FINITE ELEMENT ANALYSIS OF RC DEEP BEAMS WITH OPENINGS LOCATED IN THE MID OF SHEAR SPAN

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ABSTRACT

The research was carried out in order to study the behaviour of reinforced concrete deep beams with web openings. Openings are often provided in beam for accessibility purpose and to accommodate essential services such as power supply, ventilation system and network system access. However, the presence of openings in deep beams may lead to many problems in the beam behaviour such as reduction in the beam capacity, cause excessive cracking and deflection. Due to limited research in numerical approach, this study was performed in order to study the behaviour of reinforced concrete deep beams with web openings by validating the FEM results with the experimental study. A total of seven beams including one control beam was modelled as simply supported beams in two-dimensional analysis, using a finite element program, ATENA. In this study, the openings were placed at the mid of the shear span. The shapes and sizes of openings considered in this study were rectangular (150 x 250 mm, 200 x 250 mm, 250 x 300 mm) and circular (∅150 mm, ∅200 mm and ∅250 mm). The beams were in a cross section of 100 mm x 500 mm and 1200 mm in length. The results considered in this study were the load-deflection curve/behaviour and the crack patterns. Increasing the size of openings resulted into a reduction in the beam capacity where it was observed that BRO1, BRO2, BRO3, BCO1, BCO2 and BCO3 reduces the beam capacity by 40.36%, 54.68%, 66.98%, 39.71%, 44.72% and 47.04% respectively as compared to the control beam. It was found that the use of circular opening has advantage over using rectangular opening regarding the structural strength. Rectangular openings reduces the strength about 0.65% to 19.94% greater than circular openings due to the high stress concentration at the corners of the openings. Solid control beam failed due to flexure cracks which turned to shear cracks whereas beams with openings (rectangular and circular) failed due to the shear cracks. A fair agreement on the crack patterns obtained by FEM and experimental results were observed.

ABSTRAK

Kajian ini dijalankan bagi mengkaji sifat/kelakuan rasuk konkrit bertetulang dalam yang mempunyai pembukaan web. Pembukaan kebiasaannya diperlukan di dalam rasuk untuk kemudahan akses dan bertujuan menempatkan servis-servis yang diperlukan seperti bekalan tenaga, sistem pengudaraan dan sistem rangkaian. Walaubagaimanapun, kehadiran pembukaan di dalam rasuk konkrit bertetulang dalam boleh menyebabkan berbagai masalah dalam sifat rasuk seperti kekurangan kapasiti rasuk yang mana menyebabkan keretakan berlebihan dan lenturan. Disebabkan penyelidikan yang terhad dalam pendekatan berangka, kajian ini dijalankan bagi mengkaji sifat/kelakuan rasuk konkrit bertetulang dalam dengan pembukaan dengan mengesahkan keputusan FEM dengan keputusan eksperimen. Sebanyak tujuh (7) rasuk termasuk satu (1) rasuk kawalan dimodelkan sebagai rasuk sokongan mudah menggunakan analisis dua dimensi (2D), menggunakan program unsur terhingga iaitu ATENA. Dalam kajian ini, pembukaan telah diletakkan di pertengahan rentang ricih. Bentuk dan saiz pembukaan yang diambil kira dalam kajian ini adalah segi empat tepat (150 x 250 mm, 200 x 250 mm, 250 x 300 mm) dan bulat (∅ 150 mm, ∅ 200 mm dan ∅ 250 mm). Rasuk di dalam kajian ini adalah sepanjang 1200 mm dan mempunyai keratan rentas 100 mm x 500 mm. Keputusan yang dipertimbangkan dalam kajian ini adalah graf beban dan lenturan dan corak retakan rasuk. Berdasarkan kajian yang dijalankan, sebanyak 40.36%, 54.86%, 66.98%, 39.71%, 44.72% dan 47.04% pengurangan kapasiti rasuk berbanding dengan rasuk kawalan telah diperhatikan bagi BRO1, BRO2, BRO3, BCO1, BCO2 dan BCO3. Didapati pengunaan pembukaan bulat mempunyai kelebihan berbanding pembukaan segi empat tepat berdasarkan kekuatan struktur. Bukaan segi empat tepat mengurangkan kekuatan rasuk sebanyak 0.65% hingga 19.94% lebih besar dari pembukaan bulat kerana tekanan yang tinggi tertumpu di sudut-sudut bukaan. Rasuk kawalan gagal disebabkan oleh retakan lenturan yang beralih kepada retakan ricih manakala rasuk dengan pembukaan (segi empat tepat dan bulatan) gagal disebabkan oleh retakan ricih. Persamaan yang baik telah diperolehi bagi corak retakan hasil analisis FEM dan keputusan eksperimen.

