FINITE ELEMENT ANALYSIS OF RC DEEP BEAMS WITH OPENINGS STRENGTHENED BY CARBON FIBER REINFORCED POLYMER (CFRP)

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ABSTRACT

The research was to deal with overall behaviour of reinforced concrete deep beams with openings strengthened and un-strengthened by carbon fiber reinforced polymer at the shear span near support. The major objectives of the research are to determine the load-deflection curve, crack pattern and effects of opening shape for each beam with and without CFRP strengthening as well as identifying the most effective strengthening method. Due to limited research in numerical approach, this research was conducted by validating the finite element modelling results with experimental results. A total of eleven (11) beams with dimension of 120 x 600 x 2400 mm were modelled as simply supported beams in three-dimensional (3D) analysis by using finite element program, Ansys 12.0. In the research, two (2) types of opening shapes, rectangular (270 x 600 mm) and circularised rectangular (270 x 330 mm, Ø 270 mm) openings were placed at the mid shear span of the beams. In addition, reinforcement used was 2T16 for bottom bar, 2T10 for top bar, R6-300c/c for shear link and R6-150c/c for riser bar. Based on the analytical results, all the beams were failed in shear mode with cracking diagonally from the support to the sharp edge of the rectangular opening and around the circular edge of circularised rectangular opening. By comparing with solid beam, rectangular and circularised rectangular openings have resulted into a reduction in the beam bearing capacity by 70.6% and 68.2% respectively. As for CFRP strengthening beams with vertical surface wrap, horizontal surface wrap, vertical U-wrap and horizontal U-wrap, respectively, an increment of 10.4%, 13.6%, 28.0% and 36.0% for rectangular opening beams and 11.1%, 22.2%, 40.7% and 51.9% for circularised rectangular opening beams in terms of strength regain. Generally, there is good agreement on the crack patterns between FEA and experimental results.

ABSTRAK

Kajian ini dijalankan bertujuan untuk mengkaji sifat dan kelakuan rasuk konkrit bertetulang dalam yang mempunyai pembukaan web diperkukuhkan dan tidak diperkukuhkan dengan gentian karbon polimer bertetulang (CFRP) di rentang ricih terdekat sokongan. Objektif utama kajian ini adalah untuk menentukan graf beban-pesongan, corak retakan dan kesan rasuk bagi setiap pembukaan bentuk dengan atau tanpa pengukuhan CFRP serta mendapatkan kaedah pengukuhan yang paling berkesan. Oleh kerana penyelidikan yang terhad dalam simulasi berangka, kajian ini dijalankan bagi mengesah keputusan FEM dengan keputusan eksperimen. Sebanyak sebelas (11) rasuk dengan dimensi 120 x 600 x 2400 mm telah dimodelkan sebagai rasuk disokong mudah dalam analisis tiga-dimensi (3D), menggunakan program FEM, ANSYS 12.0. Dalam kajian ini, dua (2) jenis bentuk pembukaan, iaitu segi empat tepat (270 x 600 mm) dan segi empat tepat edaran (270 x 330 mm, 270 mm Ø) diletakkan di pertengahan rentang ricih. Di samping itu, tetulang yang digunakan adalah 2T16 bagi bar bawah, 2T10 bagi bar atas, R6-300c / c bagi pautan ricih dan R6-150c/c bagi bar lintang. Berdasarkan keputusan analisis, semua rasuk adalah gagal dalam mod ricih dengan retakan yang menyerong dari sokongan ke pinggir tajam pembukaan segi empat tepat dan sekitar pinggir bulat pembukaan segi empat tepat edaran. Berdasarkan perbandingan dengan rasuk pepejal, segi empat tepat dan segi empat tepat edaran telah menyebabkan pengurangan kapasiti rasuk sebanyak 70.6% dan 68.2% masing-masing. Bagi rasuk diperkukuhkan oleh CFRP dengan pembalutan permukaan (menegak), pembalutan permukaan (mendatar), pembalutan-U (menegak) dan pembalutan-U (mendatar), peningkatan sebanyak 10.4%, 13.6%, 28.0% dan 36.0% bagi rasuk pembukaan segi empat tepat serta 11.1%, 22.2%, 40.7% dan 51.9% bagi rasuk pembukaan segi empat tepat edaran dari segi kapasiti kekuatan masing-masing. Secara umumnya, persamaan yang baik telah diperolehi bagi corak retakan hasil FEA dan keputusan eksperimen.

