonding - Normally one layer, multiple layer possible - Stiffness of strip and use of thixotropic adhesive allow for certain surface unevenness - Simple in use high quality guarantee (pre-fabric system)	- Regardless of the shape, sharp corners should rounded - Low viscosity resign for bonding and impregnation - Often multiple layers - Often a putty is needed to prevent debonding due to unevenness - Very flexible in use, need rigorous quality control
	Quality control (wrong application and bad workmanship loss composites action between FRP and substrate structure)	Lack of long tem integrity of the system

2.3.2 Structural Strengthening using CFRP

CFRP laminates are pasted on concrete structure by using resins. There are many types of resins used with FRP. The most common resins used in the field of civil engineering are epoxy resins. There are also several others resins used such as polyester or vinyl resins. According to ACI committee 440 (1995), FRP requires the following characteristic of resin:

- Resistance to environmental workability
- Pot life consistent with the application
- Filling ability and workability
- Compatibility with and adhesion to the concrete substrate and FRP
- Development of appropriate mechanical properties of FRP

FRP are chemically bonded to the structure by using adhesives. Chemical bonding is used because it does not induce stress concentrations, is easier than the mechanical devices to be installed and does not damage the base material or the composite. The most suitable adhesive for composite materials are epoxy resin based adhesive. Adhesive is made of two-component mix. The major component contains of organic liquids (epoxy groups). A reagent is added to the above mix to obtain the final compound. The purpose of this adhesive is to bond the materials through interlocking and formation of chemical bonds. The preparation of the surfaces to be bonded plays a important role for the effectiveness of the adhesive. Treatments of the surface can be done as:

1. Construction defects, remarkable deterioration and cracking in the surface of concrete shall be repaired appropriately. Non-brittle sections, projections, level difference and other unevenness in the surface of concrete shall be removed through chipping or polishing to make the surface smooth.

2. The main aim to treat surface is to have a clean surface, free from any contaminant such as oxides, powders, oils, fat and moisture. Cleaning is

performed using solvents to obtain good interlocking. For porous surface, a priming coat may be required which must be compatible with the adhesive.

3. When continuous fiber sheets and continuous fiber strands are placed perpendicular to the corner angles, the corner angles must be rounded through chipping or polishing, or using a smoothing agent.

Table 2.2 Comparison among Epoxy and Polyester or Vinyl Resins

Epoxy Resin	Polyester or Vinyl Resin
- Contains better moisture repellent and offer good resistance to chemical attacks. - Maximum working temperature is usually below 60^{o}C. - Higher working temperature epoxy is also available. There are no limits on the minimum working temperature. - Organic liquids compose the main reagent with low molecular weight containing epoxy groups, rings composed of two atoms of carbon and one atom of oxygen.	- Polyester or Vinyl resin has lower viscosity when compared to the epoxy resins. - These resins have lower chemical resistance and chemical properties compared to epoxy resins. - At ambient temperature, these resins are in solid manner. Therefore, solvent is added before use. - These resins have polymers with high molecular weight and double bonds between carbon atoms. Therefore, these resins are capable for chemical reaction.

When the material is placed on the prepared and clean concrete surface, sufficient pressure is applied with rollers. The main aim of rollers is to ensure a uniform adhesive layer and to expel any trapped air, remove surplus adhesive epoxy from sides of plates while adhesive is uncured. Finally the impregnation resin is cured thoroughly.

Initial costs of FRP materials are significantly higher than those of conventional materials. In addition, costs associated with the activities that bring these new materials from the research laboratory to full acceptance by the construction industry can be significant. Examples of these costs include full-scale testing and non-destructive evaluation of demonstration projects. This cost premium is the main economic barrier preventing the use of FRP on a wide scale in the precast, prestressed concrete industry. This, in turn, hinders the build-up of adequate experience in FRP, which would help increase production and thereby, reduce costs. To break this cycle of high initial costs, lack of experience, and small-scale production of FRP, it is important to realize that FRP materials provide clear life-cycle benefits that could make them financially viable even if they cost more initially [Nystrom et al. (2002)]. Due to their favourable properties, especially their non-corrosive properties, FRP reinforcement could reduce bridge life-cycle costs, which include maintenance, inspection, repair, disposal, and replacement. Moreover, FRP could incorporate fibre optic sensors for structural monitoring, which would lead to increased structural sustainability.

Current FRP technologies and practices vary significantly and these products are in the introductory phase of the product life cycle [Nystrom et al. (2002)]. Thus, it may be difficult to quantify the life-cycle cost benefits of FRP materials with great level of precision except for a specific project [Ehlen (1997)]. However, generalizations can be made despite the uncertainties involved. Ehlen and Marshall (1996) analyzed the cost effectiveness of FRP bridge decks relative to reinforced concrete decks. They concluded that, once FRP composites begin to be applied and accepted, their lifecycle costs will diminish, making them more cost competitive with conventional materials. This happens for three reasons. First, spreading the new technology (NTI) costs of a composite bridge over multiple bridges of similar design can significantly reduce the life-cycle cost per bridge. Second, NTI costs diminish over time as the behaviour and performance of the material and/or design become more certain, and users accept it, thereby reducing the cost of material testing. Third, as large-scale production occurs with increasing applications and increased demand for the material, and as the number of competing material's manufacturers and suppliers increases, the cost of FRP itself will be reduced.

2.3.3 Effects of Static and Cyclic Load on RC Beams and Role of CFRP Sheets

There is a wide range of research pertaining to the use of FRP in bridge repair. Rebar, grating into concrete, and wrapping around columns and piers are just a few examples of the broad applications of these composites. [Norris & Saadatmanesh (1994)]. The following section was limited to research of FRP material externally bonded to the tensile face of concrete beams. In particular, research studying the effect of externally applied FRP materials on the flexural performance of reinforced concrete beams was reported.

A research on the difference behaviour of CFRP and steel reinforced beam was carried out by Muhammad Masood Rafi et al. (2006) shows that the behaviour between CFRP and steel reinforced beam similar in many aspects. The numbers of cracks with equal average crack spacing at failure were developed in both types of beams. Beam reinforced with steel failed by steel yielding and beam reinforced by CFRP failed by concrete crushing as per design. This research also shows that the beam reinforced with CFRP deflected more than the beam reinforced with steel. However, after yielding of steel the rate of deflection in beam reinforced with steel is more than beam reinforced with CFRP. This research was carried out by casting 4 beams with the length of 2m and the cross-sectional was 120mm X 200mm. Each of the beams was reinforced with two longitudinal bars on the tension face (CFRP bars for CFRP reinforced beams and steel bars for steel reinforced beams). 20mm concrete cover was used all around the beams. For all the beams the area and nominal yield concrete of the compression steel and nominal concrete strength were kept constant. The beams were left for air-drying and for each beam 4 cubes were cast for testing.

Another research on behaviour of CFRP strengthened the reinforced concrete beams with and without end anchorage provided at the ends of CFRP strips on the tension face of the beams which was carried out by C.-T. T. Hsu et al. (2002). This research shows that CFRP strips that are externally epoxy bonded to the tension face of the beam is an effective technique to repair and retrofit the reinforced concrete beams under both monotonic and cyclic loads. Ductility of a CFRP strengthened beam is adequate if the beam is properly designed or anchored for under-reinforced concrete section. Besides that for any over-reinforced beams the CFRP strengthened beams with and without end anchorage do not improve both the flexural strength and ductility as compared to the control beam. For this research 12 beams were cast to test the flexural strength of the beams. The variables include different beam spans, cross-sectional, steel ratios, with or without CFRP and with or without end anchorage. The beams were divided into two categories, 6 beams for under-reinforced section beams and 6 beams for over-reinforced section beams.

Tom Norris et al. (1995) have carried out research on the behaviour of damaged or under-strength concrete beams retrofitted with thin CFRP sheets. It shows that the CFRP sheets can increase the strength and stiffness of the existing concrete beam when bonded to the web and tension face. The direction of the reinforcing fibers is related to the magnitude of the increase and the mode of failure. CFRP sheets are placed perpendicular to cracks in the beam which largely increase the stiffness and strength in the beam and a brittle failure occurred due to concrete rupture as a result of stress concentration near of the CFRP. This shows that flexural or shear cracks in the beam were repaired. CFRP sheets which are placed obliquely to the cracks in the beam cause a smaller increase in strength and stiffness. This cause the beam to failure in ductile and preceded mode by warning signs such as snapping sounds or peeling of the CFRP. This research was done by casting 19 beams concrete beams which was applied with CFRP sheets at the tension flange and web. These beams were loaded to failure. Every beam had a cross-section of 127mm X 203mm. 13 beams were over-reinforced for shear by increasing the spacing of stirrups. These beams were reinforced in the manner to prevent shear failure and to isolate the flexural behaviour from shear behaviour. The 19 beams were cast for length of 2.44m and were simply supported. These beams were loaded at the quarter points to provide a region of constant moment and no shear in the centre of the beam.

Riyadh Al-Amery et al. (2006) has carried out research on the coupling of shear-flexural strengthening of RC beams. This research shows that CFRP strips enhance the shear strength of the concrete beam and contributes, compositely with the steel stirrups to the shear resistance. Besides that by using CFRP strips occurrence of debonding failure is prevented. This is done by providing an extra anchorage mechanism for the CFRP sheets. This CFRP strips also reduces the interface slip between the CFRP and the concrete section significantly. CFRP strips reduces one tenth of the slip values. This will enhance the composite action between the concrete beam and CFRP sheets leading to almost full composite state. Finally CFRP also increase the flexural strength up to 95% when this CFRP strips are used as anchor. If CFRP sheets are used alone, it will increase the flexural strength by 15%. The dominant mode of failure observed in the beams with straps is a ductile flexural failure with excessive yielding of internal steel prior to the rupture of CFRP sheets and crushing of the concrete. This research was carried out by casting 6 reinforced concrete beams with various CFRP retrofitting schemes. One of these beams was kept as a control beam for comparison and was kept without retrofitting. All the others beams were provided with either CFRP sheets for flexural strengthening or with coupled CFRP sheets and strips for overall strengthening. Two of the beams were tested in four-point bending over a total span of 2.3m and a shear span of 700mm. The other four beams were tested in three-point bending. This intended to increase the applied moment at the critical section of the beam. These beams have a width of 140mm, depth of 260mm and the CFRP strips of 50mm wide one layer with a complete loop of 75mm overlapping. These strips were spaced 200mm along the beam span. The CFRP sheets were pasted in three layers that was applied centrally in a wet lay up process along bottom surface of the beams having a width of 100mm and a length of 200mm.

An et al. (1991) developed a model to predict the stresses and forces of a reinforced concrete beam with externally applied glass fiber reinforced plastic (GFRP). This study was based on five assumptions: 1) linear strain distribution throughout the beam; 2) small deformations; 3) tensile strength of concrete was ignored; 4) shear deformation was ignored; 5) perfect bond between concrete and GFRP. They used classical flexural theory and strain compatibility effects, variables such as material strength, modulus of elasticity, and reinforcement ratios of the steel and GFRP were considered. Analytical results were compared with experimental results of an earlier research done by Saadatmanesh & Ehsani(1991). Predicted results based on model were found in well agreement with experimental.

Meier et al. since 1985 has carried out experimental studies involving bonded CFRP to reinforced concrete beams at the Swiss Laboratories for Materials Testing and Research. This experimental work is carried out to replace the steel plates with FRP laminates for repairing and strengthening of reinforced concrete beams by examining the strength and stiffness of the beams. At the earlier stage Meier et al. (1991), encompassed externally bonding CFRP sheets to twenty-six concrete beams. The beam dimension was 6” x 10” x 79” and minimally reinforced with 2 5/16” diameter bars on top and bottom and shear reinforced at ¼” link at every 8 ½”. The test set-up consisted of a four point loading on simple supports. By applying a unidirectional CFRP laminate sheets (0.012” x 8” x 79”) to the tensile side of the specimens the deflection of the strengthened beam was found to be 50% lower than that of the control beam. The cracks in the repaired beams were small and closely spaced along the length of the member. That contradicted the crack pattern of control beam, which was like a classic reinforced concrete crack pattern of fewer and larger cracks. This researcher also studied the failure modes related to FRP repaired beams which are:

- Tensile failure of the CFRP sheets (describes as sudden and explosive but is easily predicted due to cracking sound).
- Classical concrete failure in the compressive zone.
- Continuous peeling-off of the CFRP sheets due to an uneven concrete surface. It is also cause by the vertical displacement across shear cracks in the concrete.

In 1992, the researcher expanded the possible failure modes to nine. The additional six failures are:

- Shearing of the concrete in the tensile zone.
- Interlaminar shear within the CFRP sheets.
- Failure of the reinforcing steel in the tensile zone.
- Cohesive failure within the adhesive.
- Adhesive failure at the interface CFRP sheets/adhesive.
- Adhesive failure at the interface CFRP concrete/adhesive.

E.Ferrier et al. (2010) has carried out research on fatigue-loading effect on RC beams strengthened with externally bonded FRP. This research is focus on the damage behaviour of FRP-strengthened reinforced concrete structure subjected to fatigue loading. For this study, five beams were subjected to cyclic four-point bending. Beam 1, 2 and 3 (100mm x 170mm x 1200mm) were reinforced by one layer of externally bonded FRP. Beam 4, 5 and 6 were larger beams (150mm x 250mm x 2000mm). Beam 4 was not externally reinforced by composite while beam 5 was reinforced with three layers of FRP. Beam 6 was initially damaged by a flexural load corresponding to 60% of the calculated failure load and then repaired with three layers of FRP. Beam 6 was unloaded at the time of strengthening. The purpose of testing Beam1, 2 and 3 is to evaluate the effect of maximal loading level on cyclic behaviour. Beam 4, 5 and is tested to evaluate the efficiency of FRP reinforcement under high number of fatigue loads (106 cycles). After carrying out the experiment, there are several conclusions that can be made: The adhesive joint and the composite plate are strong enough for fatigue loading of 106 cycles (1Hz), concrete and steel strength limit the loading to be applied during fatigue and this limitation is not due to FRP tensile strength and adhesive layer and finally the results for the test on larger beams shows that the overall behaviour of RC beams is improved with the use of external FRP strengthening with a 40% increase in the service load.

Gheorghiu et al. (2005) have carried out research on fatigue and monotonic strength of RC beams strengthened with CFRP sheets. This research focus on the durability of RC beams externally strengthened with CFRP. The RC beams were submitted to monotonic loading or a combination of fatigue and monotonic loading. Fifteen beams (100mm x 150mm x 1215mm) were tested in research. Two of these beams were control beams, seven beams were tested monotonically using low-level cycle and final six beams were tested under monotonically using high- level cycle. From this research is obtained that during fatigue loading the strains were found to increase gradually. At the section where crack appears, the increase is significant. The overall stiffness deteriorates rapidly in the case of high-level cycling, especially at the initial stage. The CFRP-concrete interface degrades more for the high-level than the low-level cycled beams.

A research on static and dynamic behaviour of RC beam model strengthened by CFRP sheets was carried out by R. Capozucca at al. (2000). The aim of this research is to analysis the static and dynamic behaviour of RC beams strengthened by CFRP sheets after damage by cracking. Two beams with the dimension of 100mm x 150mm x 2450mm were tested. The damaged beams strengthened by CFRP sheets increases the resistance capacity but reduce the deflection. The bending stiffness of strengthened beam has increase if compared with undamaged RC beam in a same ratio. The beam pasted with two layers of CFRP sheets has higher strength compared to the beam pasted with one layer of CFRP sheets. Beam with two layers of CFRP sheets has less ductility compared to beam pasted one layer of CFRP sheets.

Abdalla et al. (1995) have carried out research on dynamic analysis of pre-stressed concrete beams with openings. The findings of this research are:

- The fundamental frequency of a simply support beam with opening located in the maximum bending zone is higher than solid beam whereas if the opening is located at shear zone then the fundamental frequency is smaller than solid beam.

- The width and depth of an opening in shear zone has higher effect on the fundamental frequency rather than the bending zone.

- The horizontal location of an opening has a significant influence on the natural frequencies of pre-stressed concrete continuous beams with openings and especially for beams with unequal spans.

- For continuous two span pre-stressed concrete beam with opening, maximum displacement occurs at the opening region even if the opening is located in the shear of the longer span.

- Horizontal stress in the opening chords consists of two parts. Firstly, on the primary moment resulting directly from the excitation load and secondly the secondary moment resulting from the shear force in the opening chords.

Preliminary experimental investigation of the fatigue bond behaviour of CFRP confined RC beams was carried out by Rteilet et al. (2005). This research is focused on the effect of the confinement provided by transverse CFRP sheets on the fatigue bond strength of steel reinforcing bars in concrete beams. A total of twenty-three beams with the dimension of 150mm x 250mm x 2000mm were tested. After carrying out this experiment, there were findings such as: For load ranges above the fatigue concrete and steel fails by a brittle splitting mode under repeated loading. The fatigue limit was about 50% of the static loading capacity of the beams and by adding CFRP it increased the fatigue bond strength. In general for the unwrapped beams the slip increased exponentially during the last 10% of the beams' life while for the wrapped beams the slip increased at a constant rate up to failure.

Gussenhoven et al. (2004) has carried out research on fatigue behaviour of RC concrete beams strengthened with different FRP laminate configurations. Thirteen small scale beams strengthened using CFRP composites were tested under repeated loads to investigate their fatigue behaviour. The beams were strengthened with different thickness and widths of composite laminates to identify parameters that would generate different failure modes. The dimension of the small scale beams are 102mm x 102mm x 914mm. This research proves that there are two primary fatigue failure modes which are fatigue fracture of reinforcing steel for beams subjected to moderate peak stresses (up to 70% of yield) or fatigue fracture of the concrete cover below the reinforcing steel for beams subjected to high steel stresses (between 70%

and 80% of yield) and stiff composite laminates. Wider laminates were more effective than narrower laminates to increase fatigue life of strengthened beams. Beam deflection was considered a more reliable indicator of damage progression than measured strains in the beams.

Shahawy et al. (1995) assessed the effectiveness of external reinforcement in terms of the cracking moment, maximum moment, deflection and crack patterns. Four beams (8” x 12” x 108”) were tested using minimum steel reinforcement (two ½” diameter bars) and varying the layers of unidirectional CFRP. In addition, non-linear finite element computer model was used to compare to the results of the experiments. The cracking moment of the CFRP repaired beams was much larger than that of the control beam. For one, two and three layers of GFRP, the cracking moment increased 12%, 61% and 105% respectively. The maximum moment also became larger and corresponded well to the theoretical data. A 13%, 66% and 105% increase was observed for the three different layers. This showed that CFRP behaved similarly before and after cracking of the beam. The deflection and cracking patterns showed results similar to experiments previously discussed. The deflection decreased inversely with the number of CFRP layers on each beam. The control had wider cracks while the repaired beams showed smaller cracks at relatively close spacing. This shows an enhanced concrete refinement due to the CFRP sheets.

2.4 Summary

The following remarks were highlighted from the previous studies related to opening in beams subjected to static and cyclic loads with strengthening of RC beams using FRP laminates and other methods that lead to determine gaps for this study:

1. Openings are divided into two types that are large and small opening depending on different researcher definition and understanding. As for this research all the openings are categorised as large opening because all the beams undergo static and cyclic loads and all the opening exceeded 0.25 times depth of the beam web.

2. Past research concluded that by applying FRP to the tensile face of a reinforced concrete beam will increases the stiffness and load capacity and decreases the deflection of reinforced concrete beams.

3. Failure modes of strengthened beams can be divided into two categories which are:

    i. Full composites action of concrete and FRP is maintained until concrete reaches crushing in compression or FRP fails in tension (classic failure).

    ii. Composite action of concrete and FRP is lost prior to failure due to debonding or peeling-off of FRP. Premature failure may occur before ultimate flexural capacity of the beam is reached owing to debonding. Therefore, bond failure mode needs careful consideration.

4. End anchorage system is used to improve the load carrying capacity of strengthened beams. Mechanical anchorage accomplished with anchor bolts and anchor plates can verify by confirming that the anchorage has sufficient strength to prevent anchorage failure.

5. The strength gain and reduction in ductility are two main sub sequences for flexural strengthening of RC beams with FRP plates. Beams which fail by crushing of concrete when a large mount of FRP used shows much reduced ductility. This mode is brittle and certainly undesirable.

6. More experimental and analytical work is needed to investigate the performance and the factors affecting the shear capacity of strengthened beams and to propose a better and more rational design approach for those members with the attention should be focused on cyclic behaviour. Researcher have proved that the CFRP strips increase the strength of the beam even if there is opening in the beam. CFRP not only increases the strength of the reinforced structure but also increases ductility and other aspects as explained above.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

Methodology of this research was encompassed on the experimental investigation to achieve the research objectives. The three main objectives of this research were to investigate the effects of various shapes of openings on the structural capacity of RC beams subjected to static and cyclic loading, to investigate the effects of traditional strengthening method (additional reinforcement bars along the edges) on returning the lost capacity and to study the effects of strengthening of beams with openings using CFRP sheets. Therefore, to achieve these objectives, two different type of test setup were adopted. In the first test, static loading was applied on the testing specimens and the load-deflection values between concrete, additional reinforcement bars along edges and CFRP sheets were obtained. In the second test, cyclic loading was applied on the testing specimens and the load-deflection values between concrete, additional reinforcement bars along edges and CFRP sheets were obtained. The following section gives brief description about the specimens used in experimental testing.

3.2 Specimen Description

The experimental work was carried out by testing twenty specimens subjected to static and cyclic load. The specimens were known as beams, which had large opening. All the twenty beams were 2500mm x 500mm x 150mm in size. Span of these beams is 2300mm where these beams are simply supported at two sides at 100mm at each side. Most of the buildings that are constructed are designed to have beams in length of 7m to 8m. Therefore, in this research the beams are design to have length of 2.5m (1/3 of actual length in practice) and also due to the machine constraint in handling too lengthy beams. The maximum length that the machine could test is 2.5m. Four of the beams were solid beams or reference beams, which had no opening but two of such beams had additional reinforcement bars at the top (2T10) and bottom (2T12) of the beams. These additional reinforcement bars for solid beams were located 800mm away from the each support with the length of 700mm. All the twenty beams had 2T10 bars at the top and 2T12 bars at the bottom of the beams.

The focus buildings for this research are offices, buildings, or hotels where these buildings are design based on live load, which varies between 3-5kPa. The size of reinforcement bars (2T10 and 2T12) was chosen based on the live load for these types of buildings. The reinforcement bars of 2T10 and 2T12 is commonly used in this type of buildings. These bars acted as the main bars in the beams. The beams also had stirrups of R6 bars with spacing of 300mm centre to centre. The yield strength for T10 and T12 bars is 460MPa and yield strength for R6 bars is 250MPa. Elastic modulus for T10, T12 and R6 bars is 230GPa. The concrete cover used was 25mm top and bottom for all the beams. According to BS 8110, the range for concrete cover should be from 25mm to 50mm. Therefore, the concrete cover used in the beams is 25mm.

There are four types of openings tested, which are square opening, rectangular opening, circular opening and elliptical opening. Beams with rectangular and elliptical openings had addition reinforcement bars along the edges. These additional reinforcement bars for beams with rectangular opening were located 800mm away from each support with the length of 700mm and for beams with elliptical opening the additional reinforcement bars were located 775mm away from each support with the length of 775mm. Beams subjected to static load were tested before cyclic load. The CFRP sheets were used to regain the strength and these CFRP sheets were applied externally to the beams.

The CFRP sheets were pasted based on the crack pattern obtain after testing the beams subjected to static and cyclic load. CFRP sheets were pasted only to the weaker beams, which were compared to solid beams. CFRP sheets were only pasted to the beams with circular and square opening subjected to static and cyclic load. Beams with rectangular and elliptical opening were added with additional reinforcement bars along the edges. Therefore, no CFRP sheets were pasted on these beams. The specimen details and beams elevation details of all the twenty beams are shown in the Table 3.1A, 3.1B, 3.1C and 3.1D and Fig. 3.1 below.