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LIST OF SYMBOLS

L	Span
D	Depth
∅	Diameter
l_o	Opening length
h_{max}	The larger of the depth above the opening and the depth below the opening
$<$	Less than
$>$	Greater than

LIST OF ABBREVIATIONS

RC	Reinforced concrete
2D	Two-dimensional
FEA	Finite element analysis
FEM	Finite element method
CB	Control beam
BRO1	Beam with rectangular openings (150 x 250 mm)
BRO2	Beam with rectangular openings (200 x 250 mm)
BRO3	Beam with rectangular openings (250 x 300 mm)
BCO1	Beam with circular openings (∅ 150 mm)
BCO2	Beam with circular openings (∅ 200 mm)
BCO3	Beam with circular openings (∅ 250 mm)
FRP	Fiber reinforced polymer

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

The use of reinforced concrete deep beams in structural engineering practice has become more prevalent in the recent years. Deep beams are often used in engineering structures such as transfer girders, foundations, water tanks, floor diaphragms, bunkers, shear walls and brackets. In fact, deep beams are very useful in tall buildings or also known as high rise buildings. In the offshore gravity type structures, deep beams also act as a transferring and supporting elements.

A deep beam is a type of a non-flexural member having a depth comparable to its span. It is considered as a deep beam when the member has a span (L) to a depth (D) ratio of less than 5. A simply supported beam is classified as a deep beam when the ratio of its effective span, L to its overall depth, D is less than 2. However, a continuous beam is considered as a deep beam when the ratio of the effective span, L to its overall depth, D is less than 2.5.

Web openings in the beam occur quite often in practice and as a result, story heights in buildings can be reduced and openings may be of different shapes and sizes depending on the purpose of providing the opening. Reinforced concrete deep beams with openings have complex stress and as investigated in the past research, the opening location, size and also shape have much effect on the structural strength of the deep beam. Various shapes are available, however the most common one is rectangular and circular openings.

The behaviour of deep beams are different from other beams in which it requires special consideration in the analysis, design and detailing of the reinforcement. There are various methods such as experimental work, elastic theory, analytical modelling and semi empirical equation are available for analysing reinforced concrete members and one of the methods available is Finite Element Analysis. In order to verify the finite element model, the simulation results are being compared with the experimental study.

1.2 PROBLEM STATEMENT

In the recent years, large openings are often required in the structural members due to electrical and mechanical conduits purpose. For instance, openings are found in floors due to staircase, elevators, ducts and pipes. It is provided through the floor beams in order to provide accessibility such as doors and windows and to allow the passage of utility pipes and service ducts. The service ducts accommodate essential services such as power supply, ventilation system, air conditioning and also network system access. In fact, openings or holes in the structural members are said to be useful for inspection purposes in beam structures.

As a result of these particular arrangements of building services, the storey height of the building can be minimized and this will help to save the cost for material and construction. However, the presence of openings interrupts the load transfer by concrete struts of these beams and cause a sharp decrease in strength and serviceability. The presence of opening in the web of a reinforced concrete beam may be resulted too many problems in the beam behaviour such as excessive cracking, deflection, reduction in the beam capacity and beam stiffness. Web opening in the reinforced concrete deep beams also causes high stress concentration around the openings.