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LIST OF SYMBOLS

m	Metre
mm	Millimetre
kN	Kilo Newton
N/mm^2	Newton per millimetre square
MPa	Mega Pascal
G35	Garde 35

LIST OF ABBREVIATIONS

RC	Reinforced Concrete
CFRP	Carbon Fiber Reinforced Polymer
FEM	Finite Element Modeling
FEA	Finite Element Analysis
3D	Three Dimensional
FRP	Fiber Reinforced Polymer
GFRP	Glass Fiber Reinforced Polymer
EC2	Eurocode 2
EC3	Eurocode 3
ACI	American Concrete Institute Code
BS	British Code
L	Length of Beam
A	Shear Span of Beam
H	Depth of Beam
NL	Number of Layer
LS	Load Step

CHAPTER 1

INTRODUCTION

1.1 Background

With the rapid growth of construction work in many developing countries nowadays especially in Malaysia, deep beam with opening design and its behavior prediction is a subject of considerable relevance. Deep beam with opening may be of different shapes, sizes and are usually located near to supports where shear is dominant. In construction, deep beam with openings are frequently required for mechanical and electrical conduits or even for means of passageways, such as openings for doors and hallways in building. By allowing openings in deep beams for utilities to pass, there can be reduction in building storey height as well as cost effective. However, realizing the effect of opening towards the strength of deep beam itself in term of shear force and bending moment, today, a relatively large number of studies have investigated the different main factors included in the problem: shear span-to depth ratio, cross sectional properties, amount, type and location of web reinforcement, concrete strength, size, shape and location of opening (Campione & Minafo, 2012). Anyhow, these studies gave more emphasis on the behavior of deep beam with opening and no comprehensive study has investigated the effects of carbon fiber reinforced polymer (CFRP) in reinforced concrete deep beam with openings. Also, study to identify the most effective wrapping method by using carbon fiber reinforced polymer seems to be lacking.

1.1.1 Finite Element Analysis

Finite element analysis is a type of numerical method which provides solutions to problems that would otherwise be difficult to obtain. It is originally developed for solving solid mechanics problems. However, it is a commonly used method for multiphysics problems nowadays. In term of fracture, it is most often involved the determination of stress intensity factors. In the field of civil engineering, finite element analysis is usually used for structure analysis such as cantilever, bridge, oil platform and reinforced concrete frame.

1.1.2 Deep Beam

Deep beam are defined as members loaded on one face and supported on the opposite face so that compression struts can develop between the loads and the supports. It is strong in resisting bending moment as well as shear force. Therefore, it has been widely used in the constructing of transfer girders in offshore structures and foundations, walls of bunkers, load bearing walls in buildings, plate elements in folded plates, pile caps, floor diaphragm and shear walls.

1.1.3 Openings

Openings in deep beams are implemented in construction to provide passage for a network of pipes and ducts. Thus, it can reduce the building storey height as well as cost of construction. However, creating an opening in the deep beam will reduce the stiffness which can leads to cracking and other complicated structural response. Therefore, a good rehabilitation method must be applied to deep beams with openings in order to regain the strength for better bearing capacity.

1.1.4 Carbon Fiber Reinforced Polymer

Carbon fiber reinforced plates are produced by pultrusion process with precise material properties. It is mostly used for flexural strengthening of dynamic and static loaded structures such as bridges, beams, ceilings or walls. While carbon fiber reinforced polymer fabrics are bidirectional fabrics with carbon, glass and aramid fibers. It was commonly used for seismic retrofitting and shears strengthening.

Essentially, this chapter provides an overview of what motivates the researcher to carry out the study. It begins with a brief background where this study would be conducted, followed by the statement of the problem, research objectives, research questions and significance of the study.

1.2 Problem Statement

The use of deep beams at lower levels in tall buildings for both residential and commercial purposes has increased rapidly because of their convenience and economic efficiency. In order to allow utilities to pass through the beam and without increasing the building floor height, an opening is required to construct at the deep beam. However, the opening near the support of deep beam will reduce the strength in term of shear force as well as bending moment resistance and different shape of opening will brings different degree of strength reduction towards the deep beam structure. Besides that, the stiffness of the deep beam will also be affected by creating a large opening with different shapes. Furthermore, a large opening is also affects the cracking pattern on the RC deep beam and causing immediately shear failure. Thus, the overall serviceability of the RC deep beam will be lower after an opening is created on it. Traditionally, engineers are solving this problem by strengthening the deep beam by installing steel plate but it might having high possibilities to damage the concrete structure or the reinforcement inside the concrete during bolting the steel plate in order to attach to the deep beam. Hence, the implementation of latest technology, carbon fiber reinforced polymer which also have very high tensile strength about 3900 N/mm^2. The efficient roll-on installation process enables the CFRP to be applied in a very short time. This can save considerable working time and also gives greater flexibility in construction planning for strengthening work.