Table 3.1A Specimen (Solid Beams) Details

Beam No	Strengthening Methods	Shape of Opening	Spam of Beam (mm)	Design Strength (MPa)	Number of Openings	Type of Loading
1	No	None	2300	+/- 35	0	Cyclic
2	No	None	2300	+/- 35	0	Static
3	No	None	2300	+/- 35	0	Cyclic
4	Additional Reinforcement Bars along Edges	None	2300	+/- 35	0	Static

Table 3.1B Specimen (Beams with Opening without Strengthening Method) Details

Beam No	Shape of Opening	Spam of Beam (mm)	Design Strength (MPa)	Number of Openings	Location of Opening from support	Type of Loading
1	Square (240 X240 mm)	2300	+/- 35	2	850mm	Cyclic
2	Square (240 X240 mm)	2300	+/- 35	2	850mm	Static
3	Circular (Φ270 mm)	2300	+/- 35	2	850mm	Cyclic
4	Circular (Φ270 mm)	2300	+/- 35	2	850mm	Static
5	Elliptical (Φ125 mm, h=750mm, d=250mm)	2300	+/- 35	1	775mm	Cyclic
6	Elliptical (Φ125 mm, h=750mm, d=250mm)	2300	+/- 35	1	775mm	Static
7	Rectangular (700mm x 250mm)	2300	+/- 35	1	800mm	Cyclic
8	Rectangular (700mm x 250mm)	2300	+/- 35	1	800mm	Static

Table 3.1C: Specimen (Beams with Opening with CFRP Sheets) Details

Beam No	Shape of Opening	Spam of Beam (mm)	Design Strength (MPa)	Number of Openings	Location of Opening from support	Type of Loading
1	Square (240 X240 mm)	2300	+/- 35	2	850mm	Cyclic
2	Square (240 X240 mm)	2300	+/- 35	2	850mm	Static
3	Circular (Φ270 mm)	2300	+/- 35	2	850mm	Cyclic
4	Circular (Φ270 mm)	2300	+/- 35	2	850mm	Static

Table 3.1D: Specimen (Beams with Opening with Additional Reinforcement Bars along the Edges) Details

Beam No	Shape of Opening	Design Strength (MPa)	Number of Openings	Location of Opening from support	Type of Loading
1	Elliptical (Φ125 mm, h=750mm, d=250mm)	+/- 35	1	775mm	Cyclic
2	Elliptical (Φ125 mm, h=750mm, d=250mm)	+/- 35	1	775mm	Static
3	Rectangular (700mm x 250mm	+/- 35	1	800mm	Cyclic
4	Rectangular (700mm x 250mm)	+/- 35	1	800mm	Static

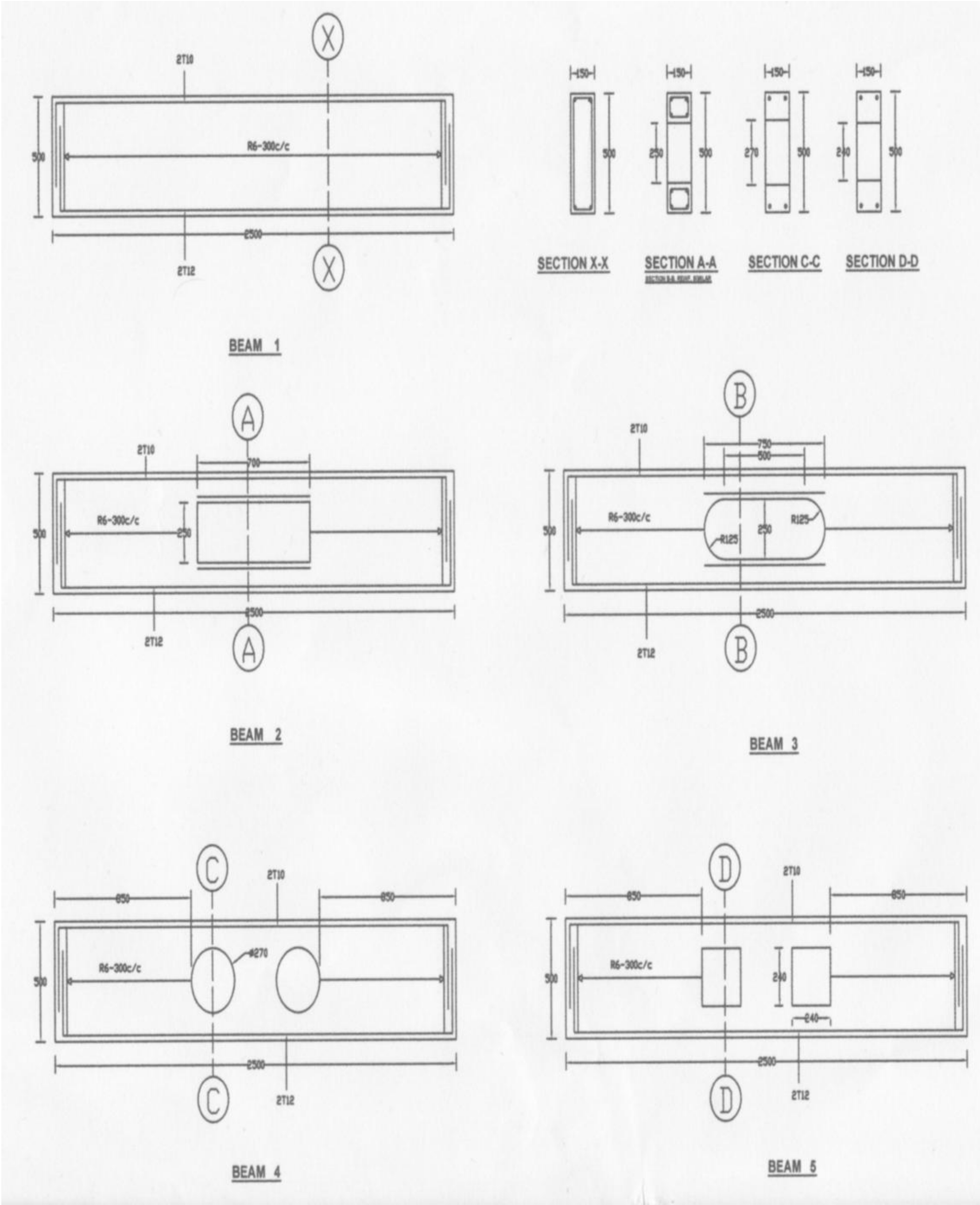

Fig. 3.1 Beams Elevation Details

3.3 Material Properties

All the beams were cast using ready mix concrete provided by Ban Loong Ready-Mixed Concrete Production Sdn. Bhd., Batu Gajah, Perak with the concrete strength, fcu of 35Mpa.The total volume of concrete includes the concrete needed to pour for the twenty beams and fifteen cubes. These fifteen cubes (100mm x 100mm x 100mm) were needed to test the concrete compressive strength. These cubes were tested on 3rd, 7th and 28th day. The strength obtained on the 28th day is the value to show the concrete compressive strength. The mix proportions were 1:2:4 where one shows the proportion for cement, two shows proportion for sand and four shows the proportion for aggregates (coarse aggregate of 14mm maximum size). Water ratio used was 0.50.

3.3.1 Epoxy-Resin and CFRP Sheets

12600mm x 100mm x 1.4mm CFRP sheets were supplied by Sika, Malaysia and known as CarboDur S1012 were used in this research as an external strengthening material. An epoxy material known as SikaDUR-30 was used to glue or paste the CFRP sheets to the concrete surface of the beams. The epoxy was consisted of two components, which is Part A and Part B. Part A was white in colour base and Part B was black in colour hardener. The mix ratio of the two parts was 3:1 by weight where Part A with three proportion and Part B with one proportion. The mixture of the two parts is light grey in colour. The material on adhesive used for bonding and CFRP properties are shown in Appendix A and B. The epoxy-resin and CFRP sheets properties are describe in Table 3.2 below.

Table 3.2 Epoxy-Resin and CFRP Sheets Properties

Material type	Ultimate Strength (MPa)	Elastic Modulus (Gpa)	Elongation at break (%)	Adhesive strength on concrete (MPa)	Adhesive strength on steel (MPa)
CFRP 10cm width	2400	150	1.4	-	-
Epoxy-resin SikaDur-30	100	12.8	-	>2	>25

3.4 Mixing, Casting and Curing of Concrete Beams

Beams elevation details are shown in Figure 3.1A-3.1D. Four of the beams were cast with two circular openings (270mm diameter) in the middle of the beam, and the other four beams were cast with two square openings (240mm X 240mm) in the middle of the beam. Similarly next four beams were cast with one large rectangular opening (70mm x 250mm) in the middle of the beam and last four beams were cast with one large elliptical opening in the middle of the beam. There are also four beams without any openings known as solid beams or reference beams. All these twenty beams were cast using ready mix concrete. There were also fifteen cubes (100mm x 100mm x 100mm) cast to check the concrete compressive strength on the 28th day. All concrete ingredients were mixed according to BS 8110: 1997. The mix proportions were made for 28 day with the targeted strength of 35MPa and the required slump test range was 75- 25mm. Before the ready mix concrete was poured in the formwork, slump test was carried out to test the workability of the concrete.

In the first part, the formwork of the twenty beams was prepared according to the dimensions referring Fig. 3.1. After completing the formwork, reinforcement bars were placed and the ready mix concrete is poured in the formwork, which is illustrated in Fig. 3.2 to 3.6. A poker was used to apply vibration to the mixture in the formwork. Three layers of the concrete mixture were placed in each formwork and poker was used to vibrate after each layer was placed. The vibration was given not more than one minute. It cannot be more than one minute as it will enhance watering and honey combing in the mixture. This will give wrong result later when tested. After finished placing all the three layers, the top surface of the concrete is levelled with a trowel. Then the concrete beams were left for three days in the formwork to harden. After three days, the formwork of the beams was opened and the beams were placed at the corridor of the lab for curing purpose by water according to BS 1881: Part 108:1983. The beams are big in size and there are no curing tanks that are big enough for these beams. Therefore, the beams were covered with sacks and watered daily. The functions of the sacks are to keep water so that the beams won't be over dried and to avoid surface cracks at the surface of the beams. After 28 days these beams were ready to be tested by using the Universal Testing Machine, UTM.

The purpose of testing the fifteen cubes was to obtain the strength of the concrete after 28 days of curing. The expected concrete compressive strength, fcu is 35Mpa. These fifteen cubes were cast using the same concrete mixture as the twenty beams. Fifteen moulds were used to place the concrete mixture. The inner faces of moulds were brushed with oil and the screws were tightened. A poker was used to apply vibration to the mixture in the mould. Three layers of mixture were placed in the each mould and poker was used to vibrate after each layer was placed. The vibration was only given for two seconds. It cannot be more than two seconds as it will enhance watering and honey combing in the mixture. This will give wrong result later when tested under compression test. After finished placing all the three layers, the top surface of the concrete is levelled with a trowel. Finally, a marker pen is used to indicate the number and date of casting at the top surface of the concrete cube. Then the cubes were left one day in the mould to harden. The next day, the moulds were opened and the cubes were placed in water tank for curing purpose.

After that on the 3rd day three cubes were tested under compression test. Then the other three cubes were tested on the 7th day. The rest nine cubes were tested on the 28th day. All the results were taken and a graph was plotted. The major purpose of testing these cubes is to find out the concrete compressive strength, fcu on the 28th day. The concrete compressive strength, fcu supposedly should be 35Mpa and this was achieved in this experiment. Figures 3.7 to 3.11 show part of test preparation.

Fig. 3.2 Formwork for Beams with Rectangular Opening

Fig. 3.3 Formwork for Beams with Elliptical Opening

Fig. 3.4 Formwork for Beams with Square Opening

Fig. 3.5 Formwork for Beams with Circular Opening

Fig. 3.6 Formwork for Solid Beams

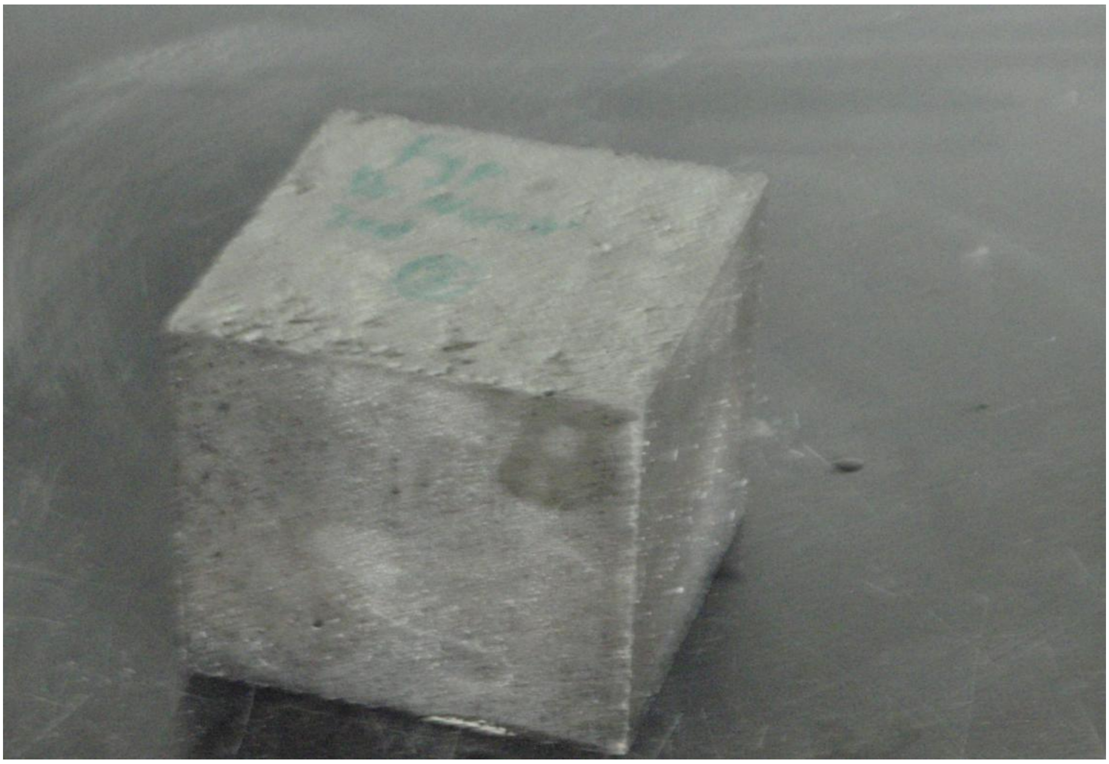

Fig. 3.7 Cube Ready for Testing

Fig. 3.8 Concrete Cube Placed under a Testing Machine

Fig. 3.9 Slump Test

Fig. 3.10 Universal Testing Machine, UTM

Fig. 3.11 Adhesive Materials: Part A (Yellow Pail) and Part B (White Tin)

3.5 Specimen Preparation before Testing

The following steps were carried out to prepare the beams before testing under static and cyclic loading by using the Universal Testing Machine, UTM:

- The concrete surface of all the twenty beams was roughened using a mechanical grinder to remove the surface laitance and flatten the surface. This is done to provide a uniform loading throughout the beams.
- The concrete surface was cleaned by using water to remove the dust or any loose particles.
- The concrete surface was painted and grid lines were drawn. These grid lines were drawn to show the crack pattern of the beams when static and cyclic load is being applied on it.
- The CFRP sheets were cut to the required length. Beam with square opening need eight pieces of 500mm x 100mm x 1.4mm and one piece of 1200mm x 100mm x 1.4mm. Beam with circular opening need one piece of 1100mm x 100mm x 1.4mm. All these CFRP sheets were cut into two sets, as there were two sets of beams.
- The CFRP sheets were cleaned with acetone. This process was repeated until the washcloth was no longer blackened.
- Uniform thickness of 1.5-3mm of adhesive layer was maintained by using aluminium guides.
- CFRP sheets were then smoothly hand-laid to achieve wrinkle-free surface, and extra epoxy was squeezed out and removed by keeping the thickness of epoxy between the acceptable range.
- The bonded surface with CFRP sheets was allowed to cure for a minimum of 7 days (to achieve its optimum strength) before testing under UTM.

3.6 Testing Procedure

The prepared beams were placed at the Universal Testing Machine. The beams were subjected to static and cyclic load. The loading was applied at the centre of the beams. All the beams were supported at end of both sides. The supports were located 100mm from the end at the both side. Once done setting up the machine and placing the beams at the correct position, the load is applied on the beams. Static loading beams are tested first. Solids beams were tested first continued with beams with openings under static loading. The static loading was applied until the beams fails. Then the results obtained are used for analysis purpose.

After finishing with static loading, cyclic loading beams are tested. Solids beams are tested first continued with beams with openings. The cyclic loading was applied until the beams fails. Then the results obtained are used for analysis purpose. After completing testing all the beams without CFRP sheets, the results were compared with the solid beams. Those beams that were weak compare to solid beam were pasted with CFRP sheets and were subjected to static and cyclic load. Beams pasted with CFRP sheets were tested following the same procedure as explained above. Static loading was carried out first and then continued with cyclic loading. All the pictures of failure mode and setup up are shown in Fig. 3.12 to 3.30.

3.7 Loading Conditions

There were two types of loading carried out for this research, which is static and cyclic loading. First static loading was carried out. Then from the results obtained cyclic loading was carried out. For static loading, all the beams were tested under a control load rate of 0.2kN/s. For cyclic loading, all the beams were subjected to medium cyclic load (10%-60%) of failure that was obtained from static test results of the beams. Fatigue or cyclic loading is effective when structure member will be subjected to minimum and maximum service load. The minimum service load is the self weight which about 10%. The maximum load can vary between 40-60% of the ultimate load. Each test for cyclic loading was performed under constant amplitude at a frequency of 5 Hz. This frequency was selected because conventional civil engineering structures are typically subjected to frequencies varying between 1 to 5 Hz (Chen et al 2001).

Fig. 3.12 Solid Beam on Testing Machine before Load is being applied

Fig. 3.13 Failure Mode of Solid Beam subjected to Static Load

Fig. 3.14 Failure Mode of Solid Beam subjected to Cyclic Load

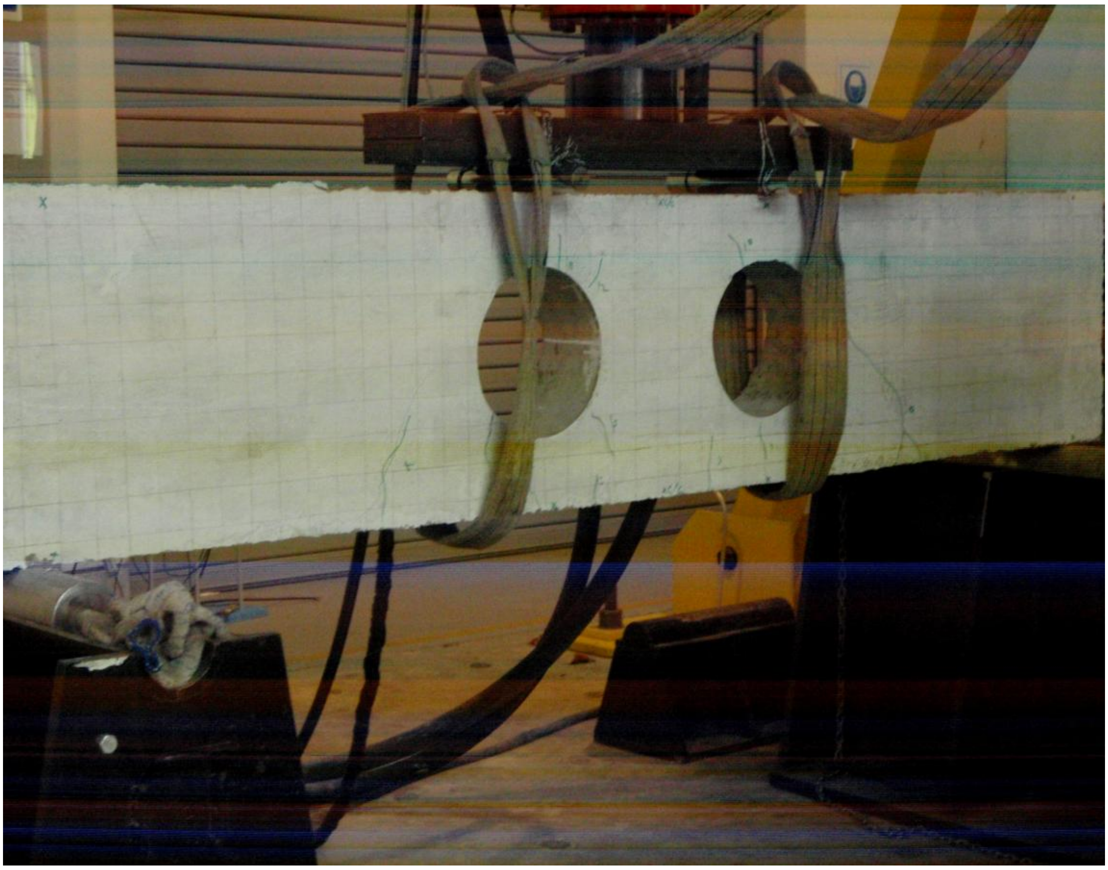

Fig. 3.15 Beam with Circular Opening subjected to Static Load

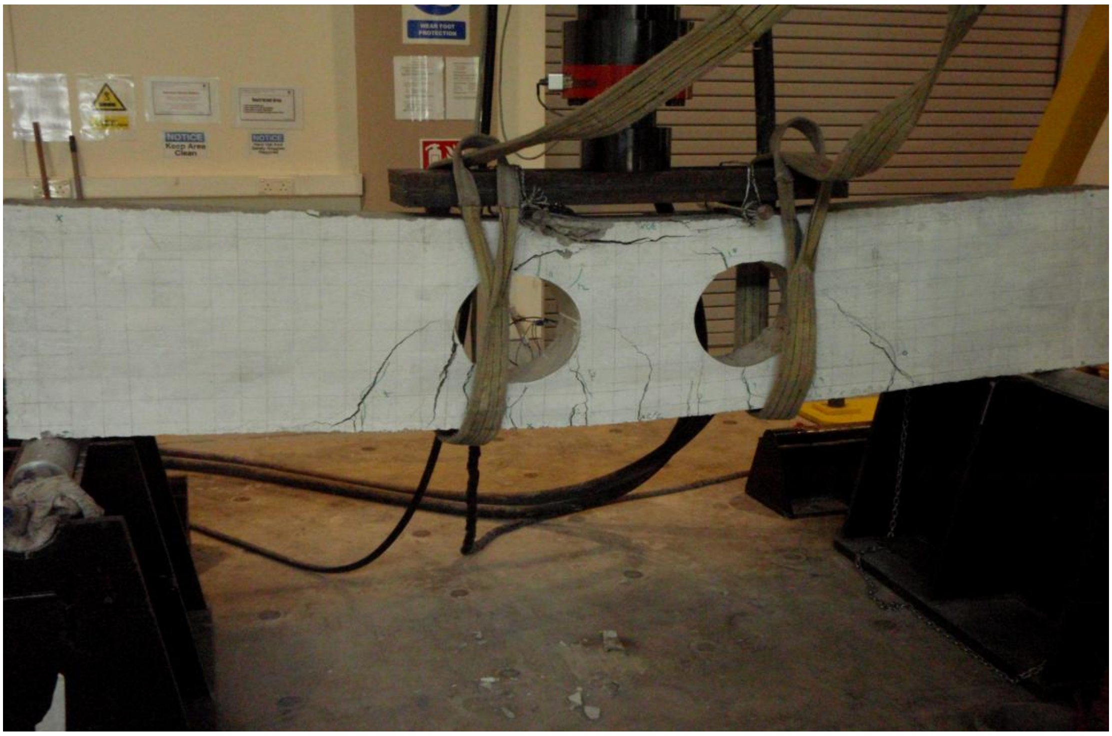

Fig. 3.16 Failure Mode of Beam with Circular Opening subjected to Static Load

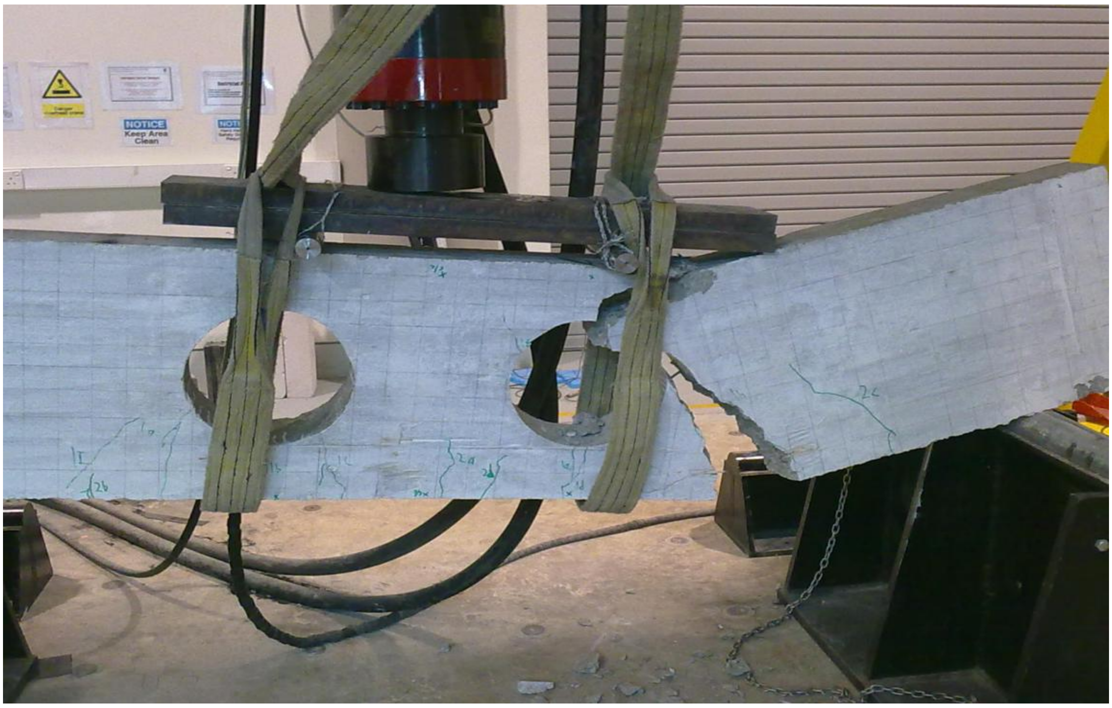

Fig. 3.17 Failure Mode of Beam with Circular Opening subjected to Cyclic Load

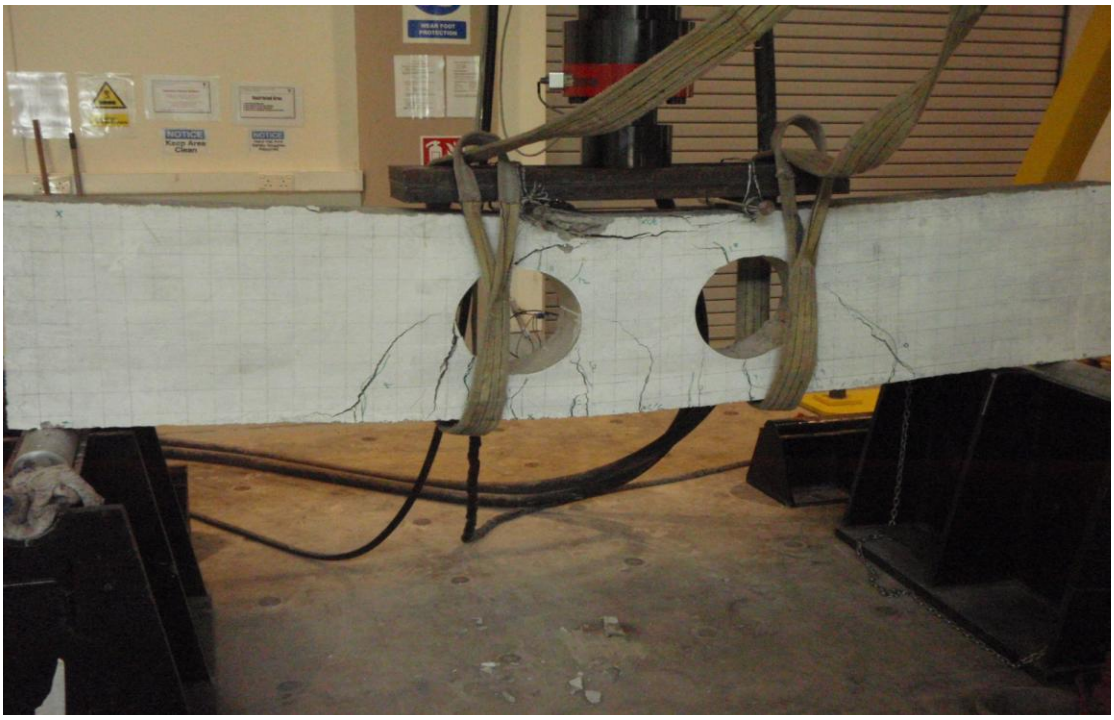

Fig. 3.18 Failure Mode of Beam with Circular Opening with CFRP Sheets subjected to Static Load