As mentioned in Section 1.1, various methods are needed to analyse the behaviour of RC deep beams but according to the research done by Mohammad (2007), neither of the method is entirely satisfactory in predicting the failure modes of deep beams. For the recent years, a lot of studies on the reinforced concrete deep beams with web openings have been carried out, however there are limited research in the area of finite element analysis. Most of the study that has been carried out involved pure experimental works without any validation using finite element method. Referring to Mohammad, it is recognized that finite element methods can provide realistic and satisfactory solutions for the nonlinear behaviour of RC deep beams. Therefore, this study is conducted to study the behaviour of reinforced concrete deep beams with web openings by validating the results with the experimental works.

1.3 OBJECTIVES OF THE STUDY

The objectives of this research are:

i. To determine the load-deflection curve and/or behaviour of reinforced concrete deep beams with openings.
ii. To determine the crack patterns of various shapes (rectangular and circular) and sizes of openings in the reinforced concrete deep beam.
iii. To validate the results obtain by the finite element analysis with the experimental works.

1.4 SCOPE OF THE STUDY

This research study considers the following conditions:

i. The shapes and sizes of openings considered in this study are rectangular and circular with the size of 150 x 250 mm, 200 x 250 mm, 250 x 300 mm and ∅150 mm, ∅200 mm and ∅250 mm, respectively.
ii. The openings were placed at the mid-point of shear span.
iii. All the beams were modelled in two-dimensional analysis (2D).
iv. All the beams were modelled as simply-supported beams, using ATENA, finite element program.
v. The results considered in this study were the load-deflection curve/behaviour and the crack pattern.

1.5 RESEARCH SIGNIFICANCE

It is important to study the behaviour of reinforced concrete deep beams with openings as the presence of openings in deep beams often resulted into many problems in the reduction of beam strength, excessive cracking and deflection. Various shapes and sizes are available however, according to Prentzas (1986), the most common shapes of opening are rectangular and circular. Openings are often required for various purposes as mentioned in the section discussed before.

In fact, there have been extensive experimental studies and analytical studies (pure ANSYS without CivilFEM) of reinforced concrete deep beam (Maaddawy and Sherif (2008), Amiri et al., (2011), Saksena et al., (2013), Alsaeq (2013), et al.).

Very few studies have been reported on the behaviour of reinforced concrete deep beams with web opening by using ATENA. Therefore, this research is conducted to study the behaviour of reinforced concrete deep beams with web openings by using a two dimensional analysis of ATENA.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION TO RC DEEP BEAMS

Beam is classified as a structural element which is able to withstand loads mainly by resisting bending. Most beams are horizontal members which works by transferring loads in a horizontal direction along their length to the supports. A beam is classified as a deep beam when the ratio of shear span to effective depth (a/d) is less than one. RC deep beams are mainly useful in building structures in which it works as a transfer girders, wall footings, shear wall, foundation and also water tanks where the walls act as vertical beams spanning between column supports (Yousif, 1986). Nowadays, the use of RC deep beams has increased and it has mostly been applied at the lower levels in tall or high rise buildings due to their convenience and economical efficiency.

2.1.1 RC Deep Beam with Web Opening

RC deep beam with web opening is one of the most preferable beam used in construction. Various shapes of openings are available in RC deep beams such as circular, rectangular, triangular, diamond, trapezoidal and even irregular shapes. According to Prentzas (1968), the most common types of openings being used are circular and rectangular openings. In addition, the size of the web openings usually varies depending on the purpose of use. Openings can be classified as small or large openings.

Different researches have different ways to classify openings as small or large openings. Another writing from Mansur (1998), explains that in order to classify the size of openings as either large or small opening is depending on the opening length, l_o and

The larger of the depth above the opening and the depth below the opening, h_{max}. It is stated that the opening is classified as small openings when $l_o \leq h_{max}$ and when $l_o \geq h_{max}$, it is considered as a large opening.

2.1.1.1 Importance of RC Deep Beam with Web Opening

The presence of web openings is sometimes necessary in order to allow for the passage of utility ducts and pipes and therefore the openings are usually present on the floors. In construction, it is compulsory for the buildings to have the service ducts to accommodate essential services such as a ventilation system, air-conditioning, network system access and also the power supply. In fact, in construction, there are times when we need to do inspection and hence holes or openings are provided in the beam for inspection purposes in the beam structure itself. Referring to Mansur and Tan (1999), the presence of web openings in the RC deep beams will help to minimize or reduce the storey height of the building and indirectly will reduce the material and construction cost.