1.3 Objectives of the Research

The research is consisted several principal aims which are important to achieve certain expected results:

i. To determine the behavior of reinforced concrete deep beam with opening strengthened and unstrengthen by carbon fiber reinforced polymer in term of load-deflection curve, crack pattern as well as stress and strain contours
ii. To identify the effects of openings in the size and shape, i.e. rectangular and circularized rectangular
iii. To identify the most effective strengthening method for deep beam with opening by carbon fiber reinforced polymer

1.4 Scopes of the Research

In this particular research, commercial software, ANSYS, is adopted to run the numerical analysis of finite element method to solve the approximate solutions of stresses, strains and displacements at each node of elements in 3-dimension. Numerical analysis will be done to identify the behaviour of RC deep beams with large openings as well as the behaviours of beams after strengthening using CFRP. A total of eleven deep beams are considered in this research. A deep beam without any opening acts as a control beam while the remaining modeled deep beams are with openings. One of the modeled deep beams with opening will not be strengthened while the remaining two deeps beams will be modeled with different strengthening methods to identify the most effective strengthening method by applying CFRP around the openings. Two most effective strengthening methods with CFRP will be selected through trial and error in Ansys Finite Element Modeling. The simply supported deep beam with opening before and after CFRP strengthening will be tested by applying four-point-loading to evaluate the crack pattern, load deflection failure, stress and strain contours. The deep beams are tested to failure by constantly increasing the force on the both point loads. The results from the Finite Element Analysis will be compared with the experimental results to determine the similarities and differences between the behaviours of deep beams.

The dimensions of the deep beam with opening that being studied are 120 x 600 mm for the cross section of width and height and length of 2400 mm. The size of opening has been decided to be 45% of reduction from the depth of the RC deep beam which is 270 mm in height for both models of rectangular and circularized rectangular opening. Meanwhile, the diameter of steel reinforcement for the RC deep beams with openings at tension region, which are bottom reinforcement, is 16 mm with a total of two reinforced steel bars. The diameter of steel reinforcement for the compression region, which is top region, is 10 mm with the number of two reinforcement steel bars. The shear link being used for this study is decided to be mild steel with 6 mm in diameter. The concrete grade used for the RC deep beam model in this research is set at grade 35 (G35).

1.5 Significance of the Research

Installed deep beam without opening need to increase the building storey height in order to ensure each floor have sufficient clear storey height, thus delaying construction progress and additional cost required especially for high rise building construction project. Since such problem is becoming more and more common in many populated countries which having rapid development such as Malaysia, deep beams with large openings strengthened by carbon fiber reinforced polymer needs to be practiced. Indeed, it can improve the durability and life span of the structure besides increasing the load bearing capacity. Moreover, the installation process of carbon fiber reinforced polymer will not damage the concrete structure compare to steel plate installation. The implementation of deep beam with opening strengthened by carbon fiber reinforced polymer not only to find a solution for reduce building storey height, in addition the use of deep beams with openings will save the construction cost since it has minimize the overall building weight as well as improving the safety during construction.

1.6 Overview of the Research

Chapter one introduced the background of the RC deep beams with openings, carbon fiber reinforced polymer strengthening and Finite Element Analysis. In this chapter also presented the challenges that are occurred in the construction site nowadays. There are also other subtopics in this chapter including research objectives, scope of the research and significance of research.

Chapter two is the literature review that listing all the findings of researches, study of journals and articles that done by the other authors. In this chapter, the functions and negative effects according to shapes, sizes as well as location are discussed. Subsequently, the different types of material properties in Finite Element Modeling and strengthening methods proposed by other authors are listed and further discuss the suitability for the research. Lastly, the results from Finite Element Analysis and verification with experimental results are also explained and discussed in this chapter.

Chapter three will discuss the research methodology that will be implemented to conduct the whole process of simulation research. From obtaining material properties, modeling of beams and CFRP, analyzing the beam models, abstracting result data and validating and justifying the results of the research is clearly stated in the chapter.

Chapter four will present and discuss on the data and results obtained from FE Analysis including crack patterns, load-deflection behaviours and stress-strain contours. Load-deflection curve will be plotted and the result will be compared with experimental results for validation purpose.