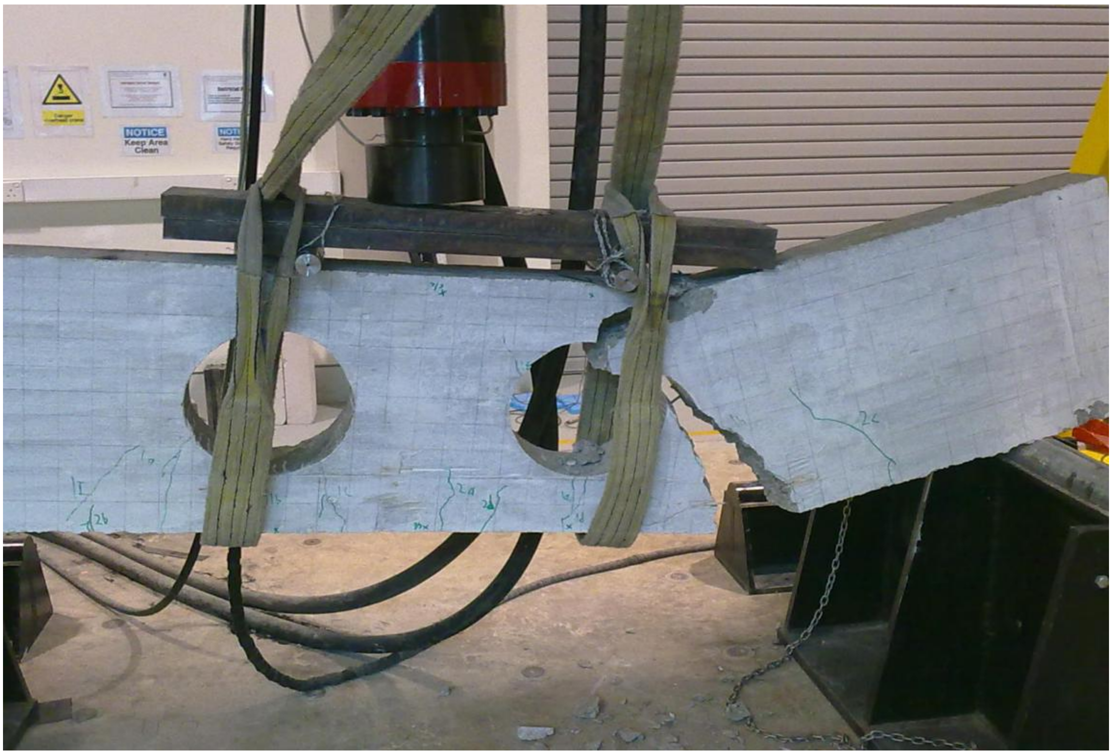

Fig. 3.19 Failure Mode of Beam with Circular Opening with CFRP Sheets subjected to Cyclic Load

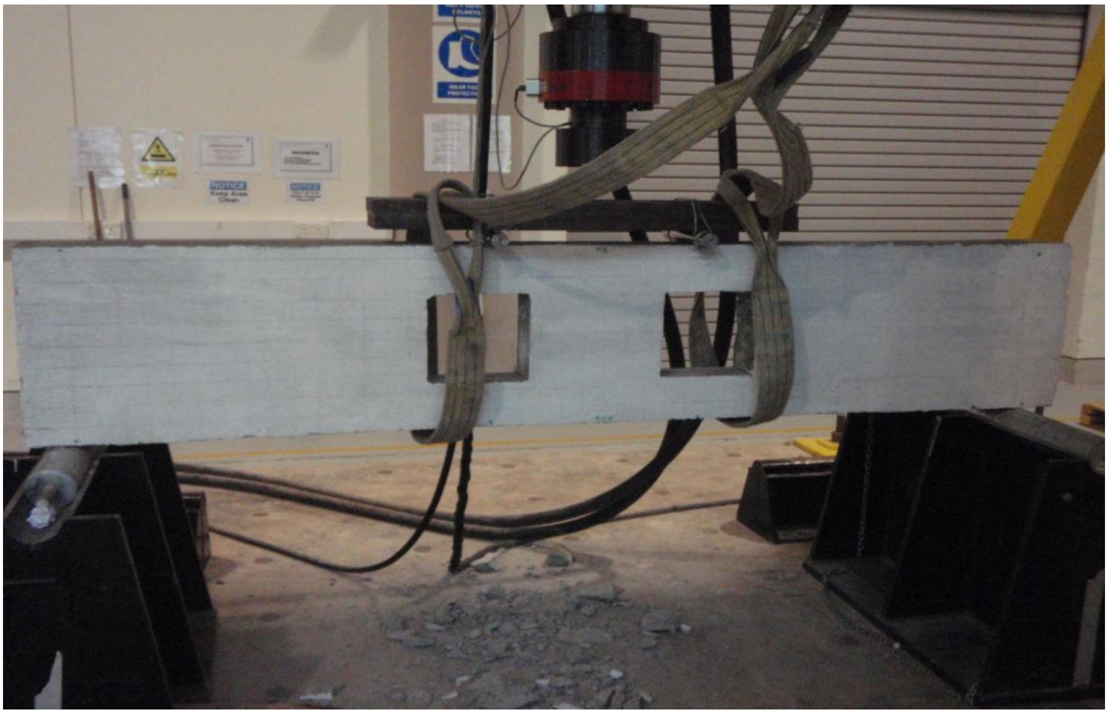

Fig. 3.20 Beam with Square Opening on Testing Machine before Load is being applied

Fig. 3.21 Failure Mode of Beam with Square Opening subjected to Static Load

Fig. 3.22 Failure Mode of Beam with Square Opening subjected to Cyclic Load

Fig. 3.23 Failure Mode of Beam with Square Opening with CFRP Sheets subjected to Static Load

Fig. 3.24 Failure Mode of Beam with Square Opening with CFRP Sheets subjected to Cyclic Load

Fig. 3.25 Beam with Elliptical Opening with Additional Reinforcement Bars along the Edges on Testing Machine before Load is being applied

Fig. 3.26 Failure Mode of Beam with Elliptical Opening with Additional Reinforcement Bars along the Edges subjected to Static Load

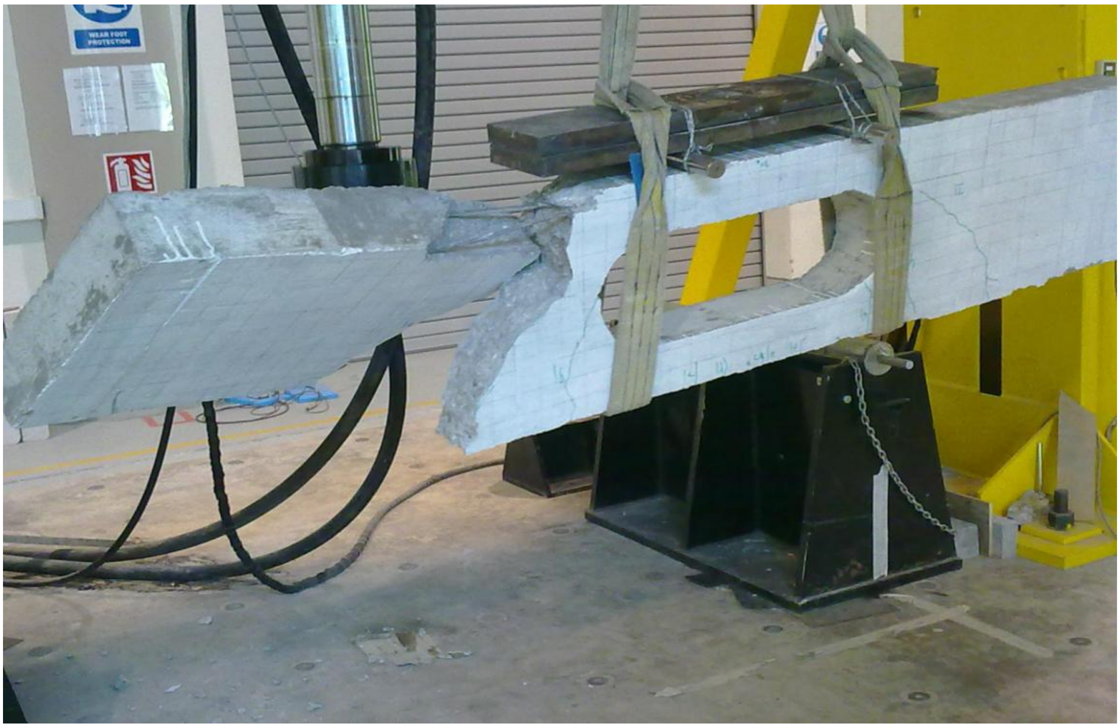

Fig. 3.27 Failure Mode of Beam with Elliptical Opening with Additional Reinforcement Bars along the Edges subjected to Cyclic Load

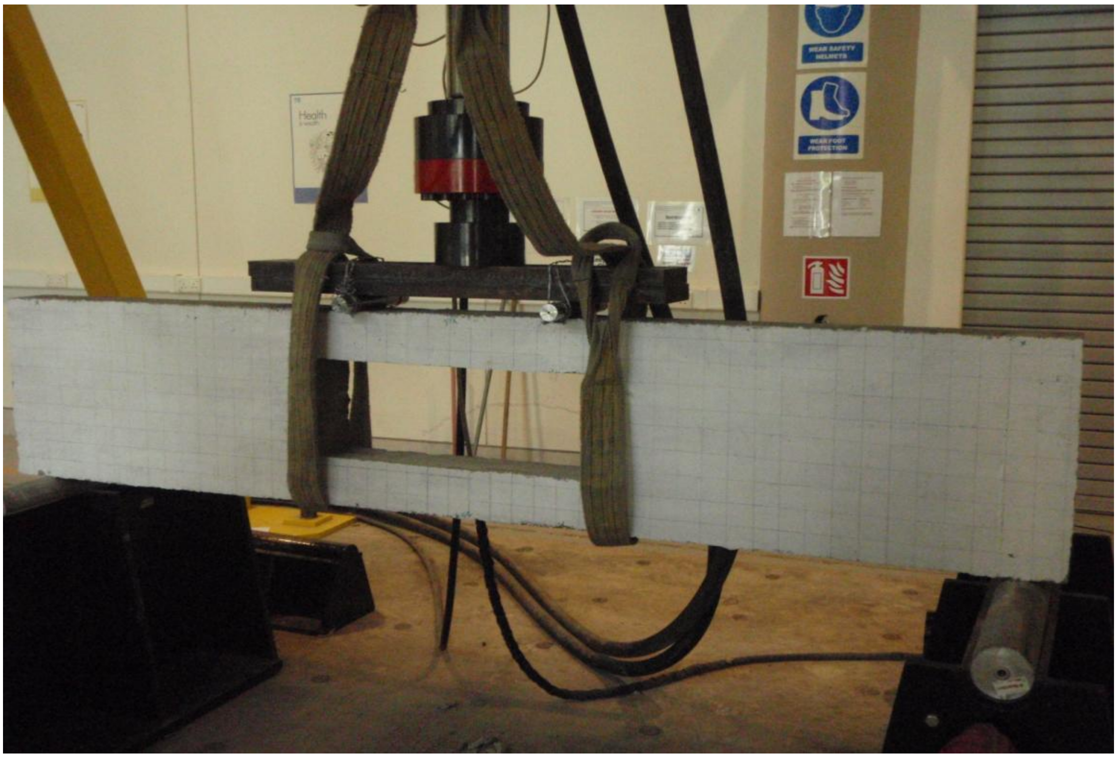

Fig. 3.28 Beam with Rectangular Opening with Additional Reinforcement Bars along the Edges on Testing Machine before Load is being applied

Fig. 3.29 Failure Mode of Beam with Rectangular Opening with Additional Reinforcement Bars along the Edges subjected to Static Load

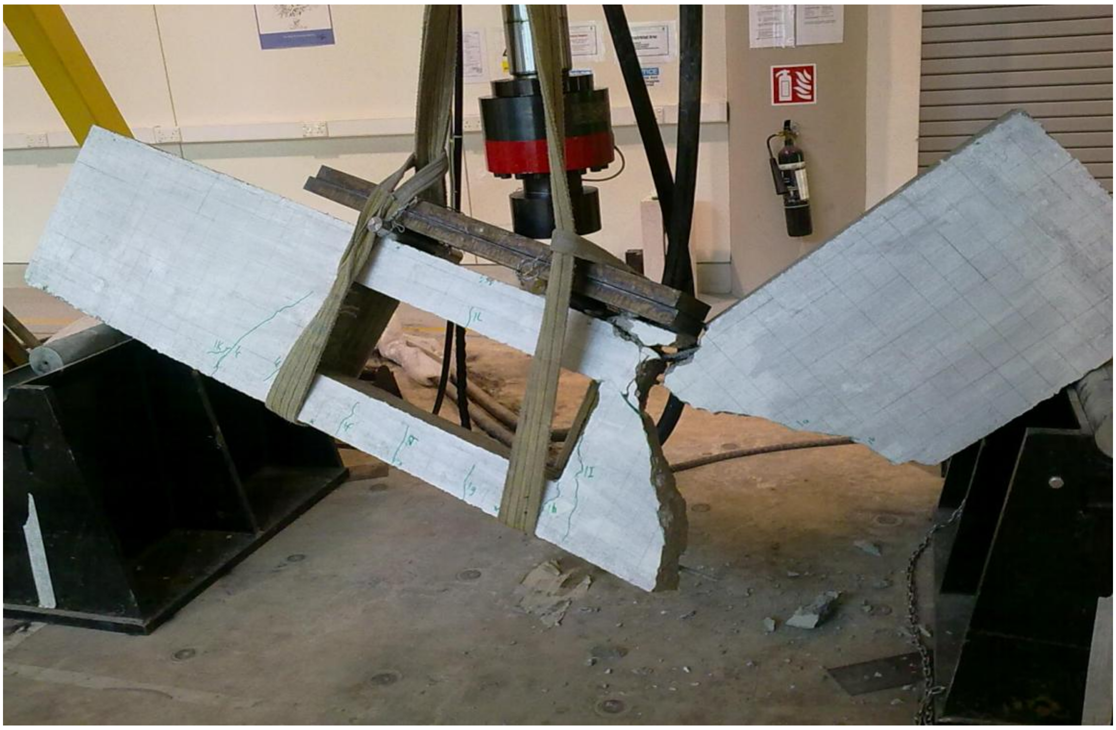

Fig. 3.30 Failure Mode of Beam with Rectangular Opening with Additional Reinforcement Bars along the Edges subjected to Cyclic Load

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the experimental results of beams testing together with the technical discussion supported with logical reasons, trends and behaviour. The principal aim of this research was to investigate the effects of opening on structural capacity of RC beams when subjected to static and cyclic loading. The main variables of the opening behaviour study were the shape of the opening, effectiveness of current procedure to investigate the capacity loss and to investigate the role of additional reinforcement bars along the edges and CFRP sheets to restore the lost capacity. Therefore, the main flow of this chapter is divided into two main parts. In the first part; static load testing results are discussed and in the second part cyclic loading results are discussed.

Concrete compressive strength is an important property of material that governs the structural behaviour of beams, columns and etc. For this research ready-mix concrete was acquired for designed grade of 35Mpa compressive strength, therefore from the supplied concrete, cubes were cast and tested at 3rd, 7th and 28th days. Average compressive strength is shown in Fig. 4.1 and the statistical parameters are given in Table 4.1. Table 4.1 shows the mean, standard deviation, median and mode value for the compressive strength of the ready-mix concrete. From the compressive strength test and statistical treatment have proved that the supplied ready-mixed concrete was in homogeneous condition and of good quality. The standard deviation value shows that the result obtains were good.

Table 4.1 Statistical Parameters of 28 Days Compressive Strength of Concrete (9 Cubes Results)

Mean	35.08 MPa
Standard Deviation	0.045
Median	35.08 MPa
Mode	35.05 Mpa

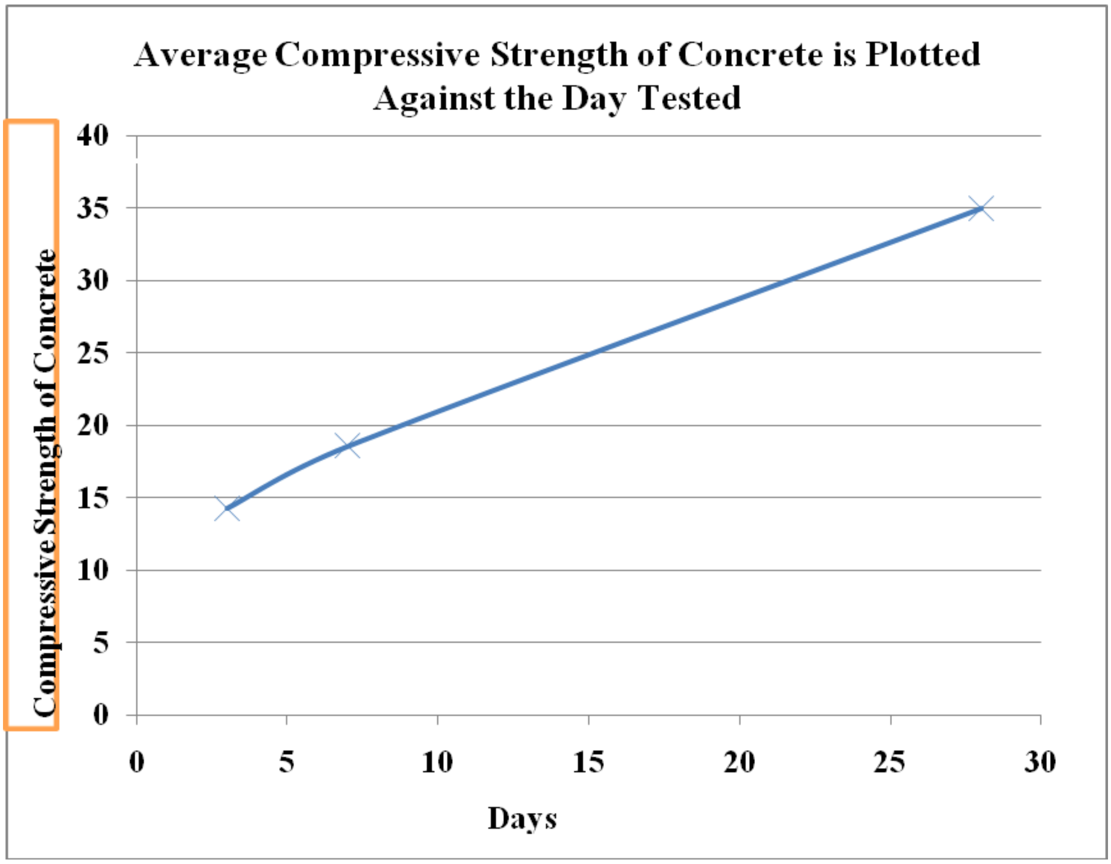

Fig. 4.1 Average Compressive Strength of the Tested 15 Cubes

4.2 Behaviour of Beams Subjected to Static Loads

In this part experimental results of all beams subjected to static loading are presented and discussed. One solid beam (as reference beam), one beam with circular opening, one beam with square opening, one beam with rectangular opening and one beam with elliptical opening were tested under static loading. All these beams were not pasted with any CFRP sheet. For the strengthening part using CFRP sheets, one beam with circular opening and one beam with square opening were tested. For the strengthening part using additional reinforcement bars, one solid beam, one beam with rectangular opening and one beam with elliptical opening were tested. Static load was applied at the rate of 0.15kN. Static loading was applied to the beam until the beam fails using hydraulic actuator of 100kN. Static load was applied as two symmetrical point loads. Fig. 4.2 shows the results plotted in graph.

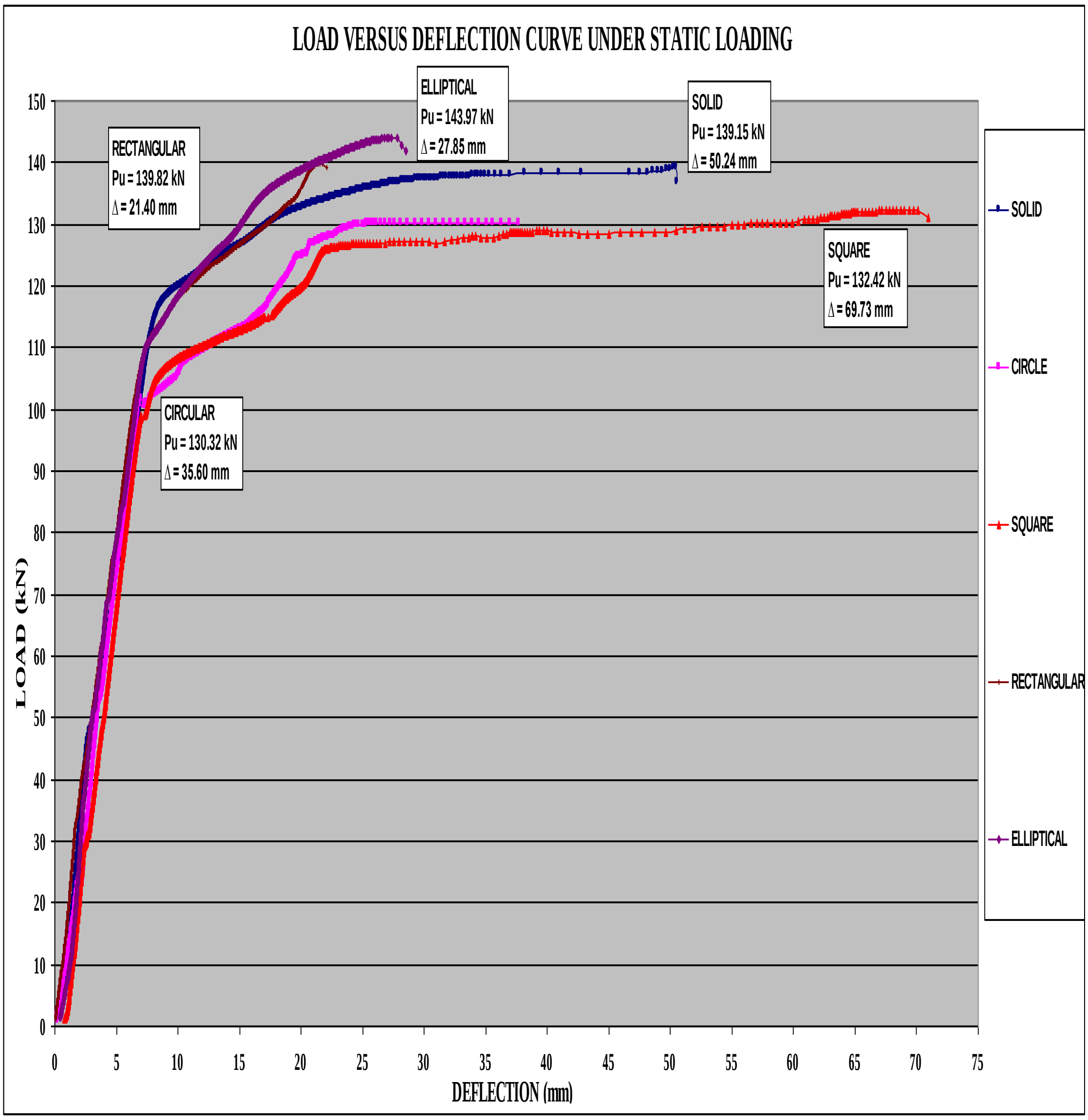

Fig. 4.2 Results of Beam subjected to Static Load

Table 4.2 Summary of Static Load

	Solid Beam (Reference Beam)	Beam with Circular Opening	Beam with Square Opening	Beam with Elliptical Opening	Beam with Rectangular Opening
Ultimate load subjected to static load	139.15 kN	130.32 kN	132.42 kN	143.97 kN	139.82 kN
% lost or gain in strength due to opening	Nil	-6.30%	-4.80%	+3.50%	+0.50%
Deflection at failure point (mm)	50.24 mm	35.60 mm	69.73 mm	27.85 mm	21.40 mm
Deflection at yield strength (mm)	8.81 mm	7.36 mm	7.80 mm	7.41 mm	7.23 mm
Load at yield strength (kN)	117.62 kN	100.10 kN	106.37 kN	110.18 kN	109.35 kN
Deflection at 35% of the ultimate load (mm)	2.41 mm	3.26 mm	3.68 mm	3.08 mm	2.84 mm
Opening proportion to the beam depth %	Nil	54% Large Opening	48% Large Opening	50% Large Opening	50% Large Opening

Fig. 4.2 shows the experimental load-deflection graph for all the beams subjected to static loading without any strengthening method. The starting linear part of the graph for all the curves has a very steep slope. This part shows to the un-cracked condition of these beams. In this region, the deflection is proportional to the applied load and the entire concrete section is considered effective in resisting the loads. Behaviour of all type of beams is similar before cracking and is shown in Fig. 4.2 where the beams are in the stiff condition. The ending of this linear part for all the curves shows the initiation of cracking in the beam. The next segment that immediately follows this linear part provides information for all the curves on the bond quality and tension stiffening effects due to crack spacing. The slope of this part is smaller than the slope of the starting linear part for all the curves. This shows that the rate of deflection per unit load is higher after the beam has cracked. This shows the reduction in the stiffness of the cracked beams. The last part of the curves shows the possible failure mechanism of the structure. As shown in Fig. 4.2, all the beams showed a very ductile behaviour and all beams failed at nearly the same load after undergoing considerable deformation with very small increase in the load once steel yielded. Similar load-deflection graph has proved that the characteristic of the curves. [Rafi et al. (2008)].