2.2 BEHAVIOUR OF RC DEEP BEAM WITH WEB OPENING

As people are aware of, the presence of a web opening in RC deep beam present some formidable problems mainly in the beam behaviour which will finally lead to the excessive cracking and deflection and also a reduction in the beam capacity. Large openings in the beam are usually required for mechanical or electrical passage purposes and it is found that the presence of large openings often interrupts the load transfer by concrete struts and finally lead to the decrease in the strength and serviceability.

According to Mansur (1992), the reduction of area in the total cross sectional dimension of a beam will causes the behaviour of the beam changes into a complex one. This happened due to the sudden change in the dimension of a cross section of the beam. Therefore, the stiffness will be reduced which will lead to deformation and excessive deflection. Hence, the design of these particular beams will need special consideration.

2.2.1 Shape of Opening

The opening shapes play an important role in the structural strength of the RC deep beam with web opening. It is found out that, the best shape for opening is the rectangular opening as shown in Figure 2.1, with the long sides being extended in the horizontal direction and circular opening is a better opening if compared to the square opening by considering the structural strength of the beam (Alsaeq, 2013).

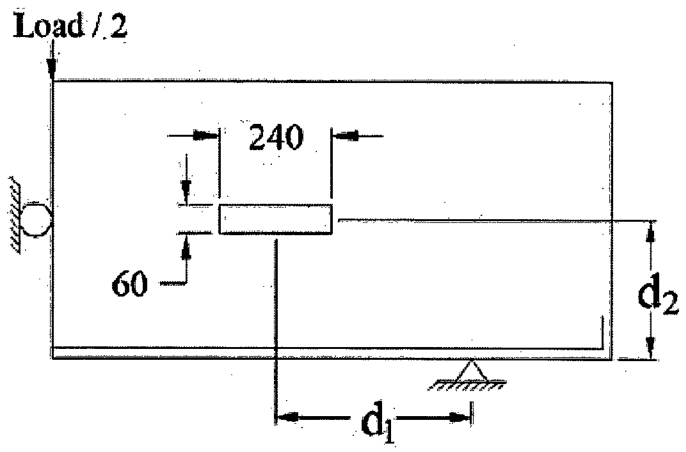

Figure 2.1: Rectangular opening provided in Alsaeq's study

Source: Alsaeq 2013

2.2.2 Effect of Opening Size

Opening size is another factor which may affect the behaviour of RC deep beam. The web openings size depends on the purpose of use. The larger the opening size being used, the greater the structural strength of the beam being reduced. For beams having a small opening, the beam action may be assumed to prevail. Hence, the design and analysis of beam with small openings may follow the similar course of action as that of a solid beam (Mansur, 2006).

The existence of the opening will create a disturbance in the normal flow of stresses, which will finally lead to the early stage of cracking focusing around the opening area. It is necessary to provide sufficient reinforcement enclosing the opening in order to control the crack widths and prevent possible failure of the beam.

2.3 FINITE ELEMENT ANALYSIS (FEA)

Finite Element Analysis (FEA) is a computer model of a material that is stressed and being analyzed for specific results. According to David Roylance (2001), even a very complicated stress problems can be solved by numerical solutions by using FEA. In the recent years, finite element method has been applied to two-dimensional problems. Finite Element Method (FEM) is useful in finding the approximate solutions of partial differential equation. With the well-developed graphic and availability of a finite element computer program such as ANSYS, LUSAS, ABAQUS, ADINA, SAP and ATENA has led to the increase in popularity of Finite Element Method (FEM).

By using many elements in the analysis, Finite Element Method (FEM) is capable of providing a realistic and satisfactory solution for both linear and nonlinear behavior of deep beam (Quanfeny and Hoogenboom, 2004; Samir and Chris, 2005). As in the case of studying the behavior of reinforced concrete deep beams, Finite Element Method (FEM) is able to provide a powerful analytical tool (Sciarmmarella, 1963; Singh, et al. 1980 and Tan, et al. 2003). In fact, in the case of structural failure, the design modifications can be determined by using Finite Element Analysis (FEA).