Chapter five is the conclusion and recommendation, the recommendation to improve the research after analyzing the results. The conclusion also considered as the last chapter, which concluding the suitability and effectiveness of carbon fiber reinforced polymer on strengthening RC deep beam with large openings.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction of Reinforced Concrete Deep Beams

Reinforced concrete (RC) deep beams are structural members commonly used as load-distribution structural elements which load is transferred to the support by a compression thrust joining the loading and reaction point. Alsaeq, (2014, as cited Yang et al, 2006) clarified that deep beams should be loaded on loading points and supported on reaction points so that compression struts can develop between the loads and supports. RC deep beams are characterized by shear span and depth ratio falls between 1 and 2 as well as subjected with loads within support zones. Therefore, Campione (2012) claimed that their strength is generally controlled by shear rather than flexural strength. Besides that, they are also considered as host zones of static and geometric discontinuities.

According to ACI 318-08 code, deep beams have clear span which is equal to or less than four times the overall member depth. In addition, the concentrated loads in beam region are twice the member depth from the face of the support.

2.2 Reinforced Concrete Deep Beams with Large Openings

In contrast to solid deep beams, a good deal of work has been done with deep beams with openings by engineers in the last few years. The web openings in deep beams are conducted in different shapes, sizes and location due to the construction requirement as well as the reduction of shear and flexural strength of the beam structures. Sometimes, openings are made with a core boring technique, and it may be necessary to determine the mechanical properties of the concrete in existing structures as shown in Figure 2.1. Campione and Minafo (2012) justified that if openings intercept the stress field joining the loading and the reaction point; it is obvious that the simple load path changes and the shear capacity are reduced.

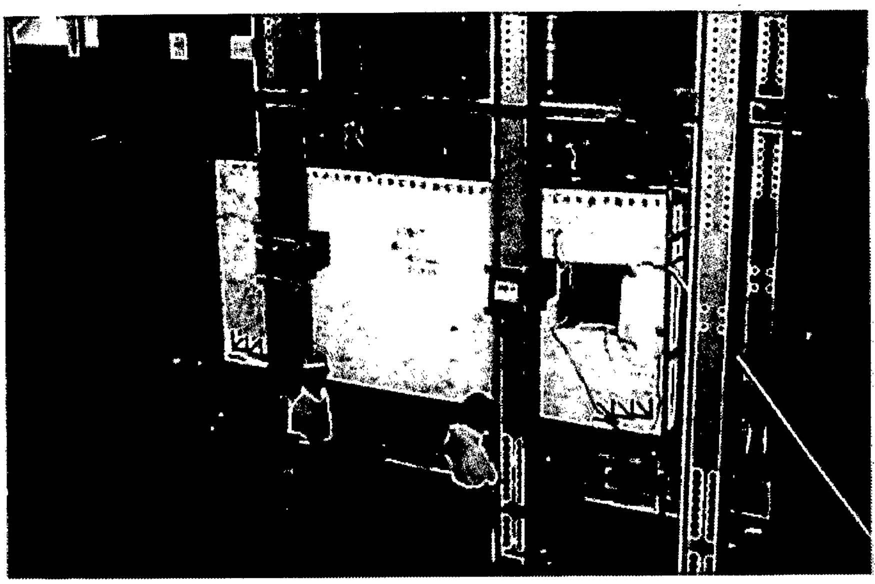

Figure 2.1: Deep beam with openings

Source: Kumar (2012)

2.2.1 Function of RC Deep Beams with Large Openings

Large openings are inevitably installed in the deep beam structure members are frequently required in order to create electrical and mechanical conduits in civil plants like electricity wiring, hydraulic piping and computer network or even for means of passageways such as openings for doors and windows in buildings (Kumar, 2012).

2.2.2 Advantages of RC Deep Beams with Large Openings

In the practical life of construction, deep beams with large openings are widely used to provide convenient passage of environmental services which reduce the storey heights of buildings and the overall weight of the concrete beams as it improves the demand on the supporting structural frame both under gravity loading and seismic excitation, indirectly it saved construction cost (Hafiz, Ahmed, Barua & Chowdhury, 2014).

2.3 Behaviour of Reinforced Concrete Deep Beams with Large Openings

Large openings on reinforced concrete deep beams as shown in Figure 2.2 which are also known as structural penetrations are effective in term of reducing building storey height and construction cost, but it also issues problems toward the structural behaviour based on different parameters such as size, shape and location of web opening, shear span-to-depth ratio, cross sectional properties, amount, type and location of web reinforcement as well as concrete strength.