Table 4.2 shows the summary of ultimate load and deflection of beams subjected to static loading. The ultimate load here refers to the maximum load carried by the beam. All the beams with opening are compared with solid beam on the ultimate load. Beam with elliptical and rectangular opening gain strength compared to solid beam. Beam with circular and square opening lost strength compared to solid beam. This is due to the additional reinforcement bars along the edges of elliptical and rectangular opening beam. Therefore, additional reinforcement bars along the edges can increase the strength and control the crack width under service load. Deflection at the failure point of solid beam is also high if compared to beam with circular, rectangular and elliptical whereas beam with square opening has higher deflection at failure point if compared to solid beam. Beam with circular opening does not have any sharp edges but beam with square opening have sharp edges. Deflection increases if many cracks appear in the beam. Sharp edges will enhance more cracks and eventually higher deflection rate at failure point. Beam with elliptical and rectangular opening has lower deflection at failure point because these beams have additional reinforcement bars along the edges. Therefore, additional reinforcement bars along the edges can decrease the deflection at failure point.

The yield strength or yield point of a material is defined as the stress at which a material begins to deform plastically. Prior to the yield point the material will deform elastically and will return to its original shape when the applied stress is removed. Once the yield point is passed some fraction of the deformation will be permanent and non-reversible. Table 4.2 shows the deflection and load at the point where the beams start its yield strength. Solid beam has slightly higher value for deflection and load at yield strength. Beams with opening have the same range of deflection and load at yield strength. Its shows that solid beam can deform more elastically rather than deform plastically whereas beams with opening deform more plastically rather than elastically. Reduction in concrete volume will reduce the yield strength of the concrete. Therefore, it is safe to have beam without opening because this beam can behave more elastically rather than plastically.

One of the important factors that affect the serviceability of a RC beam is its deflection. Service load is considered as 35% of the ultimate load [Rafi et al. (2008)]. Table 4.2 shows the service load of each beam. The service load for these beams is in the range of 2.4mm to 3.7mm. Service load for all the beams falls under the yield strength of the beam. Therefore, all the beams have good serviceability. Serviceability, in general requires that the deflection produced under working loads must be sufficiently small and cracking must be controlled with maximum crack width not exceeding some tolerable limits. Solid beam’s theoretical ultimate load value is calculated based on American Concrete Institute, "ACI 318", 2005 and is shown below. Theoretically solid beam will fail at 108kN but experimentally solid beam failed at 139.15kN. Therefore, all the beams (solid and beam with opening) have failed at higher value compared to the theoretical ultimate load.

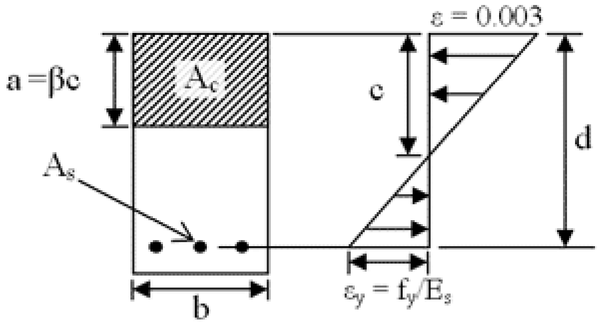

Fig 4.3 Concrete Beam at the Balanced Condition

$$a = \frac{A_s f_y}{0.85 f'_c b}$$

$$a = \frac{(227)(460)}{0.85(35)(150}$$

$a = 24$

$Mn = A_s f_y (d - a/2)$

$Mn = (227)(460)(475 - 24/2)$

$Mn = 48.35$ kN/m

As= Area of the tension steel

fy= The yield strength of the steel

f'c= The compressive strength of the concrete

b= The width of the concrete beam

a= Depth of the equivalent rectangular stress block

Mn= Nominal moment (capacity at failure)

P= Ultimate load

$M_{max} = Pa$

$Mn = Pa$

$48.35 = P(0.9)$

$P = 54$ kN

P = P + P

P **=** 2(54)

P = **<u>108 kN</u>**

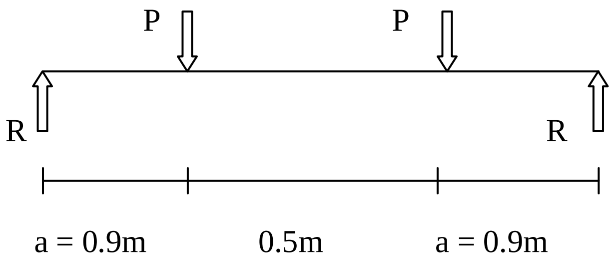

Fig 4.4 Beam Loading at Four Point Load

4.2.1 Effects of Strengthening

In this part, experimental results for solid beam with and without additional reinforcement bars and beam with circular and square opening with and without CFRP sheets subjected to static loading are presented and discussed. Based on Fig. 4.9 to 4.11, the cracking pattern is same for the beams without additional reinforcement bars and CFRP sheets. CFRP sheets are pasted perpendicular to the cracks obtained from the beam tested earlier under static loading. Beam with square opening was pasted with CFRP sheets around the opening area front and back of the beam and top and bottom of the beam. Fig. 4.10 shows that cracks in this beam were prevented as CFRP sheets blocked the cracks to continue. Therefore, by pasting CFRP sheets perpendicular to the cracks actually increases the strength of the beam. Beam with circular opening was pasted with one CFRP sheet at the bottom of the beam. This is due to circular openings are not so critical. By pasting one CFRP sheet at the bottom of the beam the strength of the beam increases and the cracking pattern is same as the beam without CFRP sheet. Refer Fig. 4.9. The solid beam with additional reinforcement bars also had the same cracking pattern as the solid beam without additional reinforcement bars. Refer Fig. 4.11.

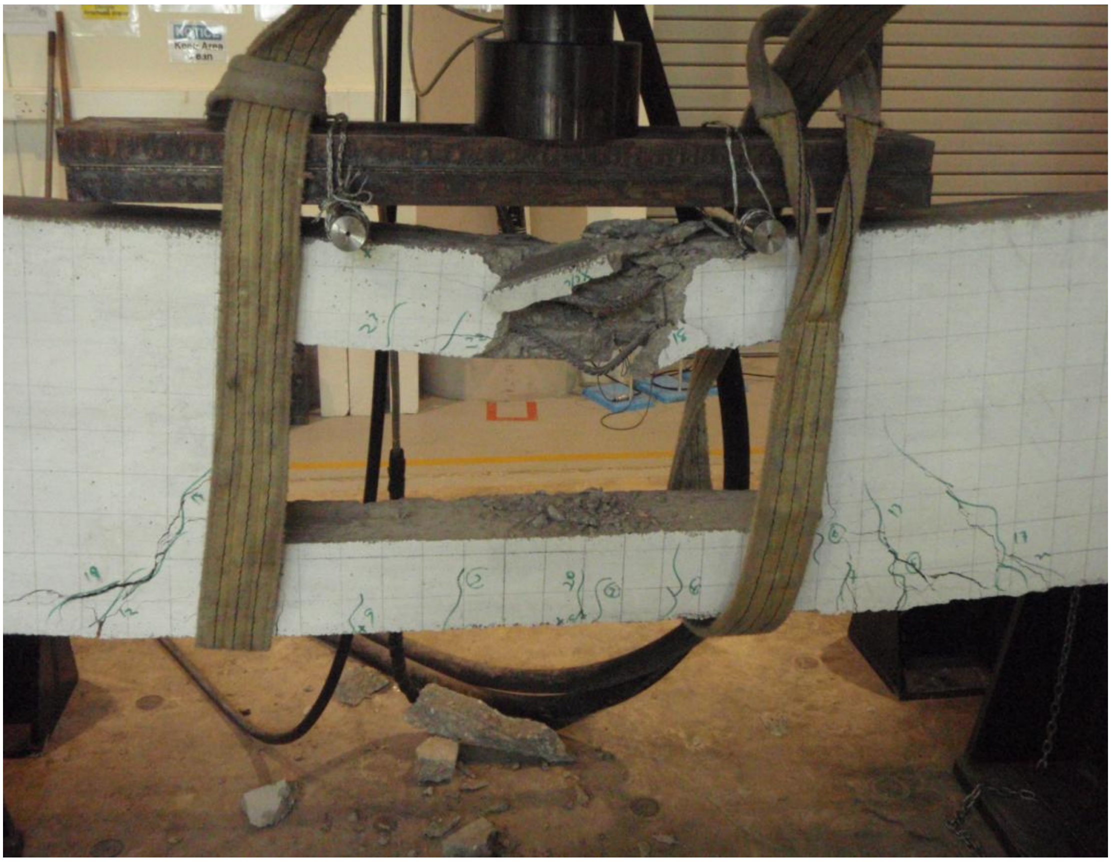

Fig. 4.5 Failure of Beam with Rectangular Opening with Additional Reinforcement Bars along the Edges subjected to Static Load

Fig. 4.6 Failure of Beam with Circular Opening subjected to Static Load

Fig. 4.7 Failure of Beam with Squarer Opening subjected to Static Load

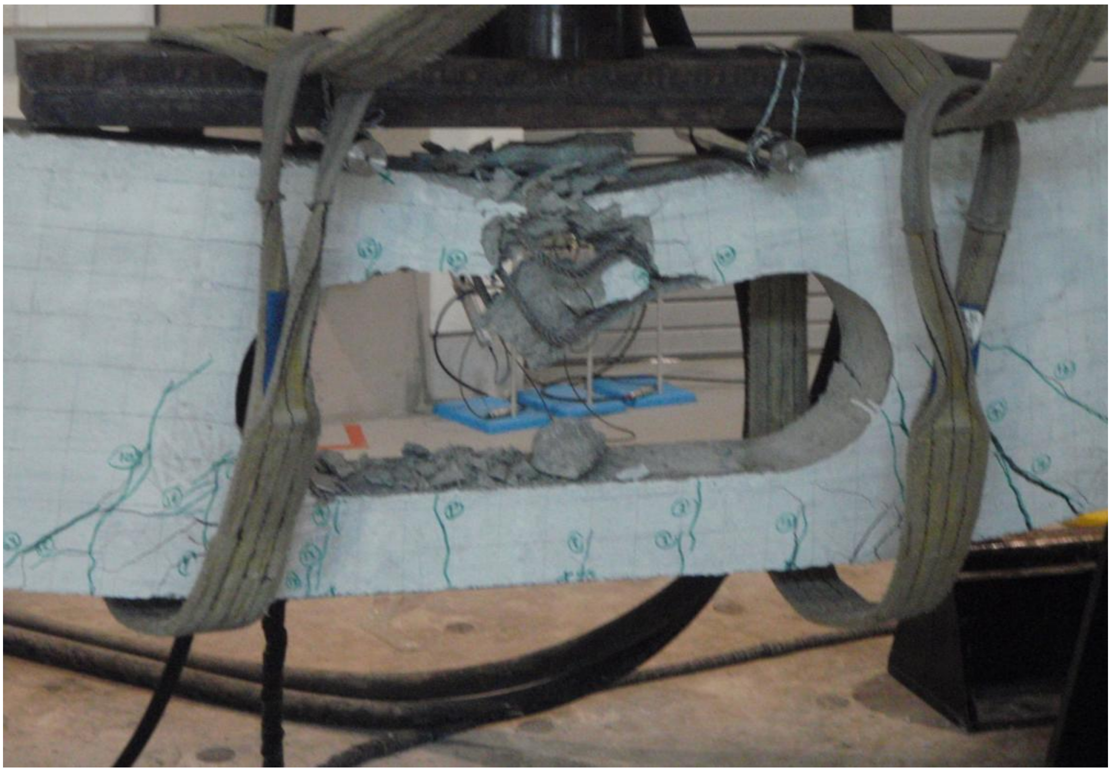

Fig. 4.8 Failure of Beam with Elliptical Opening with Additional Reinforcement Bars along the Edges subjected to Static Load

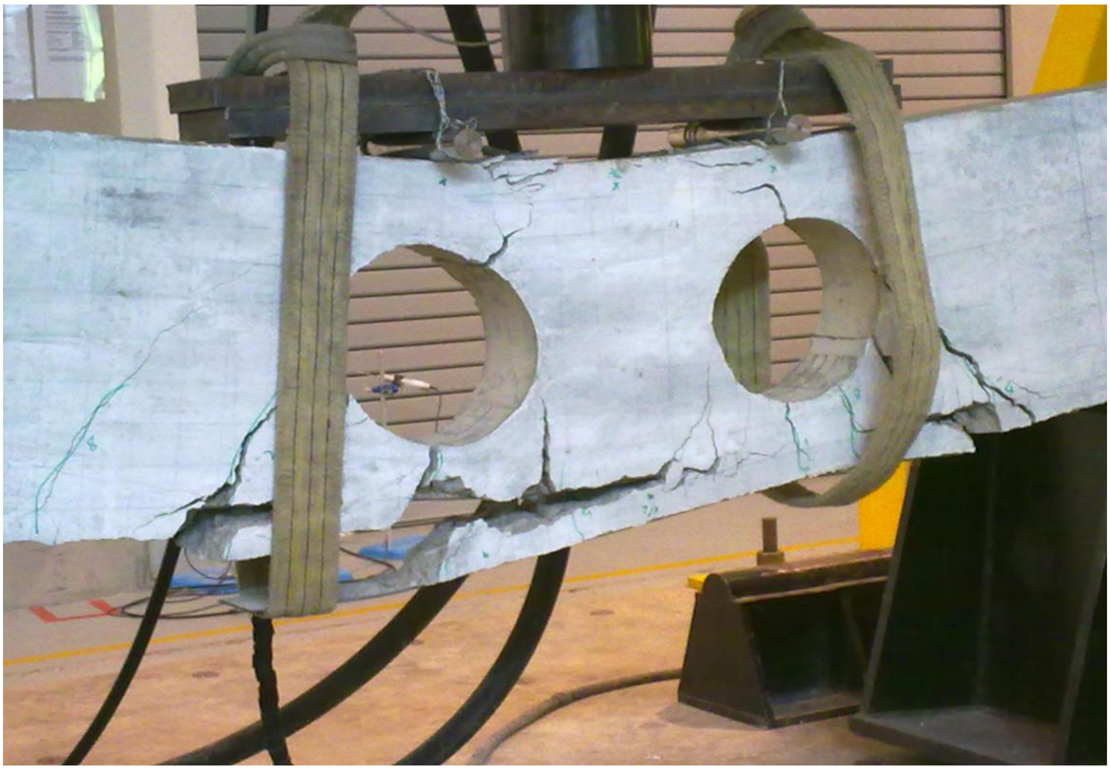

Fig. 4.9 Failure of Beam with Circular Opening with CFRP Sheets Subjected to Static Load

Fig. 4.10 Failure of Beam with Square Opening with CFRP Sheets Subjected to Static Load

Fig. 4.11 Failure of Solid Beam with Additional Reinforcement Bars subjected to Static Load

Solid beams were not pasted with any CFRP sheet but beam with circular and square opening were pasted with CFRP sheets. Beam with rectangular and elliptical opening was not pasted with any CFRP because these beams had additional reinforcement bars along the edges. The static load was applied at the rate of 0.15kN. Static load was applied until the beam fails. The static load was applied as two symmetrical point loads. Fig. 4.12 – Fig. 4.13 shows the results plotted in graph.

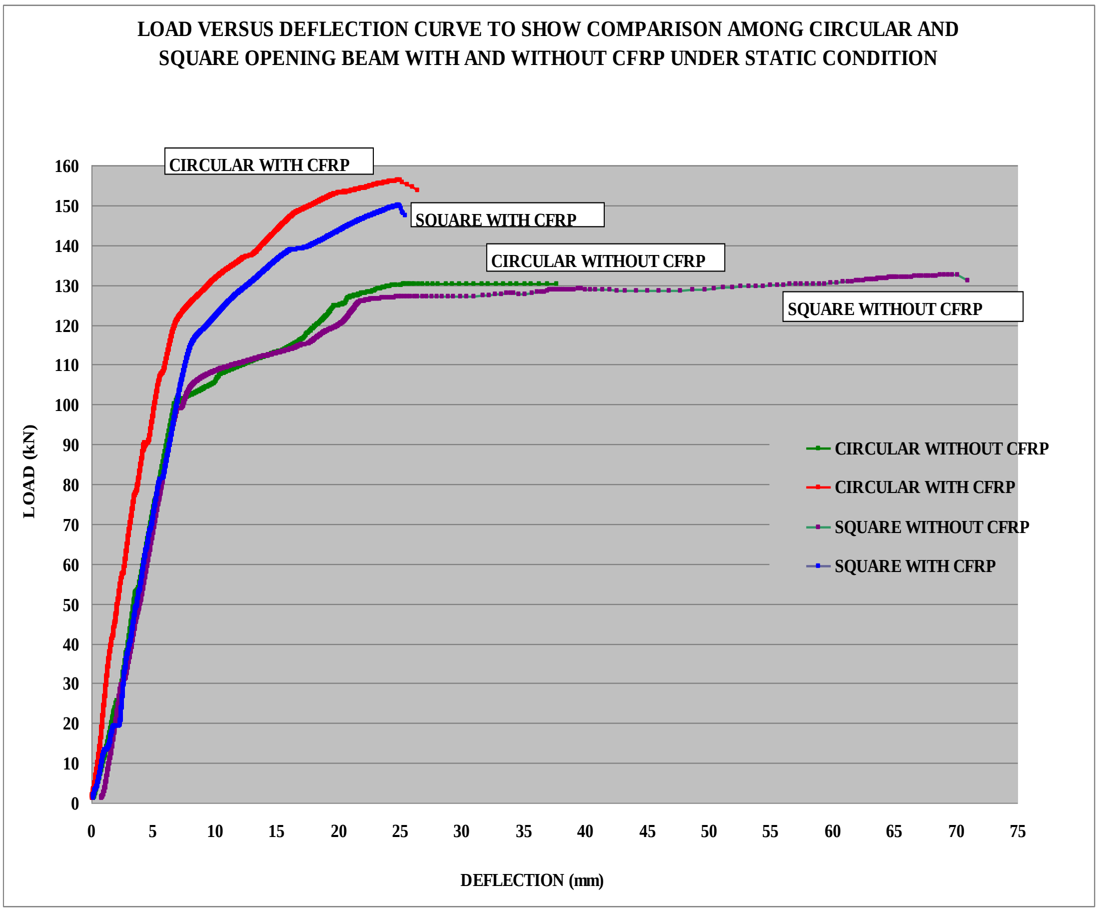

Fig. 4.12 Results of Beam with and without CFRP Sheets subjected to Static Load

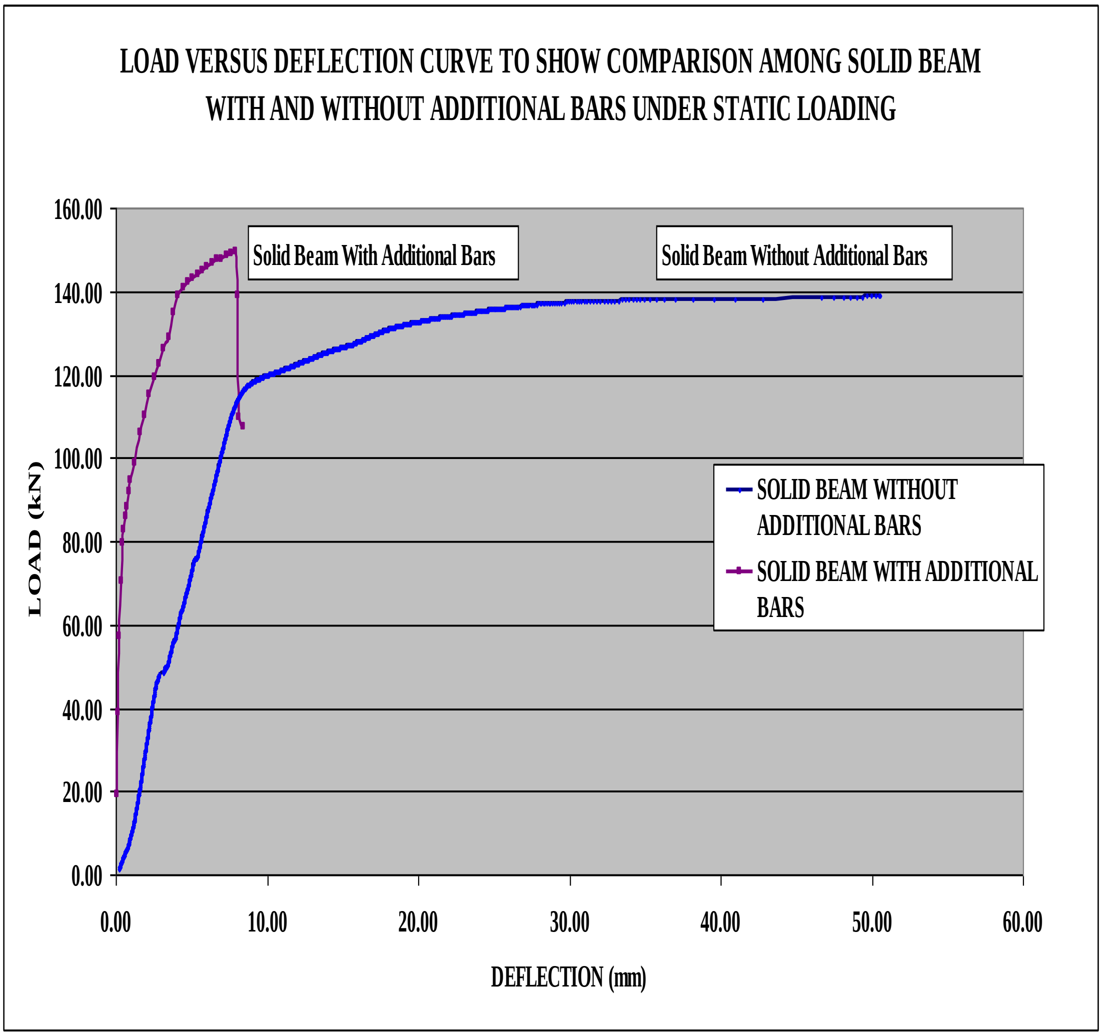

Fig. 4.13 Results of Solid Beam with and without Additional Reinforcement Bars subjected to Static Load

Table 4.3 Summary of Static Load with and without CFRP Sheets and Additional Reinforcement Bars

	Solid Beam With Additional Bars	Beam with Circular Opening With CFRP Sheets	Beam with Square Opening With CFRP Sheets
Ultimate load subjected to static load	149.40 kN	156.21 kN	150.06 kN
% gain in strength due to strengthening method	7.40%	19.90%	13.30%
Deflection at failure point (mm)	7.92 mm	25.00 mm	24.92 mm
% reduction in deflection due to strengthening method	84.20%	34.60%	64.30%
Deflection at yield strength (mm)	0.54 mm	7.09 mm	8.31 mm
% reduction in deflection at yield strength due to strengthening method	93.90%	3.70%	5.60%
Load at yield strength	82.75 kN	121.83 kN	116.21 kN
% gain or lost in load at yield strength due to strengthening method	-29.60%	+21.70%	+9.30%
Deflection at 35% of the ultimate load (mm)	0.23 mm	2.34 mm	2.83 mm
% gain or lost in deflection at 35% of the ultimate load due to strengthening method	92.90%	36.40%	8.10%

Fig. 4.12 shows the experimental load-deflection graph for all the beams with circular and square opening subjected to static loading without any strengthening method. The starting linear part of the graph for all the curves has a very steep slope. This part shows to the un-cracked condition of these beams. In this region, the deflection is proportional to the applied load and the entire concrete section is considered effective in resisting the loads. Behaviour of all type of beams is similar before cracking and is shown in Fig. 4.12 where the beams are in the stiff condition. The ending of this linear part for all the curves shows the initiation of cracking in the beam. The next segment that immediately follows this linear part provides information for all the curves on the bond quality and tension stiffening effects due to crack spacing. The slope of this part is smaller than the slope of the starting linear segment for all the curves. This shows that the rate of deflection per unit load is higher after the beam has cracked. This shows the reduction in the stiffness of the cracked beams. From Fig. 4.12, the curves show the widening gap between beam pasted with CFRP sheets and without any CFRP sheet pasted. These widening gaps show that the rate of reduction in the stiffness of beam pasted with CFRP sheets became higher with the increase in load. This is due to the low elastic modulus of CFRP sheets. The last part of the curves shows the possible failure mechanism of the structure. As shown in Fig. 4.12, all the beams showed a very ductile behaviour and all beams failed at nearly the same load after undergoing considerable deformation with very small increase in the load once steel yielded Similar load-deflection graph has proved that the characteristic of the curves. [Rafi et al. (2008)].