Two types of analysis are available which is 2-D modelling and 3-D modelling. As for 2-D modelling, the analysis conserves simplicity if compared to 3-D modelling which will produce a more accurate result (Cervenka, 2010). Numerous functions can be inserted which will then determine the system whether to behave linearly or non-linearly. Non-linear systems are able to test the material or structure until fracture.

2.3.1 How Does Finite Element Analysis Works

A Finite Element Analysis which is first being developed by R. Courant in 1943 is one of the computational technique which is able to solve various engineering problems. With the well-developed technologies nowadays, engineering problems can be solved by developing a prototype and conducting test required on the prototype without wasting time and money. As for the study of RC deep beams with web opening, the study can be done by modelling and analysing the beam by conducting necessary test.

There are several analytical tools available for analysing deep beams and FEA offers a better option by introducing computer based programs which is able to solve a variety of "real world" engineering problems. FEA uses nodes which will finally make a grid known as mesh as shown in Figure 2.2. The material and structural properties in the mesh will help to define the behaviour of the structure when subjected to certain loading conditions.

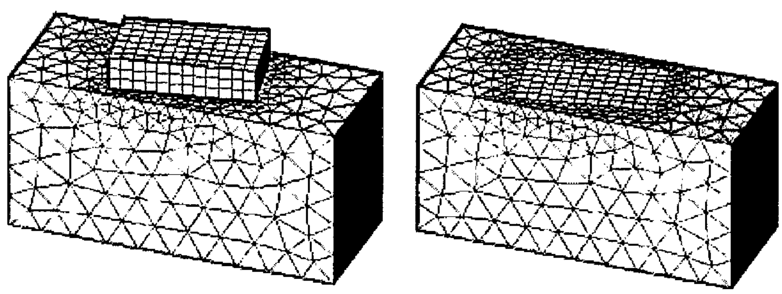

Figure 2.2: Mesh generation using finite element program

Source: Cervenka et al. 2010

Stress levels of a particular area affect the distribution of nodes assigned throughout the material. A region of a higher node density will receive a larger amounts of stress and therefore a region with a lesser node density will receive little or no stress. The mesh element will extend to each of the adjacent nodes and this indirectly helps to create many elements. There are a few factors affecting the effectiveness of the FEA which are the use of efficient finite elements, efficient programming methods and the use of appropriate numerical techniques (Klus, 1990).

2.3.2 Finite Element Idealization Using ANSYS + CivilFem

ANSYS software was first developed by Dr. John Swanson. According to Abdel Hafez (2000), ANSYS can be used to study the behaviour of reinforced concrete deep beams subjected to in plane forces if the modelling of the material characteristics is done properly. Through ANSYS, the crack pattern of various shapes and sizes of openings in the reinforced concrete deep beam can be determined. In addition, ANSYS also able to determine the load-deflection curve or behaviour of the deep beams with or without openings. Research conducted by Mahmoud et al. (1998), shows that through ANSYS we can also determine the failure load and failure mode. ANSYS + CivilFEM is an advance and comprehensive finite element analysis and design software which is now available to analyse all the structural elements.

2.3.2.1 Material Modeling of ANSYS

The correct selection of element types is an important aspect which contributes to the accurateness and the effectiveness of the results obtained. "CONCRET65" or also known as "SOLID65" are usually being used to model concrete material because the element is capable of modelling the nonlinear behaviour of concrete in both tension and compression (Hawileh et al. 2012). "CONCRET65" or "SOLID65" is defined by eight nodes having three degrees of freedom at each node.

Moreover, research conducted by Alsaeq (2013) shows that the concrete is capable of cracking, crushing, plastic deformation and creep. Steel bars are usually being model using "SPAR8" or named as "LINK8". This two-node element can also be used to model a variety of engineering structures such as trusses and cables. As for loading and support plates, SOLID45 with eight nodes and three degrees of freedom are usually selected. Research conducted by Alsaeq as shown in Figure 2.3 and Figure 2.4 uses

ANSYS 12.1 to investigate the effects of opening shape and location on the structural behaviour of reinforced concrete deep beam with openings.