Kaur, Singh and Shafiq (n.d.) also found that concrete and steel have different behaviours in compression as well as tension mode. Concrete is affected by the confinement due to the stirrups and the buckling of the steel bars in compression mode. In tension mode, the tensile loads are carried by steel reinforcement even though there are cracks in concrete in order to achieve its full load. Concrete and steel may lead to longitudinal cracking which causing several durability problems, excessive deformation and a decrease in load carrying capacity especially when the bonding between concrete and steel is weaken.

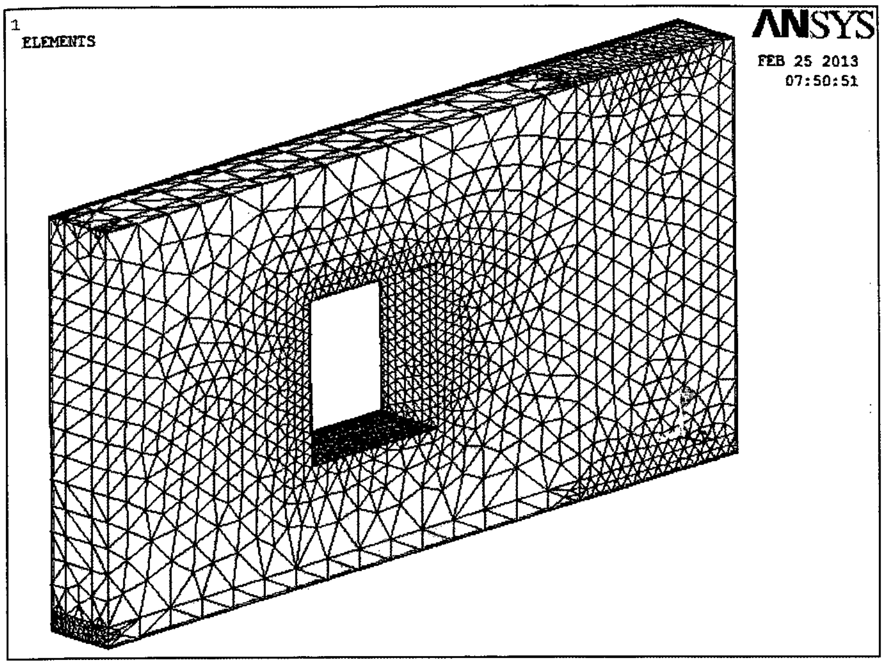

Figure 2.2: Elements of deep beams with openings in ANSYS

Source: Alsaeq (2014)

2.3.1 Effects of Opening Shapes

Most of the researches and studies are focus on four types of opening shape which are circular, square, rectangular and elliptical as these openings are mostly constructed openings on reinforced concrete deep beams in the industry. For example, reinforced deep beams with circular openings are used to accommodate service pipes and electrical supply while reinforced concrete deep beams with rectangular openings are used to accommodate rectangular air conditioning ducts.

Generally, square opening reduces the ultimate load more than the circular opening with the same size due to stress concentration occurs at the existing orthogonal corners in square opening (Hafiz, et al., 2014). In addition, Alsaeq (2014) concluded that using a circular opening instead of a square one with the equivalent size can save a 19% of structural strength. Furthermore, Kaur, Singh and Shafiq (2011) found that reinforced concrete deep beams with elliptical and rectangular opening have higher ultimate load capacity compared to solid and square opening beam.

2.3.2 Effects of Opening Sizes

Construction of an opening on a deep beam caused the loss of concrete area, which directly 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 (Kaur, Singh, & Shafiq, n.d.). On the other hand, Hafiz and his colleagues (2014) have justified that there is no effect on the ultimate load capacity towards a deep beam structure if the diameter of a circular opening of a reinforced concrete deep beam is less than 44% of the overall depth of the beam. However, the ultimate load capacity will experience at least 34.29% of reduction if the diameter of a circular opening of a reinforced concrete deep beam is more than 44% of the overall beam depth. Besides that, Campione and Minafò (2012) found that the concrete compressive strength on the load-carrying capacity significantly decreased in deep beams with openings depended on span-to-depth ratio which equivalent to the size of the openings.

2.3.3 Effects of Opening Locations

Campione and Minafo (2012) have proposed that the web opening position in the beam is one of the main factors affecting the beam structural strength based on a comparative analysis of the experimental results. Moreover, the researchers found that the failure mode mainly depended on the position of the opening and the highest load capacity reduction occurred when the opening was placed within the interior shear span (Campione, et al., 2012).