Table 4.3 shows the summary of ultimate load and deflection of beams subjected to static load. The ultimate load here refers to the maximum load carried by the beam. Solid beam with additional reinforcement bars gain its ultimate load by 7.4% compared with solid beam without any additional reinforcement bars. Beam with circular and square opening gain its ultimate strength by 19.9% and 13.3% respectively compared to beam with circular and square opening without any CFRP sheet pasted. This shows that by adding additional reinforcement bars, not much strength can be increased but by pasting CFRP sheets higher strength can be achieved. This is due to the low elastic modulus characteristic of CFRP sheets. Solid beam with additional reinforcement bars gain its deflection at failure point by 84.2% compared with solid beam without any additional reinforcement bars. Beam with circular and square opening gain its deflection at failure point by 34.6% and 64.3% respectively compared to beam with circular and square opening without any CFRP sheet pasted. This shows that by adding additional reinforcement bars and pasting CFRP sheets deflection at failure point decreases very highly. Therefore, additional reinforcement bars and CFRP sheets reduces the deflection at failure point but additional reinforcement bars do not increase much strength of the beam if compared to CFRP sheets.

Fig. 4.12 shows that after yielding beam without CFRP sheet exhibited a much faster rate of deflection than beam pasted with CFRP sheets with a negligible change in load. It also shows that load-carrying capacity for beam pasted with CFRP sheets dropped gradually after crushing of concrete. This shows that despite being over-reinforced with CFRP sheets, these beams can have a ductile failure mode as well as a kind of energy dissipation mechanism (Rafi et al, 2008). Table 4.3 shows the deflection and load at the point where the beams start its yield strength. Solid beam with additional reinforcement bars has higher percentage value for deflection and load at yield strength. Beams pasted with CFRP sheets have the same range of deflection at yield strength. Its shows that solid beam with additional reinforcement bars can deform more plastically rather than deform elastically whereas beams pasted with CFRP deform more elastically rather than plastically. Therefore, pasting CFRP sheets is better than adding additional reinforcement bars because beam can behave more elastically rather than plastically.

Service load is considered as 35% of the ultimate load. Table 4.3 shows the service load for beam with additional reinforcement bars and CFRP sheet [Rafi et al. (2008)]. The service load for these beams is in the range of 0.23mm to 2.38mm. Service load for all the beams falls under the yield strength of the beam. Additional reinforcement bars and CFRP sheets actually reduces the service load. By adding additional reinforcement bars service load is reduce to 92.9% whereas by pasting CFRP sheets service load is reduce to 36.4% for beam with circular opening and 8.10% for beam with square opening. Therefore, all the beams have good serviceability.

4.3 Behaviour of Beams Subjected to Cyclic Loads

In this part experimental results of all beams subjected to cyclic loading are presented and discussed. One solid beam (as reference beam), one beam with circular opening, one beam with square opening, one beam with rectangular opening (with additional bars along edges) and one beam with elliptical opening (with additional bars along edges) were tested under cyclic loading. All these beams were not pasted with any CFRP sheet. For the strengthening part using CFRP sheets, one beam with circular opening and one beam with square opening were tested. For cyclic loading, all the beams were tested under medium cyclic load (10%-60%) of failure that was obtained from static test results of the beams. Each test for cyclic loading was performed under constant amplitude at a frequency of 5 Hz at 0.2s (1 complete cycle in 0.2s). This frequency was selected because conventional civil engineering structures are typically subjected to frequencies varying between 1 to 5 Hz (Chen et al 2001). Cyclic loading was applied to the beam until the beam fails using hydraulic actuator of 100kN.

The applied load causes the beams to undergo sustained vibrations. These vibrations are divided into two components which are transient component and steady-state component. The transient component occurs at the start of vibration and steady-state component lasts as long as the exciting force. After the transient component has died, only the steady-state component remains. Solid beam is the weakest beam if compared to other beams with opening. Solid beam failed at 123750 cycles. Beam with circular opening failed at 418250 cycles, beam with square opening failed at 419181 cycles, beam with rectangular opening failed at 234568 cycles and beam with elliptical opening failed at 360731 cycles. Beam with circular and square opening had no additional reinforcement bars along the edges whereas beam with rectangular and elliptical opening had additional reinforcement bars along the edges. Therefore, it shows that beam with opening can stand more cyclic load rather than solid beam. The reason is that solid beam is heavier in mass if compared to beams with opening whereas beams with opening is less heavy due to the lost in concrete volume. Besides that, opening in beam acts as spring where it allows the energy to dissipate when cyclic load is being applied. For solid beam there is no opening for the energy to dissipate. Therefore, beam with opening is better than solid beam when subjected to cyclic loading. Beam with rectangular and elliptical opening had additional reinforcement bars along the edges but the strength to stand cyclic load is lower than beam with circular and square opening. This is due to the size of the opening where circular and square openings are not as large as rectangular and elliptical openings. Fig. 4.14 - 4.18 shows the results plotted in graph. Load versus deflection graph for all the beams subjected to cyclic loading with and without strengthening method is shown in Appendix C.

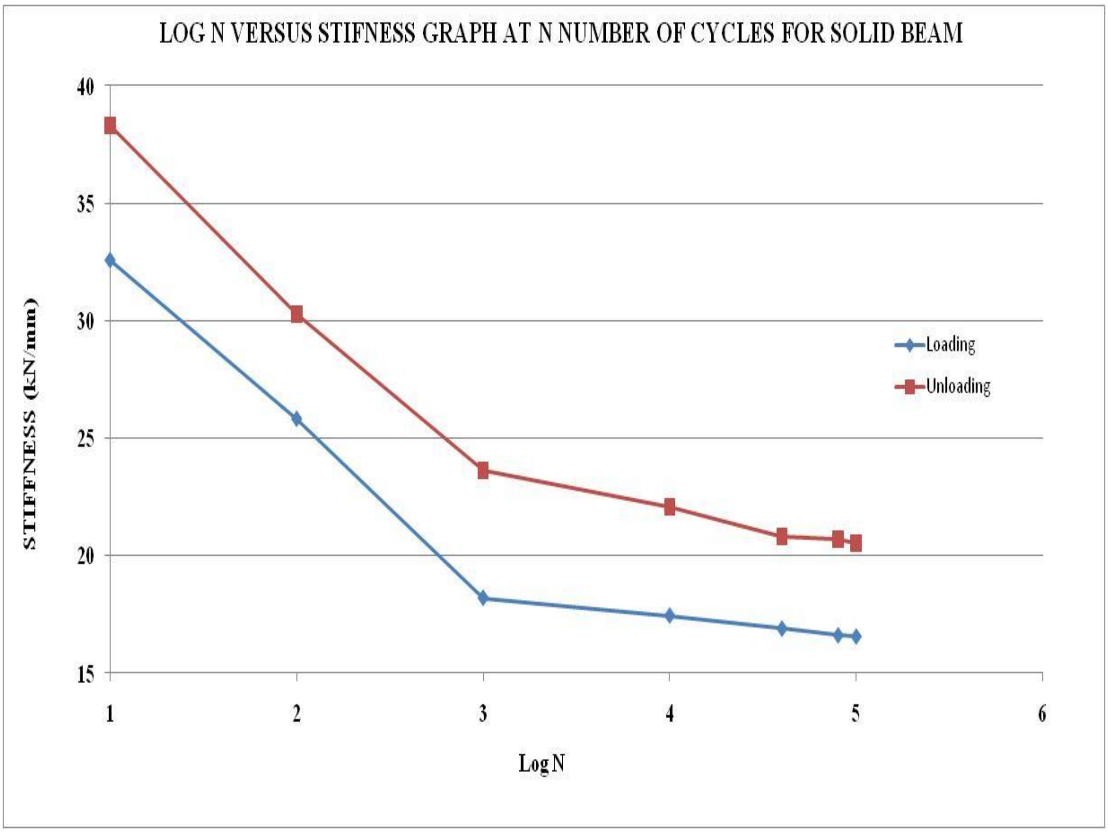

Fig. 4.14 Graph for Solid Beam subjected to Cyclic Load

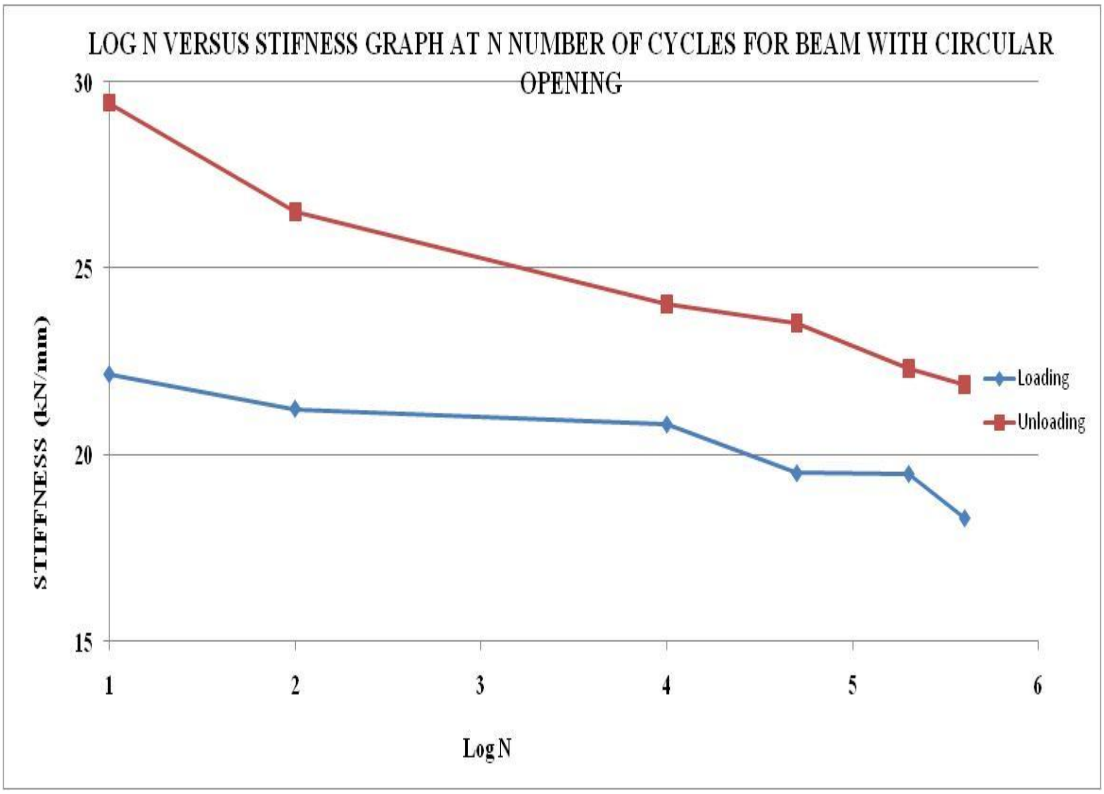

Fig. 4.15 Graph for Beam with Circular Opening subjected to Cyclic Load

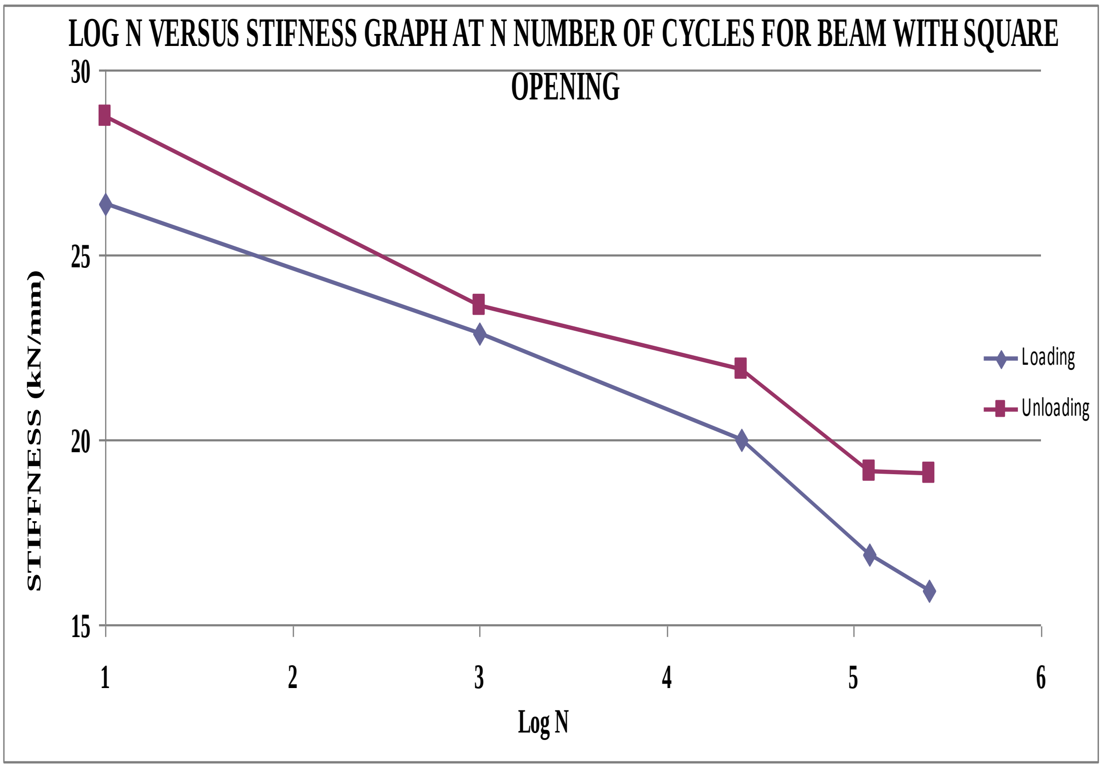

Fig. 4.16 Graph for Beam with Square Opening subjected to Cyclic Load

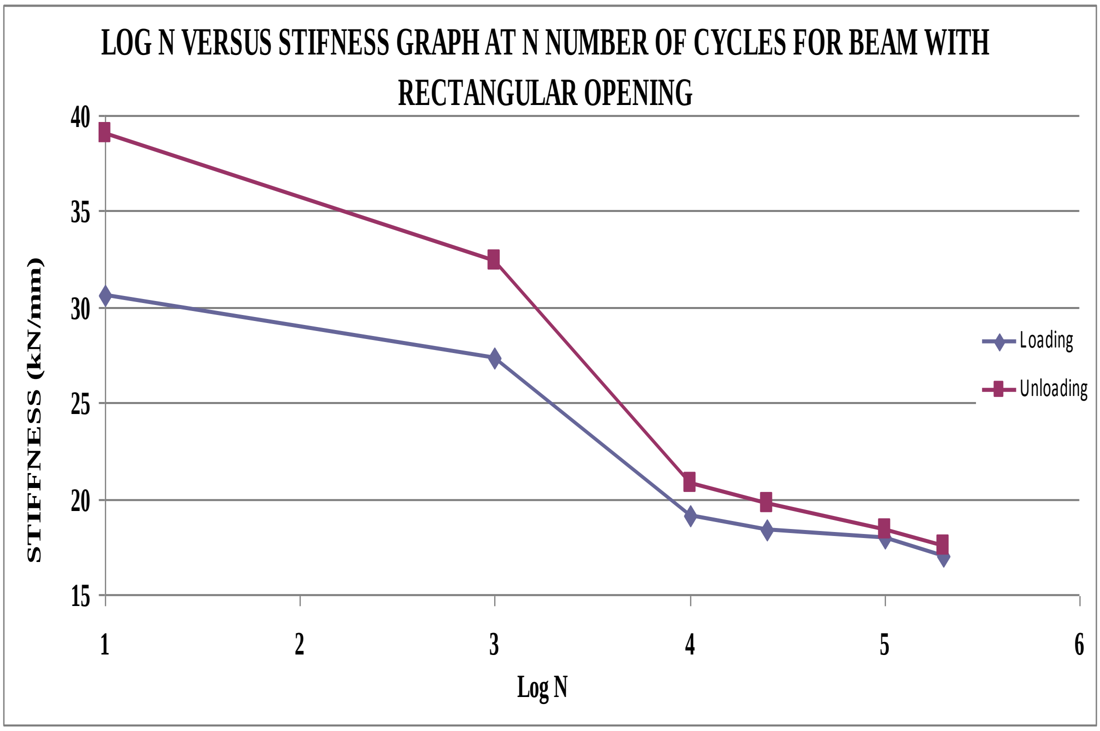

Fig. 4.17 Graph for Beam with Rectangular Opening with Additional Reinforcement Bars along the Edges subjected to Cyclic Load

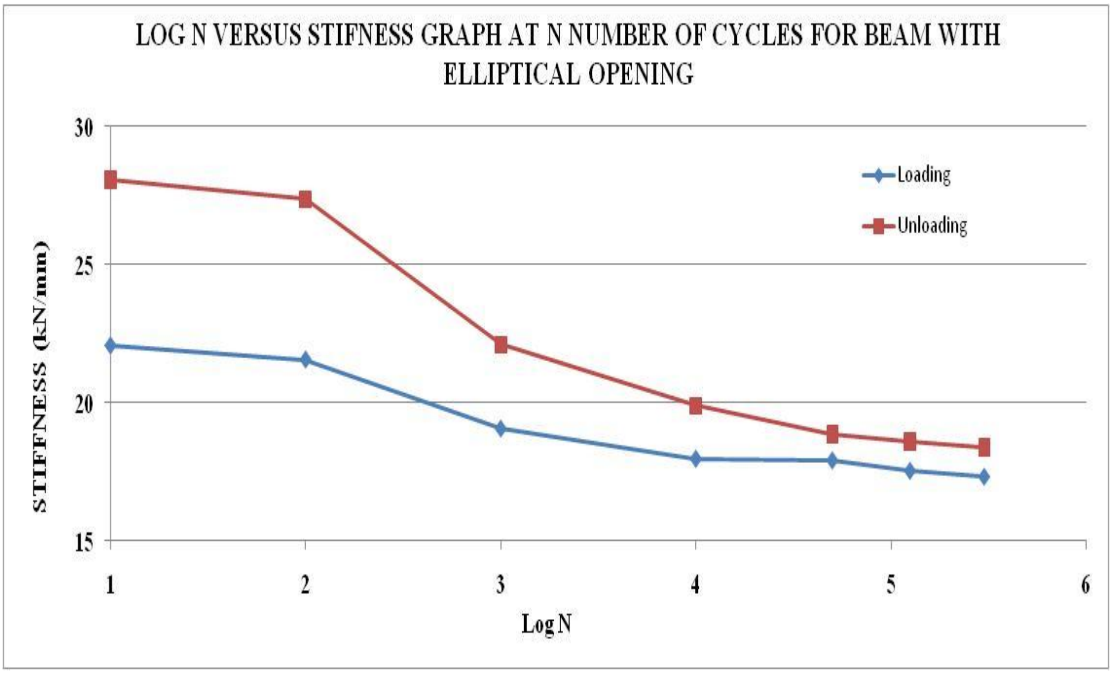

Fig. 4.18 Graph for Beam with Elliptical Opening with Additional Reinforcement Bars along the Edges subjected to Cyclic Load

Table 4.4 Summary of Stiffness Lost subjected to Cyclic Load

	Stiffness Lost at N number of Cycle					
	10	100	1000	10000	100000	Remarks
Solid Beam	32.56	25.81	18.19	17.43	16.74	Loading
Beam with Circular Opening	22.15	21.23	21.01	20.81	20.65	Loading
Beam with Square Opening	26.39	24.98	22.88	21.55	16.92	Loading
Beam with Rectangular Opening (Additional Reinforcement Bars along the Edges)	30.65	29.23	27.33	19.12	17.92	Loading
Beam with Elliptical Opening (Additional Reinforcement Bars along the Edges)	22.07	21.56	19.07	17.98	17.54	Loading

Table 4.5 Summary of Stiffness Lost subjected to Cyclic Unload

	Stiffness Lost at N number of Cycle					
	10	100	1000	10000	100000	Remarks
Solid Beam	38.29	30.26	23.60	22.05	20.52	Unloading
Beam with Circular Opening	29.43	26.52	25.02	24.05	23.01	Unloading
Beam with Square Opening	28.71	26.58	23.64	22.50	19.16	Unloading
Beam with Rectangular Opening (Additional Reinforcement Bars along the Edges)	39.03	35.23	32.36	17.98	17.58	Unloading
Beam with Elliptical Opening (Additional Reinforcement Bars along the Edges)	28.06	27.36	22.10	19.89	18.4	Unloading

Table 4.6 Percentage of Stiffness Lost subjected to Cyclic Load

	Stiffness Lost at N number of Cycle					
	10	100	1000	10000	100000	Remarks
Solid Beam	-	20.7%	29.5%	4.2%	4.0%	Loading
Beam with Circular Opening	-	4.1%	1.0%	1.0%	0.8%	Loading
Beam with Square Opening	-	5.3%	8.4%	5.8%	21.5%	Loading
Beam with Rectangular Opening (Additional Reinforcement Bars along the Edges)	-	4.6%	6.5%	42.9%	6.5%	Loading
Beam with Elliptical Opening (Additional Reinforcement Bars along the Edges)	-	2.3%	11.5%	5.7%	2.4%	Loading

Table 4.7 Percentage of Stiffness Lost subjected to Cyclic Unload

	Stiffness Lost at N number of Cycle					
	10	100	1000	10000	100000	Remarks
Solid Beam	-	21.0%	22.0%	6.6%	6.9%	Unloading
Beam with Circular Opening	-	9.9%	5.7%	3.9%	4.3%	Unloading
Beam with Square Opening	-	7.4%	11.1%	4.8%	14.8%	Unloading
Beam with Rectangular Opening (Additional Reinforcement Bars along the Edges)	-	9.7%	8.1%	35.6%	15.7%	Unloading
Beam with Elliptical Opening (Additional Reinforcement Bars along the Edges)	-	2.5%	19.2%	10%	7.5%	Unloading

Fig. 4.14, table 4.4 and 4.5 shows that solid beam decreases its stiffness at the early cycles for loading and unloading part. Major lost of stiffness occurs from 100th to 1000th cycles. It shows that solid beam become weaker and this part corresponds to the major cracked condition of solid beam. Less stiffness is lost towards 10000th to 100000th cycles. It shows that minor cracks appear in the solid beam. Even less stiffness is lost towards reaching the failure point of the solid beam. The percentage of stiffness lost for solid beam is shown in Table 4.6 and 4.7. If compared to beams with opening, solid beam lost the most stiffness throughout the cyclic loading.

Fig. 4.15, table 4.4 and 4.5 shows that beam with circular opening decreases its stiffness at the early cycles for loading and unloading part. Major lost of stiffness occurs from 10th to 100th cycles. It shows that beam with circular opening become weaker and this part corresponds to the major cracked condition of beam with circular opening. Less stiffness is lost towards 10000th to 100000th cycles. It shows that minor cracks appear in the beam with circular opening. Even less stiffness is lost towards reaching the failure point of the beam with circular opening. The percentage of stiffness lost for beam with circular opening is shown in Table 4.6 and 4.7. If compared to solid beam and other beams with opening, beams with circular opening lost its major stiffness at the starting cycles whereas toward the end only minor stiffness is lost.

Fig. 4.16, table 4.4 and 4.5 shows that beam with square opening decreases its stiffness at the end cycles for loading and unloading part. Major lost of stiffness occurs from 100th to 100000th cycles. It shows that beam with square opening become weaker and this part corresponds to the major cracked condition of beam with square opening. Less stiffness is lost at the beginning 10th to 100th cycles. It shows that minor cracks appear in the beam with square opening at the starting cycles. Even less stiffness is lost towards reaching the failure point of the beam with square opening. The percentage of stiffness lost for beam with square opening is shown in Table 4.6 and 4.7. If compared to solid beam and other beams with opening, beams with square opening lost its major stiffness at the end cycles whereas toward the beginning only minor stiffness is lost. This is due to the sharp edges in square opening.

Fig. 4.17, table 4.4 and 4.5 shows that beam with rectangular opening decreases its stiffness at the end cycles for loading and unloading part. Major lost of stiffness occurs from 1000th to 100000th cycles. It shows that beam with rectangular opening become weaker and this part corresponds to the major cracked condition of beam with rectangular opening. Less stiffness is lost at the beginning 10th to 100th cycles. It shows that minor cracks appear in the beam with rectangular opening at the starting cycles. Even less stiffness is lost towards reaching the failure point of the beam with rectangular opening. The percentage of stiffness lost for beam with rectangular opening is shown in Table 4.6 and 4.7. If compared to solid beam and other beams with opening, beams with rectangular opening lost its major stiffness at the end cycles whereas toward the beginning only minor stiffness is lost. This is due to the sharp edges in rectangular opening. Beam with rectangular opening has additional reinforcement bars but it still acts in the same manner as the beam with square opening. This beam lost most of its stiffness at the 10000th cycle which is even more than solid beam (percentage wise).

Fig. 4.18, table 4.4 and 4.5 shows that beam with elliptical opening decreases its stiffness at the early cycles for loading and unloading part. Major lost of stiffness occurs from 100th to 1000th cycles. It shows that beam with elliptical opening become weaker and this part corresponds to the major cracked condition of beam with elliptical opening. Less stiffness is lost towards 10000th to 100000th cycles. It shows that minor cracks appear in the beam with elliptical opening. Even less stiffness is lost towards reaching the failure point of the beam with elliptical opening. The percentage of stiffness lost for beam with elliptical opening is shown in Table 4.6 and 4.7. Beam with elliptical opening acts in the same manner as solid beam and the only different is that beam with elliptical opening lost less stiffness throughout cyclic loading. This is due to the additional reinforcement bars along the opening area.