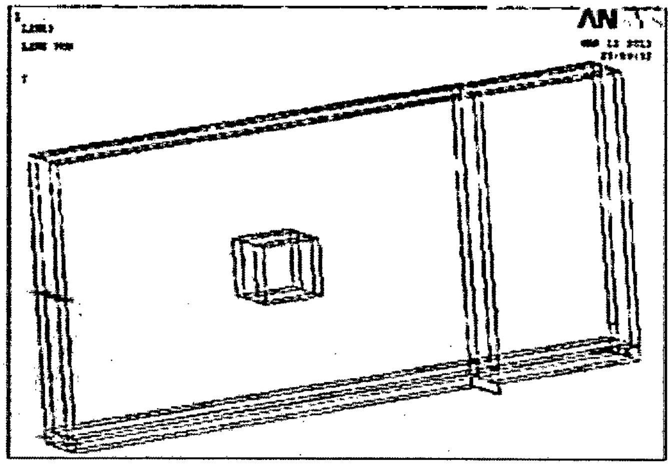

Figure 2.3: Modelling of half of the beam using ANSYS 12.1

Source: Alsaeq 2013

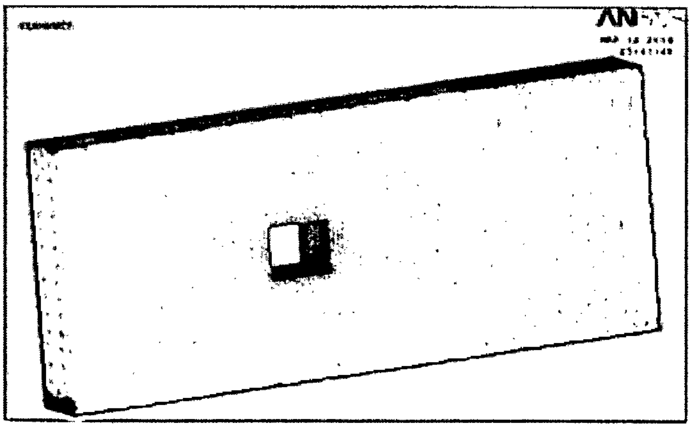

Figure 2.4: Modelling of the beam (Finite Element Mesh) using ANSYS 12.1

Source: Alsaeq 2013

2.3.3 Finite Element Idealization Using ATENA

ATENA is a software for analysis of concrete and reinforced concrete structures in which the software simulates the real behaviour of concrete cracking, crushing and reinforcement yielding. This particular finite element program gives the users an opportunity to check and verify their concrete structures. Research conducted by Chin et al. (2012), shows that the simulation by using a two dimensional nonlinear finite element analysis (ATENA) is capable of predicting the crack pattern as well as the load deflection relationship of beams.

2.3.3.1 Material Modelling of ATENA

Similarly with ANSYS software, material selection plays an important role in the accurateness of the results obtained. As for ATENA software, SBETA material model is selected to represent concrete and the tensile behaviour of concrete was modelled by nonlinear fracture mechanics combined with the crack band method (V. Cervenka, 1999). SBeta Material is selected in this study because it is suitable to model concrete in 2D and in fact, it does includes the following effects of concrete behaviour such as :

- Non-linear behaviour in compression including hardening and softening
- Fracture or concrete in tension based on the non-linear fracture mechanics
- Biaxial strength failure criterion
- Reduction of compressive strength after cracking
- Tension stiffening effect
- Reduction of the shear stiffness after cracking (variable shear retention)
- Two crack models which are fixed crack direction and rotated crack direction

Reinforcement can be modelled in two distinct forms which are discrete reinforcement and smeared reinforcement (Cervenka et al., 2010). Discrete reinforcement is a form of reinforcing bars and it is being modelled by truss elements whereas smeared reinforcement is a component of composite material and can be considered either as a single material in the element. However, in this study, reinforcement and shear links were simulated by using discrete reinforcement represented by bar reinforcement elements.