4.3.1 Effects of Strengthening

Beam with circular opening failed at 458555 cycles, beam with square opening failed at 519181 cycles, beam with rectangular opening failed at 234568 cycles and beam with elliptical opening failed at 360731 cycles. Beam with circular and square opening had no additional reinforcement bars along the edges whereas beam with rectangular and elliptical opening had additional reinforcement bars along the edges. By pasting CFRP sheets beam with circular opening gain 10% more strength compared with beam without CFRP sheets and beam with square opening gain 24% strength compared with beam without CFRP sheets. Based on Fig. 4.21 to 4.27, the cracking pattern is the same for the beams without additional reinforcement bars and CFRP sheets. CFRP sheets are pasted perpendicular to the cracks obtained from the beam tested earlier under cyclic loading. Beam with square opening was pasted with CFRP sheets around the opening area front and back of the beam and top and bottom of the beam. Fig. 4.27 shows that cracks in this beam were prevented as CFRP sheets blocked the cracks to continue. Therefore, by pasting CFRP sheets perpendicular to the cracks actually increases the strength of the beam. Beam with circular opening was pasted with one CFRP sheet at the bottom of the beam. This is due to circular openings are not so critical. By pasting one CFRP sheet at the bottom of the beam the strength of the beam increases and the cracking pattern is same as the beam without CFRP sheet. Refer Fig. 4.26. Therefore, it shows that beam with opening can stand more cyclic load if pasted with CFRP sheets. Fig. 4.19 - 4.20 shows the results plotted in graph.

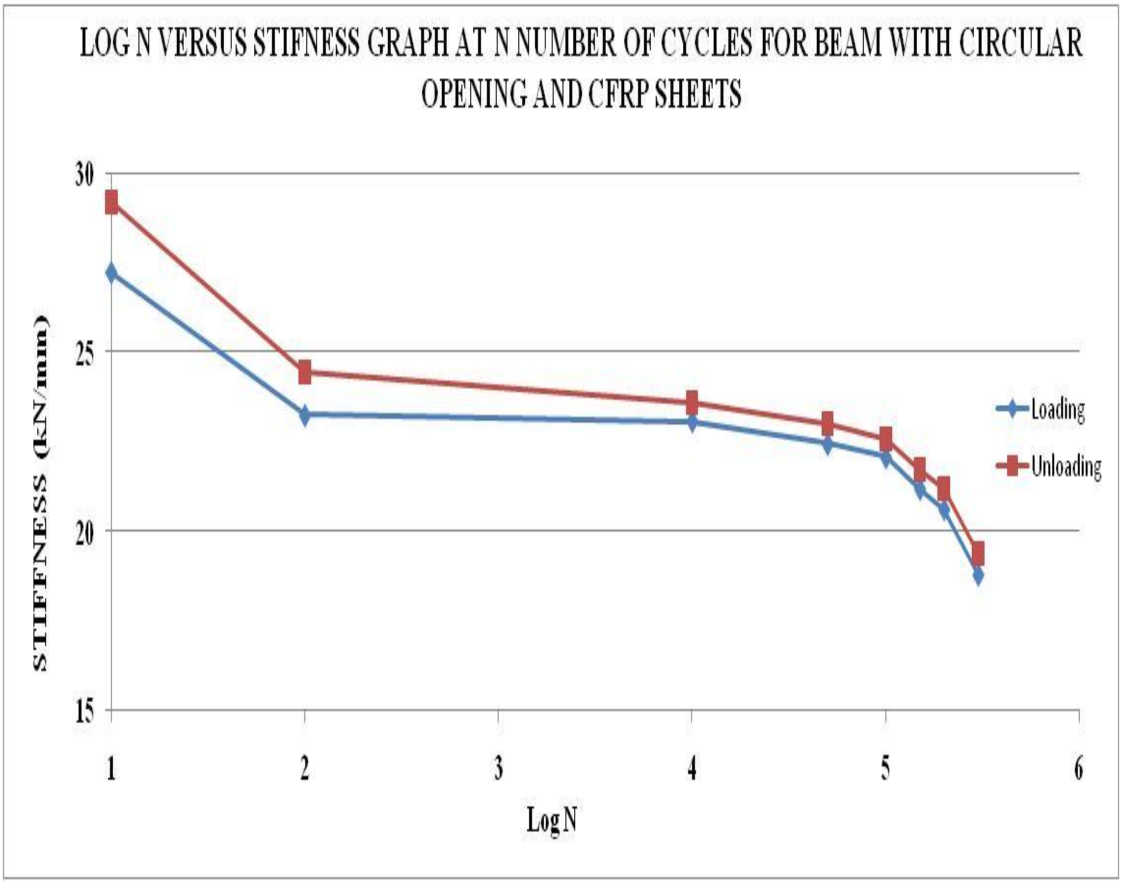

Fig. 4.19 Graph for Beam with Circular Opening with CFRP Sheets subjected to Cyclic Loading

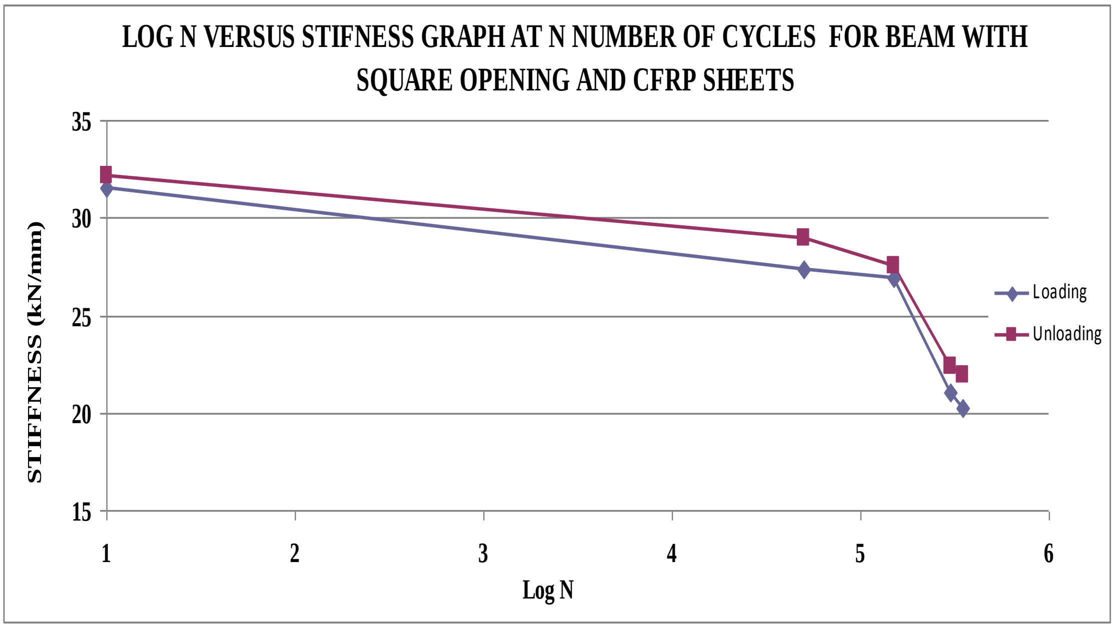

Fig. 4.20 Graph for Beam with Square Opening with CFRP Sheets subjected to Cyclic Loading

Table 4.8 Summary of Stiffness Lost subjected to Cyclic Load with CFRP Sheets and Additional Reinforcement Bars

	Stiffness Lost at N number of Cycle					
	10	100	1000	10000	100000	Remarks
Solid Beam	32.56	25.81	18.19	17.43	16.74	Loading
Beam with Circular Opening (CFRP Sheets)	27.22	23.24	23.24	23.07	22.07	Loading
Beam with Square Opening (CFRP Sheets)	31.54	30.51	29.51	28.41	27.21	Loading
Beam with Rectangular Opening (Additional Reinforcement Bars along the Edges)	30.65	29.23	27.33	19.12	17.92	Loading
Beam with Elliptical Opening (Additional Reinforcement Bars along the Edges)	22.07	21.56	19.07	17.98	17.54	Loading

Table 4.9 Summary of Stiffness Lost subjected to Cyclic Unload with CFRP Sheets and Additional Reinforcement Bars

	Stiffness Lost at N number of Cycle					
	10	100	1000	10000	100000	Remarks
Solid Beam	38.29	30.26	23.60	22.05	20.52	Unloading
Beam with Circular Opening (CFRP Sheets)	29.18	24.44	24.44	23.57	22.58	Unloading
Beam with Square Opening (CFRP Sheets)	32.16	31.78	30.26	29.56	27.97	Unloading
Beam with Rectangular Opening (Additional Reinforcement Bars along the Edges)	39.03	35.23	32.36	17.98	17.58	Unloading
Beam with Elliptical Opening (Additional Reinforcement Bars along the Edges)	28.06	27.36	22.10	19.89	18.4	Unloading

Table 4.10 Percentage of Stiffness Lost subjected to Cyclic Load with CFRP Sheets and Additional Reinforcement Bars

	Stiffness Lost at N number of Cycle					
	10	100	1000	10000	100000	Remarks
Solid Beam	-	20.7%	29.5%	4.2%	4.0%	Loading
Beam with Circular Opening (CFRP Sheets)	-	14.6%	0%	0.7%	4.3%	Loading
Beam with Square Opening (CFRP Sheets)	-	3.3%	3.3%	3.7%	4.2%	Loading
Beam with Rectangular Opening (Additional Reinforcement Bars along the Edges)	-	4.6%	6.5%	42.9%	6.5%	Loading
Beam with Elliptical Opening (Additional Reinforcement Bars along the Edges)	-	2.3%	11.5%	5.7%	2.4%	Loading

Table 4.11 Percentage of Stiffness Lost subjected to Cyclic Unload with CFRP Sheets and Additional Reinforcement Bars

	Stiffness Lost at N number of Cycle					
	10	100	1000	10000	100000	Remarks
Solid Beam	-	21.0%	22.0%	6.6%	6.9%	Unloading
Beam with Circular Opening (CFRP Sheets)	-	16.2%	0%	3.6%	4.2%	Unloading
Beam with Square Opening (CFRP Sheets)	-	1.2 %	4.8%	2.3%	5.4%	Unloading
Beam with Rectangular Opening (Additional Reinforcement Bars along the Edges)	-	9.7 %	8.1%	35.6%	15.7%	Unloading
Beam with Elliptical Opening (Additional Reinforcement Bars along the Edges)	-	2.5 %	19.2%	10%	7.5%	Unloading

Fig. 4.19, table 4.8 and 4.9 shows that beam with circular opening decreases its stiffness at the early cycles for loading and unloading part. Major lost of stiffness occurs from 10th to 100th cycles. It shows that beam with circular opening become weaker and this part corresponds to the major cracked condition of beam with circular opening. Less stiffness is lost towards 10000th to 100000th cycles. It shows that minor cracks appear in the beam with circular opening. Even less stiffness is lost towards reaching the failure point of the beam with circular opening. The percentage of stiffness lost for beam with circular opening is shown in Table 4.10 and 4.11. If compared to beam with circular opening without CFRP sheets, this beam has similar percentage of stiffness lost and has the same pattern of stiffness lost. The reason is that this beam is pasted with only one sheet of CFRP sheet and not many changes occur. Even though only one CFRP sheet is pasted but the strength is increased by 10%.

Fig. 4.20, table 4.8 and 4.9 shows that beam with square opening decreases its stiffness at the end cycles for loading and unloading part. Major lost of stiffness occurs from 100th to 100000th cycles. It shows that beam with square opening become weaker and this part corresponds to the major cracked condition of beam with square opening. Less stiffness is lost at the beginning 10th to 100th cycles. It shows that minor cracks appear in the beam with square opening at the starting cycles. Even less stiffness is lost towards reaching the failure point of the beam with square opening. The percentage of stiffness lost for beam with square opening is shown in Table 4.10 and 4.11. If compared to beam with square opening without CFRP sheets, this beam undergoes very small stiffness lost and has the same pattern of stiffness lost. CFRP sheet is pasted perpendicular to the cracks and the strength is increased by 24%.

By referring to Table 4.10 and 4.11, shows that the percentage of stiffness lost for beams pasted with CFRP sheets and has additional reinforcement bars along the edges is less compared to solid. Beams that are pasted with CFRP sheets have less percentage of stiffness lost if compared to beams that have additional reinforcement bars along the edges.

Fig. 4.21 Failure of Solid Beam subjected to Cyclic Load

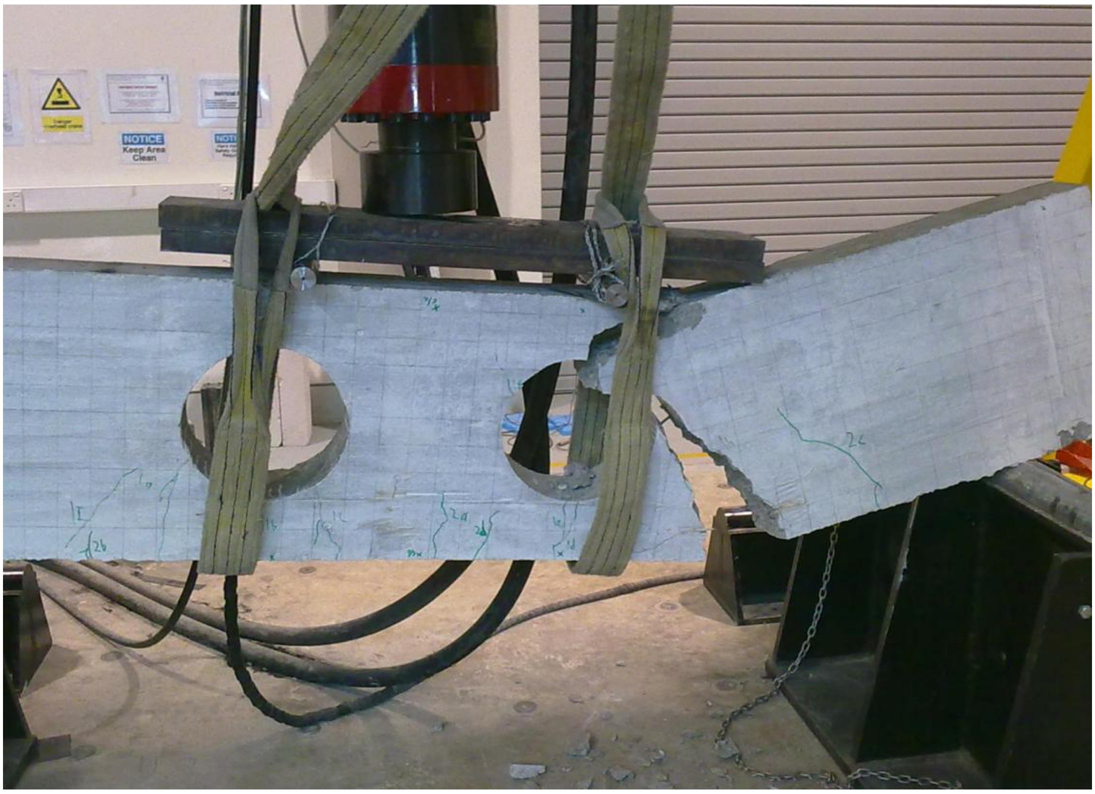

Fig. 4.22 Failure of Beam with Circular Opening subjected to Cyclic Load

Fig. 4.23 Failure of Beam with Square Opening subjected to Cyclic Load

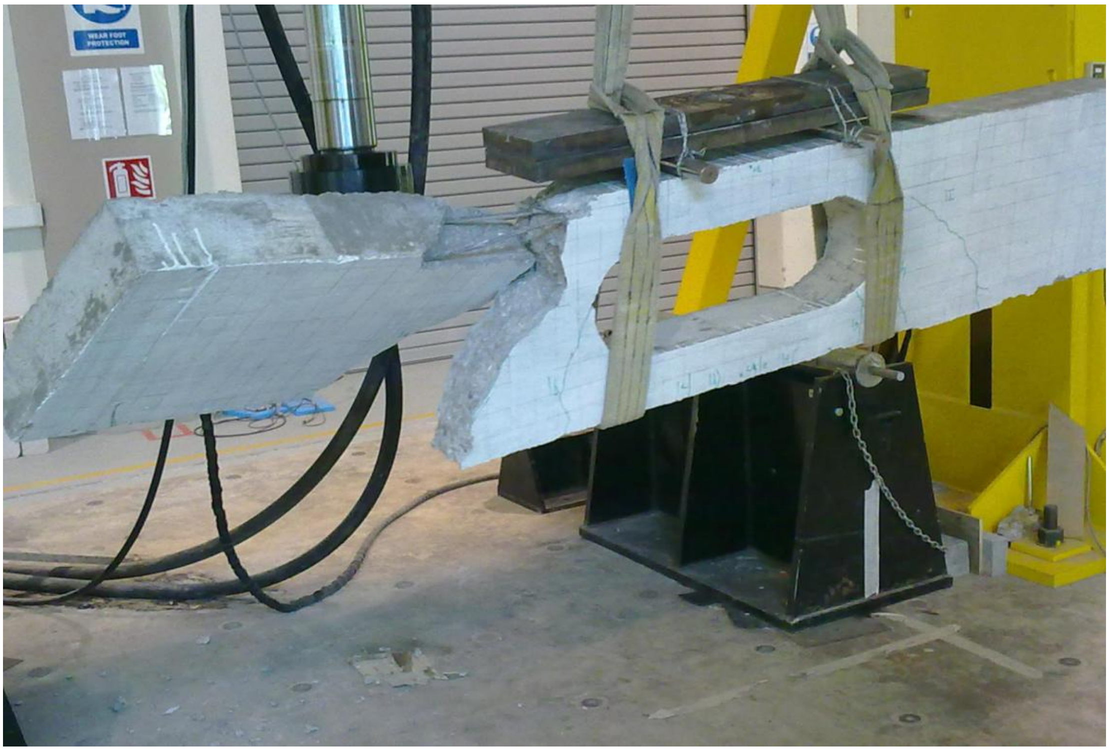

Fig. 4.24 Failure of Beam with Elliptical Opening with Additional Reinforcement Bars along the Edges subjected to Cyclic Load

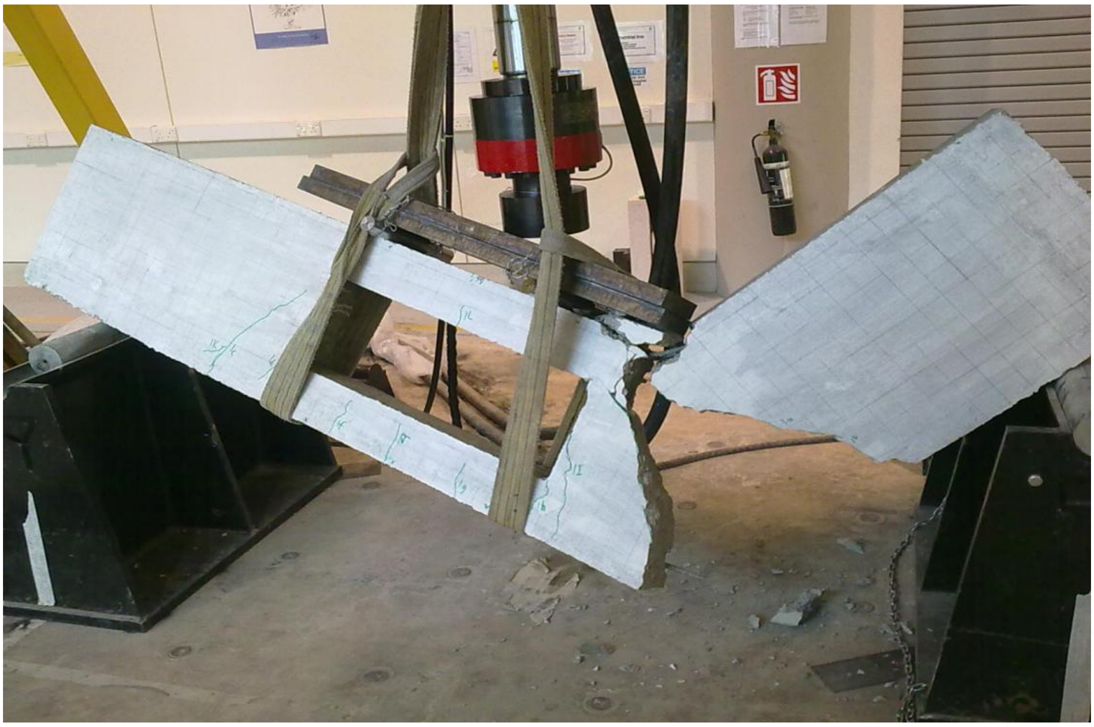

Fig. 4.25 Failure of Beam with Rectangular Opening with Additional Reinforcement Bars along the Edges subjected to Cyclic Load

Fig. 4.26 Failure of Beam with Circular Opening with CFRP Sheets subjected to Cyclic Load

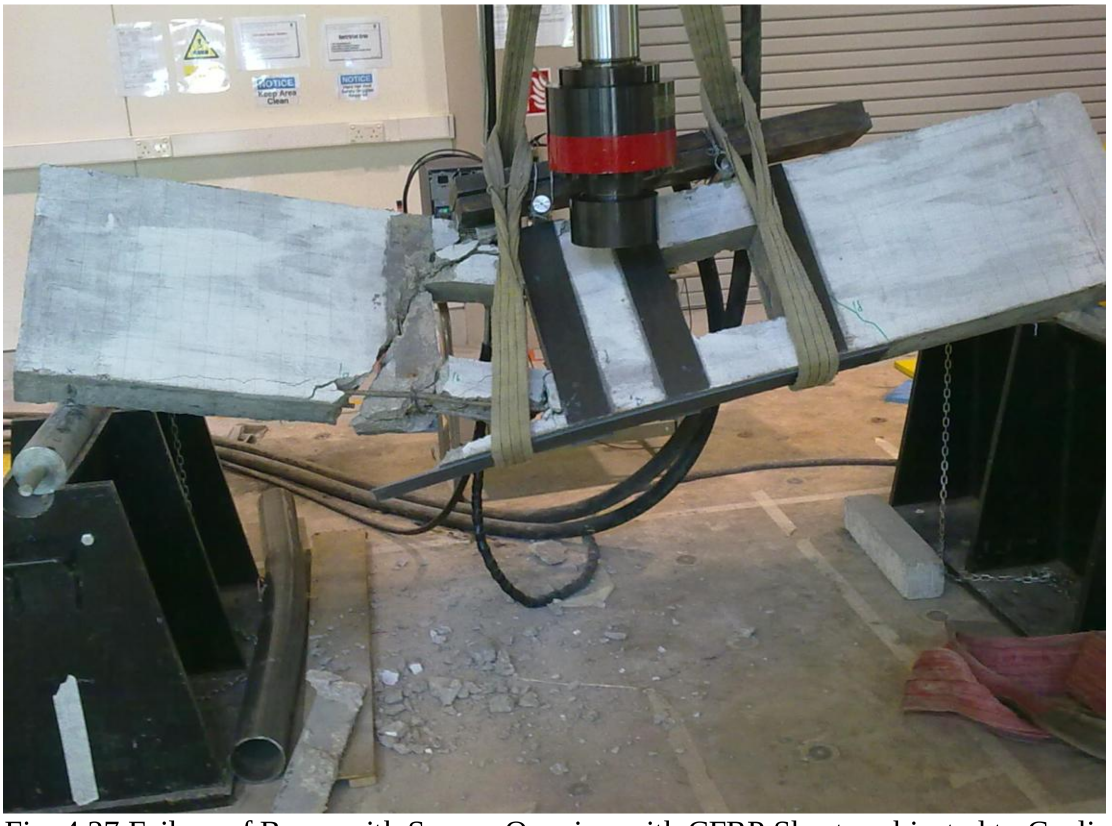

Fig. 4.27 Failure of Beam with Square Opening with CFRP Sheets subjected to Cyclic Load

4.4 Effects of Size and Shape of Opening in Provided Bending Zone

In this research all the openings are known as large opening. Even though openings that are circular, square or nearly square in shape may be considered as small opening (Mansur and Tan, 1999), provided that the depth (or diameter) of the opening is in a realistic proportion to the beam size, say, about less than 40% of the overall beam depth. The opening depth for beam with square opening is 48% of the overall beam depth and opening diameter for beam with circular opening is 54% of the overall beam depth. Therefore, beam with square and circular opening is known as large opening beam. Openings in beams will change the simple beam behaviour to a more complex one. This is due to abrupt changes in the sectional configuration. Therefore, opening corners are subjected to higher stress concentration that may lead to cracking which is unacceptable from aesthetic and durability viewpoints. Excessive deflection under service load will rise due to reduction in stiffness of the beam.

Puncturing a large opening in a reinforced concrete beam will reduce its load-carrying capacity considerably. The most critical large opening is rectangular opening. Tests conducted on such beams have indicated that the chords members behave like a Vierendeel panel, with points of contraflexure occurring approximately at midpoints of the chords members. There are two types of chords; top chord that is located at the top of the beam and bottom chord that is located at the bottom of the beam. The opening area is divided into two; the high-moment ends of the chord members and low-moment ends of the chord. High-moment ends are subject to positive moments that are sagging moments while low-moment ends are subjected to negative moments that are hogging moments. If the opening is not reinforced (Siao and Yap, 1990), the compression chord will split diagonally with crushing of the concrete at the high-moment end that will cause brittle and undesirable failure. Therefore, beam with rectangular and elliptical opening were placed with additional reinforcement bars along the edges. These additional reinforcement bars were placed due to the openings are huge and located at the centre of the beams. Beam with circular and square opening was not placed with any additional reinforcement bars along the edges because these openings are not as huge as the rectangular and elliptical opening. All the beams with opening had similar cracking pattern and failure mode. In this case, cracks first appear either in top or bottom chord member at the high-moment end of the opening. These cracks initiated at the bottom faces of the chord members. As the load increased, cracks also appeared from top faces of the chords members at the low-moment end of the opening.

More cracks appeared with increasing load. The order of appearance of these cracks was from the ends to the centre of the opening. The solid section of the beams cracked only later stage of loading. At each corner of the opening, the cracks in the chord members progressively converged to a common point where crushing of the concrete occurred at collapse. It can be seen in Fig 4.5 to Fig 4.10 and Fig. 4.21 to Fig 4.27 that the bottom chord was severely cracked at failure. The middle half of the top chord, which was subjected to axial compression, remained virtually un-cracked even at collapse. At failure crushing of the concrete was observed on the top and bottom faces of the chord members at the high- and low-moment ends of the opening respectively.

In general, the ultimate strength of a beam decreases with increasing length or depth of opening or with increasing moment-to-shear ratio at the centre of the opening. Based on this it is shown in Table 4.2 that even with additional reinforcement bars the beam with rectangular and elliptical opening slightly increases the ultimate load. This is due to the bigger length and depth of the openings. Beam with square and circular opening had no additional reinforcement bars along the edges and the ultimate load is lower than the solid beam. This proves that large opening will reduce the strength of the beam when subjected to static loading.

Solid beam is weaker than beams with opening when subjected to cyclic load. Openings in beam allows energy to dissipate and also act as spring when cyclic load is being applied but too large opening will cause the beam to become weaker due to lost of concrete volume in the beam. This is proved by beams with elliptical and rectangular opening which are weaker compared to beam with square and circular opening but these beams are better than solid beam when subjected to cyclic load.

CHAPTER 5

CONCLUSIONS

5.1 Conclusion

Based on the results and discussion on the effects of opening in RC beams and the experimental investigation; the following conclusions were made:

Beams subjected to static load

1. At early stage when static load is being applied on the beams, all the beams are in the un-cracked condition. Behaviour of all beams is similar before cracking where the beams are in the stiff condition. This is due to the deflection is proportional to the applied load and the entire concrete section is considered effective in resisting the loads. As the static load is continued being applied on the beams, the beams becomes weaker and initiation of cracking in the beam beginnings. Finally, when the beams could not undergo anymore static load, the beams will fail. This procedure is also same in the beams using strengthening method (CFRP sheets and additional reinforcement bars along the edges). Strengthening method either pasting CFRP sheets or adding additional reinforcement along the edges reduces the rate of stiffness in the beams and this allows the beams to undergo higher static load. This is due to the low elastic modulus of CFRP sheets

2. Beam with elliptical and rectangular opening gain strength compared to solid beam. Therefore, additional reinforcement bars along the edges can increase the strength and control the crack width under static load. Beam with elliptical and rectangular opening has lower deflection at failure point because these beams have additional reinforcement bars along the edges. Therefore,

additional reinforcement bars along the edges can decrease the deflection at failure point.

3. Deflection at the failure point of solid beam is also high if compared to beam with circular, rectangular and elliptical. Beam with circular and square opening lost strength compared to solid beam. Beam with square opening has higher deflection at failure point if compared to solid beam. Beam with circular opening does not have any sharp edges but beam with square opening have sharp edges. Sharp edges will enhance more cracks and eventually higher deflection rate at failure point.

4. Solid beam has slightly higher value for deflection and load at yield strength. Beams with opening have the same range of deflection and load at yield strength. Its shows that solid beam can deform more elastically rather than deform plastically whereas beams with opening deform more plastically rather than elastically. Reduction in concrete volume will reduce the yield strength of the concrete. Therefore, it is safe to have beam without opening subjected to static loading because this beam can behave more elastically rather than plastically.

5. Solid beam with additional reinforcement bars gain its ultimate load by 7.4% compared with solid beam without any additional reinforcement bars. Beam with circular and square opening gain its ultimate strength by 19.9% and 13.3% respectively compared to beam with circular and square opening without any CFRP sheet pasted. This shows that by adding additional reinforcement bars, not much strength can be increased but by pasting CFRP sheets higher strength can be achieved. This is due to the low elastic modulus characteristic of CFRP sheets.

6. Solid beam with additional reinforcement bars gain its deflection at failure point by 84.2% compared with solid beam without any additional reinforcement bars. Beam with circular and square opening gain its deflection at failure point by 34.6% and 64.3% respectively compared to beam with circular and square opening without any CFRP sheet pasted. This shows that

by adding additional reinforcement bars and pasting CFRP sheets deflection at failure point decreases very highly.

7. Solid beam with additional reinforcement bars has higher percentage value for deflection and load at yield strength. Beams pasted with CFRP sheets have the same range of deflection at yield strength. Its shows that solid beam with additional reinforcement bars can deform more plastically rather than deform elastically whereas beams pasted with CFRP deform more elastically rather than plastically. Therefore, pasting CFRP sheets is better than adding additional reinforcement bars because beam can behave more elastically rather than plastically.

Beams subjected to cyclic load

1. Beam with opening can stand more cyclic load rather than solid beam. The reason is that solid beam is heavier in mass if compared to beams with opening whereas beams with opening acts as spring and allows the energy to dissipate when cyclic load is being applied. Therefore, beam with opening is better than solid beam when subjected to cyclic loading. Beam with rectangular and elliptical opening had additional reinforcement bars along the edges but the strength to stand cyclic load is lower than beam with circular and square opening. This is due to the size of the opening where circular and square openings are not as large as rectangular and elliptical openings.

2. Solid beam decreases its stiffness at the early cycles for loading and unloading part. Major lost of stiffness occurs from 100th to 1000th cycles. Less stiffness is lost towards 10000th to 100000th cycles. Even less stiffness is lost towards reaching the failure point of the solid beam. If compared to beams with opening, solid beam lost the most stiffness throughout the cyclic loading.

3. Beam with circular opening decreases its stiffness at the early cycles for loading and unloading part. Major lost of stiffness occurs from 10th to 100th cycles. Less stiffness is lost towards 10000th to 100000th cycles. Even less stiffness is lost towards reaching the failure point of the beam with circular opening. If compared to solid beam and other beams with opening, beams

with circular opening lost its major stiffness at the starting cycles whereas toward the end only minor stiffness is lost.

4. Beam with square opening decreases its stiffness at the end cycles for loading and unloading part. Major lost of stiffness occurs from 100th to 100000th cycles. Less stiffness is lost at the beginning 10th to 100th cycles. Even less stiffness is lost towards reaching the failure point of the beam with square opening. If compared to solid beam and other beams with opening, beams with square opening lost its major stiffness at the end cycles whereas toward the beginning only minor stiffness is lost. This is due to the sharp edges in square opening.

5. Beam with rectangular opening decreases its stiffness at the end cycles for loading and unloading part. Major lost of stiffness occurs from 1000th to 100000th cycles. Less stiffness is lost at the beginning 10th to 100th cycles. Even less stiffness is lost towards reaching the failure point of the beam with rectangular opening. If compared to solid beam and other beams with opening, beams with rectangular opening lost its major stiffness at the end cycles whereas toward the beginning only minor stiffness is lost. This is due to the sharp edges in rectangular opening. Beam with rectangular opening has additional reinforcement bars but it still acts in the same manner as the beam with square opening.

6. Beam with elliptical opening decreases its stiffness at the early cycles for loading and unloading part. Major lost of stiffness occurs from 100th to 1000th cycles. Less stiffness is lost towards 10000th to 100000th cycles. Even less stiffness is lost towards reaching the failure point of the beam with elliptical opening. Beam with elliptical opening acts in the same manner as solid beam and the only different is that beam with elliptical opening lost less stiffness throughout cyclic loading. This is due to the additional reinforcement bars along the opening area.

7. Beam with circular opening with CFRP sheets has percentage of stiffness lost and has the same pattern of stiffness lost if compared to beam with circular

opening without CFRP sheets. The reason is that this beam is pasted with only one sheet of CFRP sheet and not many changes occur. Even though only one CFRP sheet is pasted but the strength is increased by 10%.

8. Beam with square opening with CFRP sheets undergoes very small stiffness lost and has the same pattern of stiffness lost if compared to beam with square opening without CFRP sheets. The reason is that this beam is pasted with CFRP sheets that are perpendicular to the cracks and the strength is increased by 24%.

9. The percentage of stiffness lost for beams pasted with CFRP sheets and has additional reinforcement bars along the edges is less compared to solid. Beams that are pasted with CFRP sheets have less percentage of stiffness lost if compared to beams that have additional reinforcement bars along the edges.

5.2 Recommendation for Future Research

In this research, the effects of opening in RC beams at the bending zone using strengthening methods was investigated, however the study is limited to the behaviour of such element under cyclic and static loading condition. The parametric analysis in this research is limited to the bending zone. The following are the main recommendations for further research of this study:

- To study the effects of opening in RC beams at the shear zone using strengthening methods.
- To increase the range of the parametric analysis by adding the effect of other controlling factor that might affect the behaviour of such element under static and cyclic loading.

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APPENDIX A

MATERIAL ON ADHESIVE USED FOR BONDING

Edition 7.1.2008
Identification no. 332-15
Sikadur 30

Construction

Sikadur® 30

High-modulus, high-strength, structural epoxy paste adhesive for use with Sika CarboDur® reinforcement.

Description	Sikadur 30 is a 2-component, 100% solids, moisture-tolerant, high-modulus, high-strength, structural epoxy paste adhesive. It conforms to the current ASTM C-881 and AASHTO M-235 specifications.
Where to use	■ Adhesive for bonding external reinforcement to concrete, masonry, steel, wood, stone, etc. ■ Structural bonding of composite laminates (Sika CarboDur CFRP) to concrete. ■ Structural bonding of steel plates to concrete. ■ Suitable for use in vertical and overhead configurations. ■ As a binder for epoxy mortar repairs.
Advantages	■ Long pot life. ■ Long open time. ■ Tolerant of moisture before, during and after cure. ■ High strength, high modulus, structural paste adhesive. ■ Excellent adhesion to concrete, masonry, metals, wood and most structural materials. ■ Fully compatible and excellent adhesion to Sika CarboDur CFRP composite laminate. ■ Paste consistency ideal for vertical and overhead applications of Sika CarboDur. ■ High abrasion and shock resistance. ■ Convenient easy mix ratio A:B=3:1 by volume. ■ Solvent-free. ■ Color-coded components to ensure proper mixing control.
Coverage	Type S 512 CarboDur: approx. 50 LF/gal.; Type S 812 CarboDur: approx. 32 LF/gal.; Type S 1012 CarboDur: approx. 22 LF/gal.
Packaging	1 gal. units.

Typical Data *(Material and curing conditions @ 73°F (23°C) and 50% R.H.)*

Shelf Life	2 years in original, unopened containers.
Storage Conditions	Store dry at 40°-95°F (4°-35°C). **Condition material to 65°-85°F (18°-29°C) before using.**
Color	Light gray.
Mixing Ratio	Component 'A': Component 'B' = 3:1 by volume.
Consistency	Non-sag paste.
Pot Life	Approximately 70 minutes @ 73°F (23°C) (1 qt.)

Tensile Properties (ASTM D-638)

7 day	Tensile Strength	3,600 psi (24.8 MPa)
	Elongation at Break	1%
	Modulus of Elasticity	6.5 X 10^5 psi (4,482 MPa)

Flexural Properties (ASTM D-790)

14 day	Flexural Strength (Modulus of Rupture)	6,800 psi (46.8 MPa)
	Tangent Modulus of Elasticity in Bending	1.7 X 10^6 psi (11,721 MPa)

Shear Strength (ASTM D-732) **14 day** Shear Strength 3,600 psi (24.8 MPa)

Bond Strength (ASTM C-882): Hardened Concrete to Hardened Concrete

2 day (moist cure)	Bond Strength	2,700 psi (18.6 MPa)
2 day (dry cure)	Bond Strength	3,200 psi (22.0 MPa)
14 day (moist cure)	Bond Strength	3,100 psi (21.3 MPa)
	Hardened Concrete to Steel	2,600 psi (17.9 MPa)
2 day (moist cure)	Bond Strength	3,000 psi (20.6 MPa)
2 day (dry cure)	Bond Strength	2,600 psi (17.9 MPa)
14 day (moist cure)	Bond Strength	

Heat Deflection Temperature (ASTM D-648)
7 day [fiber stress loading=264 psi (1.8 MPa)] 118°F (47°C)

Water Absorption (ASTM D-570) 7 day (24 hour immersion) 0.03%

Compressive Properties (ASTM D-695) - Compressive Strength, psi (MPa)

	40°F* (4°C)	**73°F* (23°C)**	**90°F* (32°C)**
4 hour	-	-	5,500 (37.9)
8 hour	-	3,500 (24.1)	6,700 (46.2)
16 hour	-	6,700 (46.2)	7,400 (51.0)
1 day	750 (5.1)	7,800 (53.7)	7,800 (53.7)
3 day	6,800 (46.8)	8,300 (57.2)	8,300 (57.2)
7 day	8,000 (55.1)	8,600 (59.3)	8,600 (59.3)
14 day	8,500 (58.6)	8,600 (59.3)	8,900 (61.3)
28 day	8,500 (58.6)	8,600 (59.3)	9,000 (62.0)

Compressive Modulus **7 day** 3.9 x 10^5 psi (2,689 MPa)

*Material cured and tested at the temperatures indicated.

®

Construction

How to Use

Surface Preparation

The concrete surface should be prepared to a minimum concrete surface profile (CSP) 3 defined by the ICRI surface-profile chips. Localized out-of-plane variations, including form lines, should not exceed 1/32 in. (1 mm). Surface must be clean and sound. It may be dry or damp, but free of standing water and frost. Remove dust, laitance, grease, curing compounds, impregnations, waxes, foreign particles, disintegrated materials, and other bond inhibiting materials from the surface. Existing uneven surfaces must be filled with an appropriate repair mortar (e.g., Sikadur 30 with the addition of 1 part oven-dried sand). The adhesive strength of the concrete must be verified after surface preparation by random pull-off testing (ACI 503R) at the discretion of the engineer. Minimum tensile strength, 200 psi (1.4 MPa) with concrete substrate failure.

Preparation work

Concrete - Blast clean, shotblast or use other approved mechanical means to provide an open roughened texture.

Steel - Should be cleaned and prepared thoroughly by blastcleaning to a white metal finish.

CarboDur - Wipe clean with appropriate cleaner (e.g. MEK).

Mixing

Pre-mix each component. Proportion 1 part Component 'B' to 3 parts Component 'A' by volume into a clean pail. Mix thoroughly for 3 minutes with Sika paddle on low-speed (400-600 rpm) drill until uniform in color. Mix only that quantity which can be used within its pot life.

To prepare an epoxy mortar: slowly add up to 1 part by loose volume of an oven-dried aggregate to 1 part of the mixed Sikadur 30 and mix until uniform in consistency.

Application

For bonded, external reinforcement:

Apply the neat mixed Sikadur 30 onto the concrete with a trowel or spatula to a nominal thickness of 1/16" (1.5 mm). Apply the mixed Sikadur 30 onto the CarboDur laminate with a "roof-shaped" spatula to a nominal thickness of 1/16" (1.5 mm). Within the open time of the epoxy, depending on the temperature, place the CarboDur laminate onto the concrete surface. Using a hard rubber roller, press the laminate into the epoxy resin until the adhesive is forced out on both sides. Remove excess adhesive. Glue line should not exceed 1/8 inch (3 mm). The external reinforcement must not be disturbed for a minimum of 24 hours. The epoxy will reach its design strength after 7 days.

For interior vertical and overhead patching: Work the material into the prepared substrate, filling the cavity. Strike off level. Lifts should not exceed 1 inch (25 mm).

Limitations

- Minimum substrate and ambient temperature is 40°F (4°C).
- Do not thin. Addition of solvents will prevent proper cure.
- Use oven-dried aggregate only.
- Maximum glue line of neat epoxy is 1/8 inch (3 mm).
- Maximum epoxy mortar thickness is 1 inch (25 mm) per lift.
- Minimum age of concrete must be 21-28 days, depending upon curing and drying conditions.
- Porous substrates must be tested for moisture vapor transmission prior to mortar applications.
- Not an aesthetic product. Color may alter due to variations in lighting and/or UV exposure.

Warning

Component 'A' - IRRITANT; SENSITIZER - Contains epoxy resin, calcium carbonate, and silica (quartz). Can cause skin sensitization after prolonged or repeated contact. Eye irritant. High concentrations of vapor may cause skin/respiratory irritation. Harmful if swallowed.

Component 'B' - CORROSIVE; SENSITIZER - Contains amines, calcium carbonate, and silica (quartz). Contact with eyes or skin causes severe burns. Can cause skin sensitization after prolonged or repeated contact. Eye irritant. May cause respiratory/skin irritation. Sanding of cured product may result in exposure to a chemical known in the state of California to cause cancer.

First Aid

Eyes: Hold eyelids apart and flush thoroughly with water for 15 minutes. **Skin:** Remove contaminated clothing. Wash skin thoroughly for 15 minutes with soap and water. **Inhalation:** Remove person to fresh air. **Ingestion:** Do not induce vomiting. **In all cases, contact a physician immediately if symptoms persist.**

Clean Up

In case of spills or leaks, wear suitable chemical resistant gloves/goggles/clothing, contain spill, collect with absorbent material, and transfer to suitable container. Ventilate area. Avoid contact. Dispose of in accordance with current, applicable local, state and federal regulations. Uncured material can be removed with solvent. Strictly follow manufacturer's warnings and instructions for use. Cured material can only be removed mechanically.

Handling & Storage

Avoid direct contact with skin and eyes. Wear chemical resistant gloves/goggles/clothing. Use only with adequate ventilation. In absence of adequate general and local exhaust ventilation, use a properly filled NIOSH respirator. Wash thoroughly after handling product. Launder clothing before reuse. Store in a cool dry well ventilated area.

KEEP CONTAINER TIGHTLY CLOSED • KEEP OUT OF REACH OF CHILDREN • NOT FOR INTERNAL CONSUMPTION • FOR INDUSTRIAL USE ONLY

Prior to each use of any Sika product, the user must always read and follow the warnings and instructions on the product's most current Technical Data Sheet, product label and Material Safety Data Sheet which are available online at www.sikaconstruction.com or by calling Sika's Technical Service Department at 800-933-7452. Nothing contained in any Sika materials relieves the user of the obligation to read and follow the warnings and instruction for each Sika product as set forth in the current Technical Data Sheet, product label and Material Safety Data Sheet prior to product use.

Visit our website at www.sikaconstruction.com **1-800-933-SIKA NATIONWIDE**

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BSI ISO 9000:2000

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APPENDIX B

CFRP PROPERTIES

Product Data Sheet
Edition 0308 / 2
Sika® CarboDur® Plates

Sika® CarboDur® Plates

Pultruded carbon fiber plates for structural strengthening

System Description

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

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

Uses

To strengthen structures for:

Load increase:

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

Damage to structural elements:

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

Service improvements:

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

Change in structural system:

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

Change of specification:

- Earthquakes
- Changed design philosophy

Design or construction defects:

- Insufficient / inadequate reinforcement
- Insufficient / inadequate structural depth

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

Tests

Approvai / Standards	Deutsches Institut für Bautechnik Z-36.12-29, 2006: General Construction Authorisation for Sika® CarboDur®. SOCOTEC Rapport No. HX0823, 2000: Rapport d'enquete technique / cahier des charges - Sika® CarboDur® / SikaWrap® (French). NBI Teknisk Godkjenning, NBI Technical Approval, No. 2178, 2001 (Norwegian). ZAG, Technical Approval No. S418/99-620-2, za uporabo nacina ojacitev armirano betonskih in prednapetih elementov konstrukcij z dolepljenjem lamel iz karbonskih vlaken "Sika® CarboDur®" v Republiki Sloneniji (Slovenian). TSUS, Building Testing and research institutes, Technical approval No. 5502A/02/0633/0/004, 2003: Systém dodatocného zosilnovania zelezobetonovych a drevenych konstrukcil Sika CarboDur® (Slovak). Instytut badawczy drog i mostow, technical approval No. AT/2003-04-0336, System materialow Sika® CarboDur® do wzmacniania konstrukcji obiektow mostowych (Polish). Fib, Technical Report, bulletin 14: Externally bonded FRP reinforcement for RC structures, July 2001 (International). ACI 440.2R-02, Guide for the Design and construction of Externally Bonded FRP Systems for strengthening concrete structures, October 2002 (USA). Concrete Society Technical Report No. 55, Design guidance for strengthening concrete structures using fiber composite material, 2000 (UK). SIA 166, Klebebewehrungen, 2003 / 2004 (CH).

Product Data — Sika® CarboDur® CFRP plates

Form

Appearance / Colour	Carbon fiber reinforced polymer with an epoxy matrix, black.
Packaging	Cut to size according parts list in reusable packaging. Supplied in rolls of 250 m in reusable packing boxes.

Types

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

Type	Width	Thickness	Cross sectional area
Sika® CarboDur® S1.525/60	15 mm	2.5 mm	37.5 mm²
Sika® CarboDur® S2.025/80	20 mm	2.5 mm	50 mm²
Sika® CarboDur® S512/80	50 mm	1.2 mm	60 mm²
Sika® CarboDur® S612/90	60 mm	1.2 mm	72 mm²
Sika® CarboDur® S613/100	60 mm	1.3 mm	78 mm²
Sika® CarboDur® S812/120	80 mm	1.2 mm	96 mm²
Sika® CarboDur® S912/140	90 mm	1.2 mm	108 mm²
Sika® CarboDur® S1012/160	100 mm	1.2 mm	120 mm²
Sika® CarboDur® S1014/180	100 mm	1.4 mm	140 mm²
Sika® CarboDur® S1213/200	120 mm	1.3 mm	156 mm²
Sika® CarboDur® S1214/220	120 mm	1.4 mm	168 mm²
Sika® CarboDur® S1512/240	150 mm	1.2 mm	180 mm²

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

Type	Width	Thickness	Cross sectional area
Sika® CarboDur® M614/110	60 mm	1.4 mm	84 mm²
Sika® CarboDur® M914/170	90 mm	1.4 mm	126 mm²
Sika® CarboDur® M1014/190	100 mm	1.4 mm	140 mm²
Sika® CarboDur® M1214/230	120 mm	1.4 mm	168 mm²

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

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

Storage

Storage Conditions / Shelf Life — Unlimited (no exposure to direct sunlight, dry).

Technical Data

Density	1.60 g/cm³
Temperature Resistance	> +150°C
Fiber Volume Content	> 68% (type S)

Mechanical / Physical Properties

Plate Properties

		Sika CarboDur S	Sika CarboDur M	Sika CarboDur H
E-Modulus*	Mean value	165,000 N/mm²	210,000 N/mm²	300,000 N/mm²
	Min. value	> 160,000 N/mm²	> 200,000 N/mm²	> 290,000 N/mm²
	5% Fractile-Value	162,000 N/mm²	210,000 N/mm²	-
	95% Fractile-Value	180,000 N/mm²	230,000 N/mm²	-
Tensile Strength*	Mean value	3,100 N/mm²	3,200 N/mm²	1,500 N/mm²
	Min. value	> 2,800 N/mm²	> 2,900 N/mm²	> 1,350 N/mm²
	5% Fractile-Value	3,000 N/mm²	3,000 N/mm²	-
	95% Fractile-Value	3,600 N/mm²	3,900 N/mm²	-
Strain at break* (min. value)		> 1.70%	> 1.35%	> 0.45%
Design strain**		< 0.85%	< 0.65%	< 0.25%

* Mechanical values obtained from longitudinal direction of fibers.

**These values should be used for design as the maximum strains in the CFRP-plates and must be adapted to local design regulations as necessary. Dependent upon the structure and the load situation, they may also have to be decreased by the responsible Engineer according to requirements and standards.

System Information

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

Application Details

Consumption

Width of plate	Sikadur®-30
50 mm	0.35 kg/m
60 mm	0.40 kg/m
80 mm	0.55 kg/m
90 mm	0.70 kg/m
100 mm	0.80 kg/m
120 mm	1.00 kg/m
150 mm	1.20 kg/m

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

Substrate Quality

Evenness / plane or level: (according to FIB14)
The surface to be strengthened must be levelled, with variations and formwork marks not greater than 0.5 mm. Plane and level of the substrate to be checked with a metal batten. Tolerance for 2 m length max. 10 mm and for 0.3 m length 4 mm. These tolerances shall be adapted to local guidelines if there are any. They might be more restrictive.

Substrate strength (concrete, masonry, natural stone) must be verified in all cases): Mean adhesive tensile strength of the prepared concrete substrate should be 2.0 N/mm², min. 1.5 N/mm². If these values can not be reached, then see the SikaWrap® fabric Product Data Sheets for alternative Sika® solutions.

Concrete must be older than 28 days (dependent on environment and strengths).

Substrate Preparation

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

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

Repairs and levelling must be undertaken with structural repair materials such as Sikadur®-41 repair mortar or Sikadur®-30 adhesive, filled max. 1 : 1 by weight with Sikadur®-501 quartz sand. The prior wetting of the substrate with Sikadur®-30 improves the bond (wet in wet). If levelling has been conducted more than 2 days before applying the plates, the levelled surface has to be ground again to ensure a proper bond between Sikadur®-41 and Sikadur®-30 (see the relevant Product Data Sheets).

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

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

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

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

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

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

Application Conditions / Limitations

Substrate Temperature See the Product Data Sheets of Sikadur®-30 and Sikadur®-30 LP.

Ambient Temperature See the Product Data Sheets of Sikadur®-30 and Sikadur®-30 LP.

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

Dew Point See the Product Data Sheets of Sikadur®-30 and Sikadur®-30 LP.

Application Instructions	
Mixing	See the Product Data Sheets of Sikadur®-30 and Sikadur®-30 LP.
Mixing Time	See the Product Data Sheets of Sikadur®-30 and Sikadur®-30 LP.
Application Method / Tools	Place the Sika® CarboDur® plate on a table and clean the unlabelled side with Colma Cleaner using a white rag. Wait > 10 minutes to allow the surface to dry completely. Apply the well-mixed Sikadur®-30 adhesive with a special "dome" shaped spatula onto the cleaned CarboDur® laminate. Apply the Sikadur®-30 adhesive carefully to the properly cleaned and prepared substrate, with a spatula to form a thin layer for substrate wetting. Within the open time of the adhesive, place the Sikadur®-30 coated Sika® CarboDur® plate onto the Sikadur® coated concrete surface. Using a Sika® rubber roller, press the plate into the adhesive until the material is forced out on both sides of the laminate. Remove surplus adhesive. Intersections / multiple layers: Where there are to be plate intersections or crossovers, the first Sika® CarboDur® plate should be cleaned with Sika® Colma Cleaner before overlaying with adhesive and then the second plate applied. If more than one plate is to be bonded together, they all have to be cleaned on both sides with Sika® Colma Cleaner - use Sikadur®-330 or Sikadur®-30 adhesive in these instances (for details see the Product Data Sheets of Sikadur®-330 and Sikadur®-30). Quality assurance: For quality control of curing rate and strength, samples may be made up on site if requested by code or project engineer. Average standard values after curing 7 days at +23°C are: - Compressive strength > 75 N/mm^2 - Flexural tensile strength > 35 N/mm^2 These values can differ by up to 20% dependent on the circumstances. The following are the most important factors which can have an influence on the mechanical properties of the samples: - Mixing ratio (A : B = 3 : 1 exactly) - Air entrapment in the sample (from mixing or filling into the mould!) - Curing temperature / time - Contamination of the adhesive! Therefore care should be taken to avoid these situations. When the Sikadur®-30 has cured, test for voids by tapping the surface of the plate with metallic object or impuls-thermography. Application Tools: Sika® Colma Cleaner: For cleaning of Sika® CarboDur® plate before bonding, cleaning of application tools. In 1 and 5 kg pails, 20 kg mini drum and 160 kg drum. Sika® CarboDur® Rubber Roller: For pressing the Sika® CarboDur® plate onto the surface. Sales unit 1 pce. Sika® Mixing Spindle: For minimizing air entrapment. Sales unit 1 pce.
Cleaning of Tools	Clean all tools and application equipment with Sika® Colma Cleaner immediately after use. Cured material can only be removed mechanically.
Potlife	See the Product Data Sheets of Sikadur®-30 and Sikadur®-30 LP.

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

Value Base

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

Health and Safety Information

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

Legal Notes

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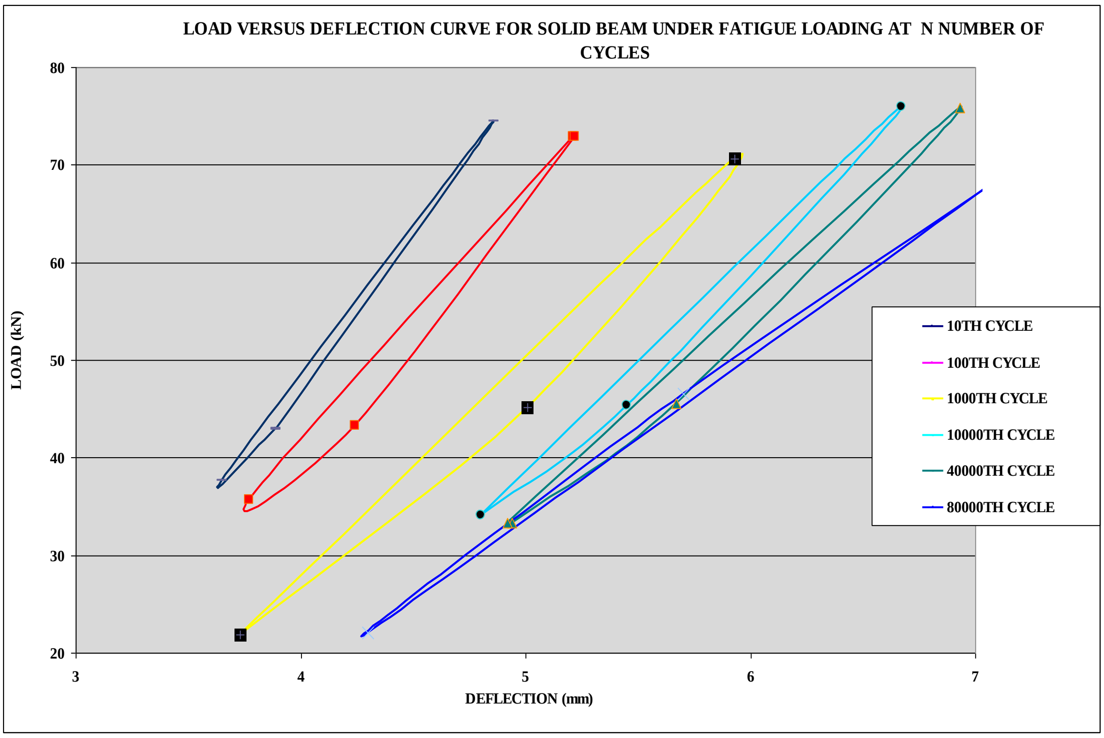
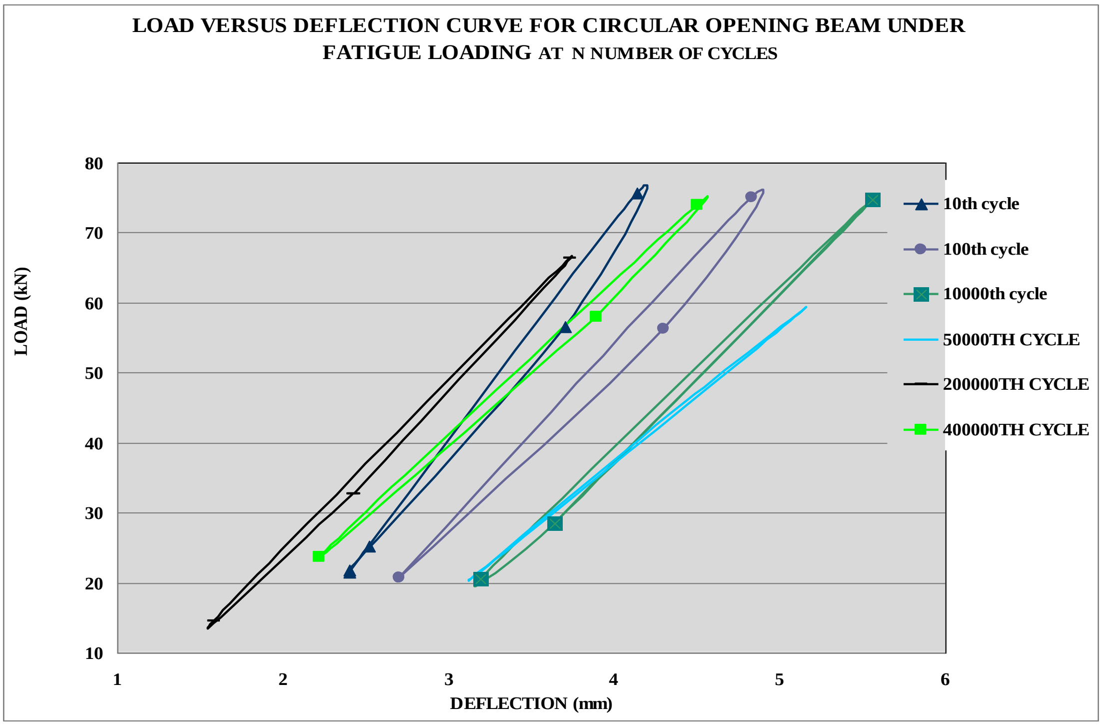
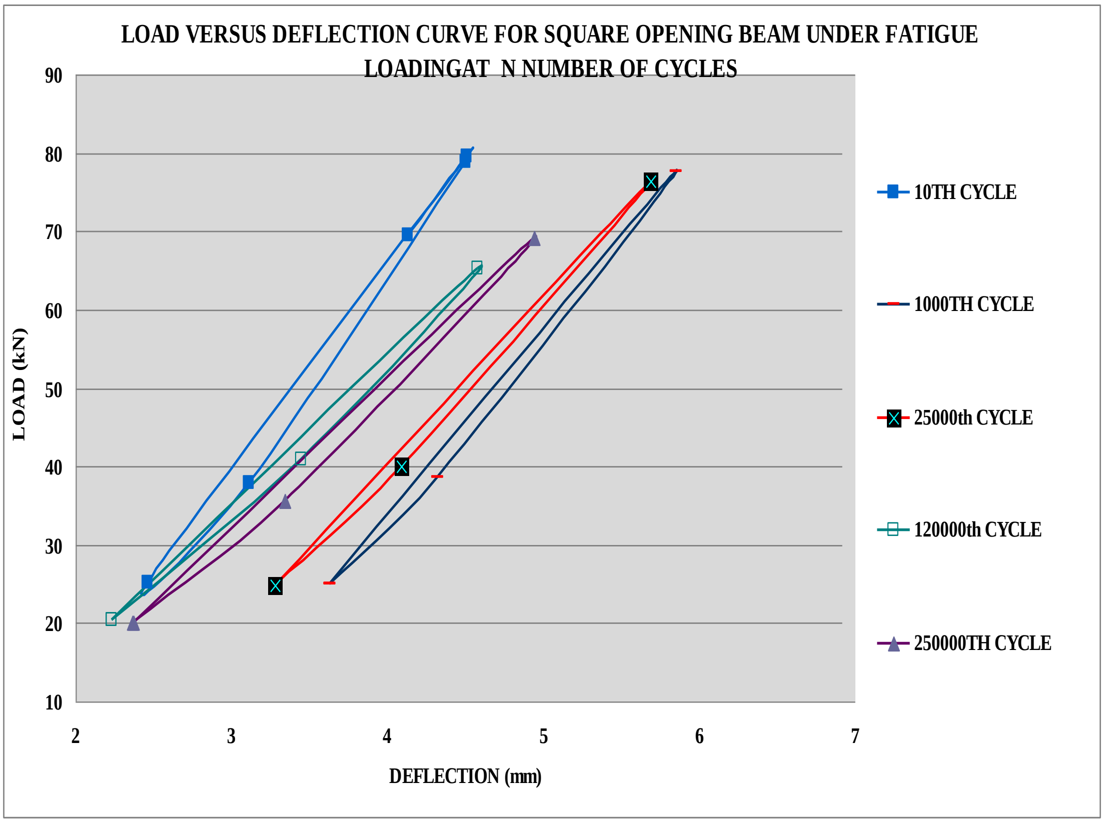
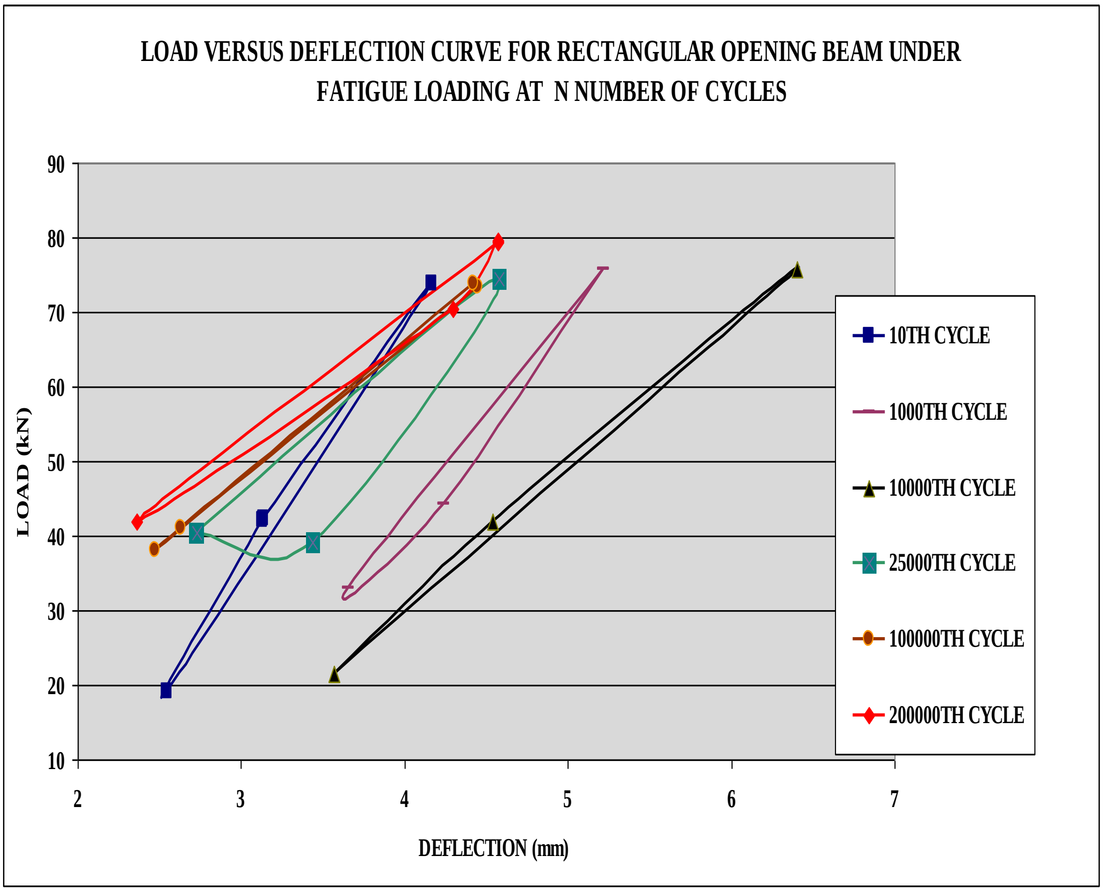
APPENDIX C

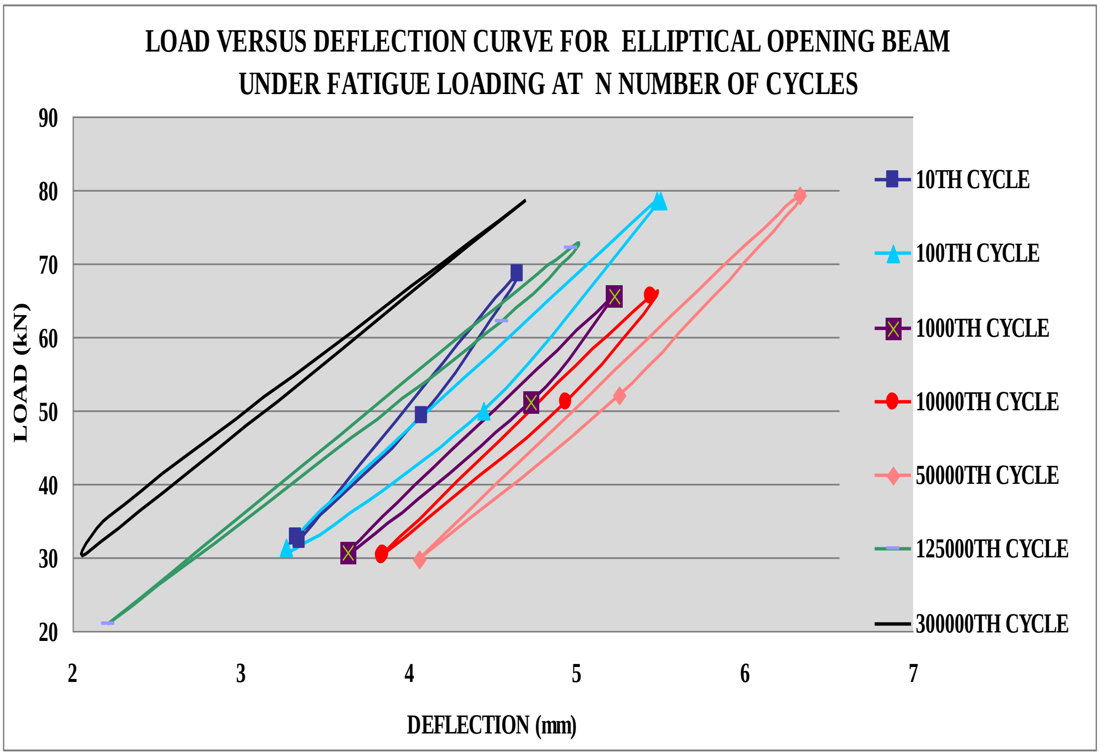
LOAD VERSUS DEFLECTION CURVES FOR BEAM SUBJECTED TO CYCLIC LOADING



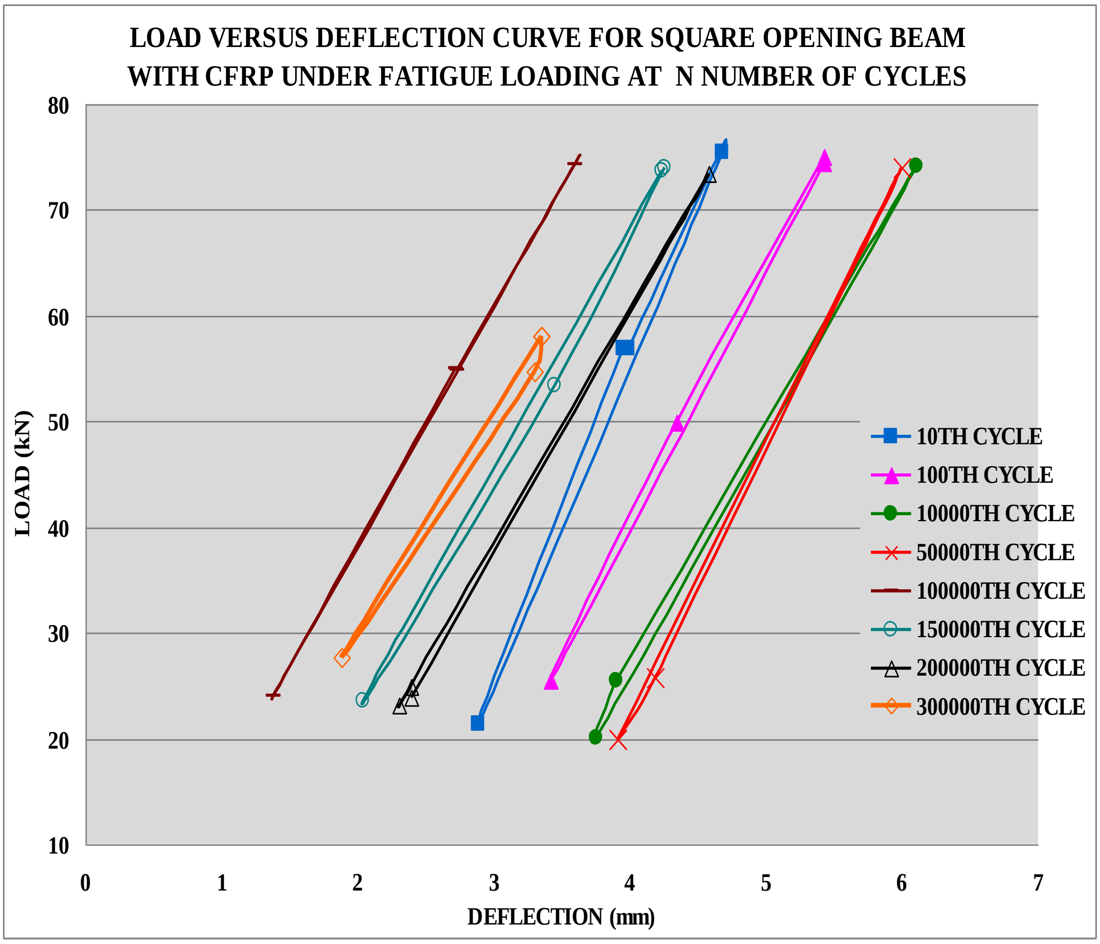



LOAD VERSUS DEFLECTION CURVE FOR SQUARE OPENING BEAM UNDER FATIGUE LOADINGAT N NUMBER OF CYCLES
LOAD (kN)
DEFLECTION (mm)
10TH CYCLE
1000TH CYCLE
25000th CYCLE
120000th CYCLE
250000TH CYCLE

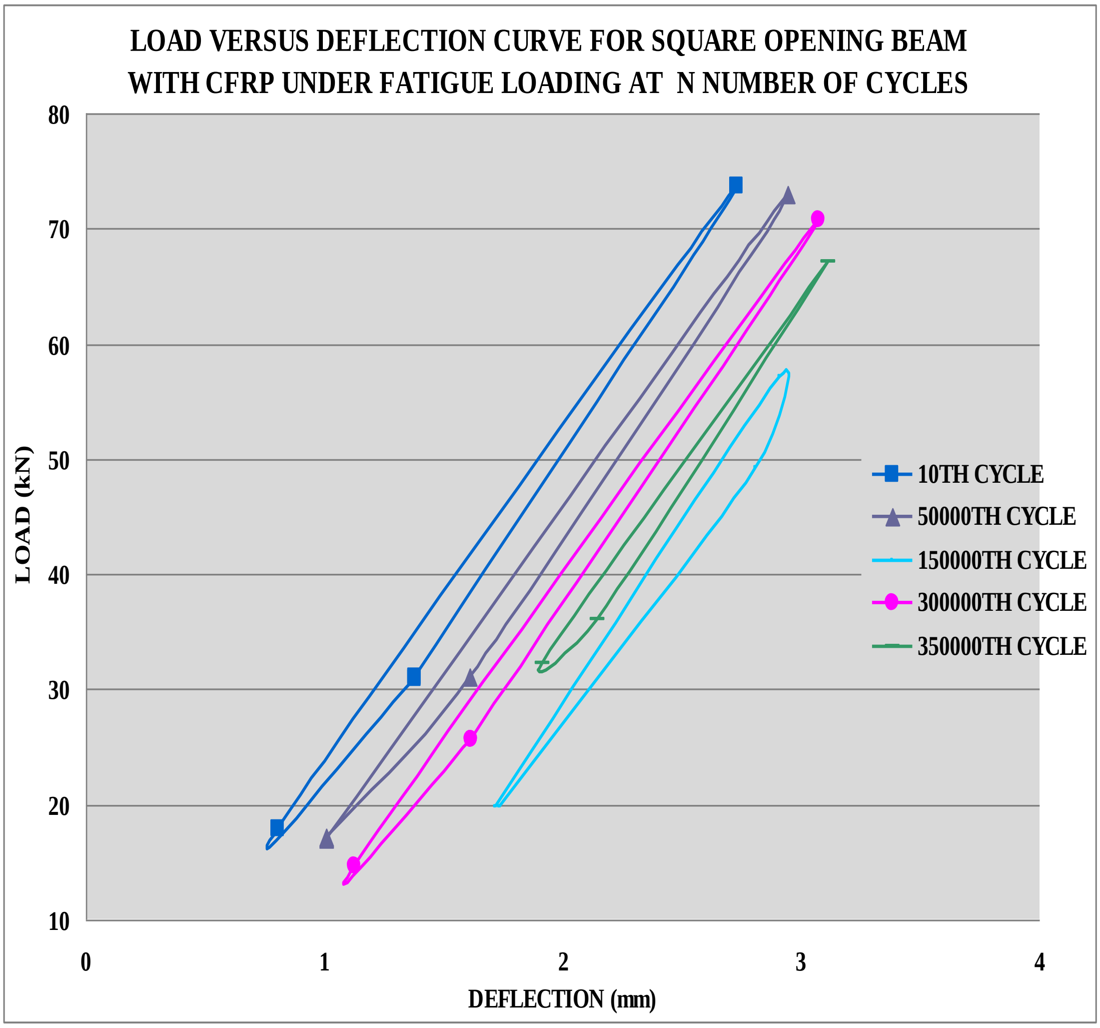

LOAD VERSUS DEFLECTION CURVE FOR RECTANGULAR OPENING BEAM UNDER FATIGUE LOADING AT N NUMBER OF CYCLES
LOAD (kN)
DEFLECTION (mm)
10TH CYCLE
1000TH CYCLE
10000TH CYCLE
25000TH CYCLE
100000TH CYCLE
200000TH CYCLE



LOAD VERSUS DEFLECTION CURVE FOR ELLIPTICAL OPENING BEAM
UNDER FATIGUE LOADING AT N NUMBER OF CYCLES
LOAD (kN)
90
80
70
60
50
40
30
20
2
3
4
5
6
7
DEFLECTION (mm)
10TH CYCLE
100TH CYCLE
1000TH CYCLE
10000TH CYCLE
50000TH CYCLE
125000TH CYCLE
300000TH CYCLE



LOAD VERSUS DEFLECTION CURVE FOR SQUARE OPENING BEAM
WITH CFRP UNDER FATIGUE LOADING AT N NUMBER OF CYCLES
LOAD (kN)
80
70
60
50
40
30
20
10
0
1
2
3
4
5
6
7
DEFLECTION (mm)
10TH CYCLE
100TH CYCLE
10000TH CYCLE
50000TH CYCLE
100000TH CYCLE
150000TH CYCLE
200000TH CYCLE
300000TH CYCLE


LOAD VERSUS DEFLECTION CURVE FOR SQUARE OPENING BEAM
WITH CFRP UNDER FATIGUE LOADING AT N NUMBER OF CYCLES
LOAD (kN)
80
70
60
50
40
30
20
10
0
1
2
3
4
DEFLECTION (mm)
10TH CYCLE
50000TH CYCLE
150000TH CYCLE
300000TH CYCLE
350000TH CYCLE