CHAPTER 1

INTRODUCTION

1.1. General

A network of pipes and ducts utilizes such as water supply, and sewage systems, electricity, telephone, air-conducting, and internet cables are main requirements for any construction building. Previously, passage of these pipes and ducts are usually placed underneath the beams, as shown in Figure (1.1), covered by a suspended ceiling to keep the aesthetic shape of the building, thus it creates a dead space in each floor and increases the overall height of the building. Consequently, the loads on the foundation and on the load-carrying structural members are increased, which results additional cost especially for the high-rise building. In modern buildings, construction provided transverse openings in the reinforced concrete beams to passage of the utility ducts and pipes to prevent the presence of the dead space and decrease the overall height of the building, as shown in Figure (1.2). Consequently, the loads on the foundation and on the load-carrying structural members are reduced and a more economical design achieved. Nevertheless, presence of the openings represents a source of weakness for the reinforced concrete beams. Result to abrupt reduction in the dimension of the beam's cross section at opening locations and stress concentrations around the opening areas, which may be change the behavior of beams and lead to earlier failure.

Many practical and theoretical studies were developed to study the effect of small and large openings on the behavior of reinforced concrete beams and the change in its behavior especially (The pattern of cracks, modes of failure, the cracking and ultimate loads, the maximum mid-span deflection and difference between deflection of two edges of the opening, and the relation between load and deflection). Also, many researchers reported different methods to cure the changing in the behavior of reinforced concrete beams which result from the presence of the opening, and take the precautions to reduce the stresses concentration around the opening area to prevent the earlier failure.

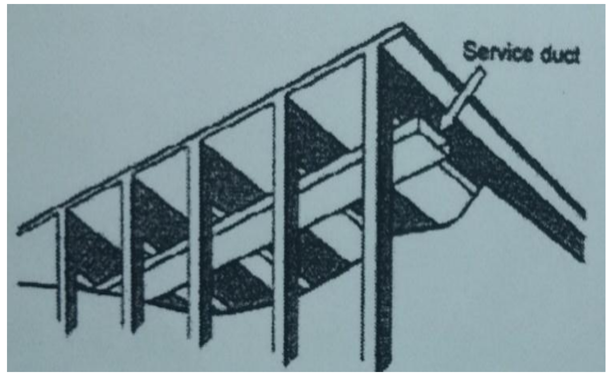

Figure (1.1) Practical and graphical sketches display passage the ducts beneath the beams.

Figure (1.2) Practical and graphical sketches display passage the ducts through the beams.

On the other hand, the properties of normal reinforced concrete may be changed according to design requirements. Recently, it is common to use the high strength concrete (HSC) as alternative to normal strength concrete in some construction buildings as (high rise building, sky scrapers, and large span bridges), which have a structural elements subjected to high compressive stresses, Because high strength concrete have (higher compressive and shear strengths, higher stiffness, and better durability) when compared to the conventional normal strength concrete.

As a result of the prominence of high strength concrete recently, this study is prepared to investigate the effect of presence a large rectangular web Openings on the behavior of high strength reinforced concrete beams with rectangular cross sections and subjected to different types of load (uniform – two concentrated loads). Also beams with openings and made from normal strength concrete were analyzed to make a comparison between behavior of these beams and the other beams with high strength concrete. The change in behavior of high strength R.C. beam (ultimate and cracking loads, pattern of cracks, and deflection) due to various parameters: Opening Length, Opening Depth, Position of the opening along the beam axis, Ultimate cylinder compressive strength, Main reinforcement ratio, reinforcement and stirrups on top and bottom the opening, and the Type of load were predicted using nonlinear finite element (ANSYS Program), also all the results were analyzed and discussed.

1.2. Research Objectives

The main objective of this research is to study the effect of a large rectangular opening on the behavior of simply-supported high strength reinforced concrete beams with rectangular cross section to describe the behavior and get elementary analysis for these beams to take precautions and choose appropriate location and conditions for the opening during design process.

1.3. Thesis Organization

Five chapters were developed to achieve the thesis objectives, these chapters are classified as follows:

Chapter 1 Presents a general introduction protrudes the importance of the topic, also clarify the objectives and the plan of this research.

Chapter 2 Presents a summary for many previous researches that were studied and implemented in this topic.

Chapter 3 Presents a general introduction for the used finite element program in this research (ANSYS 14.5), also explains all details for the finite element models and the used analytical technique. Finally, a verification models is presented to check the adequacy of proposed chosen element types, material properties, real constant, and based convergence criterion.

Chapter 4 Contains analytical study for a fifty simply-supported reinforced concrete beams to investigate the behavior of beams with openings such as (Pattern of cracks and mode of failure, Cracking load, Failure load, Deflection, and Load-Deflection relation) according to change various parameters: Opening Length, Opening Depth, Position of the opening along the beam axis, Ultimate cylinder compressive strength, Main reinforcement ratio, reinforcement and stirrups on top and bottom the opening, and the Type of load.

Chapter 5 Presents a summary and conclusion for the carried out work in this thesis and gives suggestions for future studies.

CHAPTER 2

Literature Review

2.1 Introduction

Providing an opening in reinforced concrete beams is often a problem for the structural engineers. Several studies had been carried out to study the effect of openings, whether it rectangular, square, circular, etc., in reinforced concrete beams at both flexural and shear zones. Also, some of these carried out to study and give suggestions of strengthening methods for the reinforced concrete beams with opening. This chapter is prepared to view some of these researches.

2.2 Previous Researches

2.2.1. Openings in normal strength concrete beams

Ali Ibrahim [1] Investigated the effect of openings on the behavior of reinforced concrete beams. Different methods were used to analyze the behavior of beams with openings: the vierendeel girder method, the rigid frame method, and the trussed beam method. The author concluded that: presence of openings at shear zone causes great reduction in the ultimate load especially when the concentrated load was applied across the opening. The deflection shape and strain distribution for beams with openings was differed comparison to the other solid beams (beams without openings).

Hanson [2] conducted an experimental program on longitudinally reinforced concrete T-beams with small-square openings, the specimens were tested to simulate the joist on either side of a continuous support. The main parameters in this study were: the size of opening and the opening location at both horizontal and vertical directions. The results obtained from this study showed that: presence of opening adjacent to the support has no effect on the reduction of strength, the strength of beam gradually decreased when the opening shifted away from the support until it reached to a constant value. The vertical position of opening has a minor effect on the behavior of beam, while increase the size of opening lead to almost linear reduction in strength. He also suggested that, provided stirrups on either side of the opening are required to improve the strength of beam.
(**Somes** and **Corley**) also reported a similar study but, the openings were circular in shape. Figure (2.1) shows schematically typical shear failures for some beams with square and circular openings as tested by Hanson’” and Somes and Corley”.

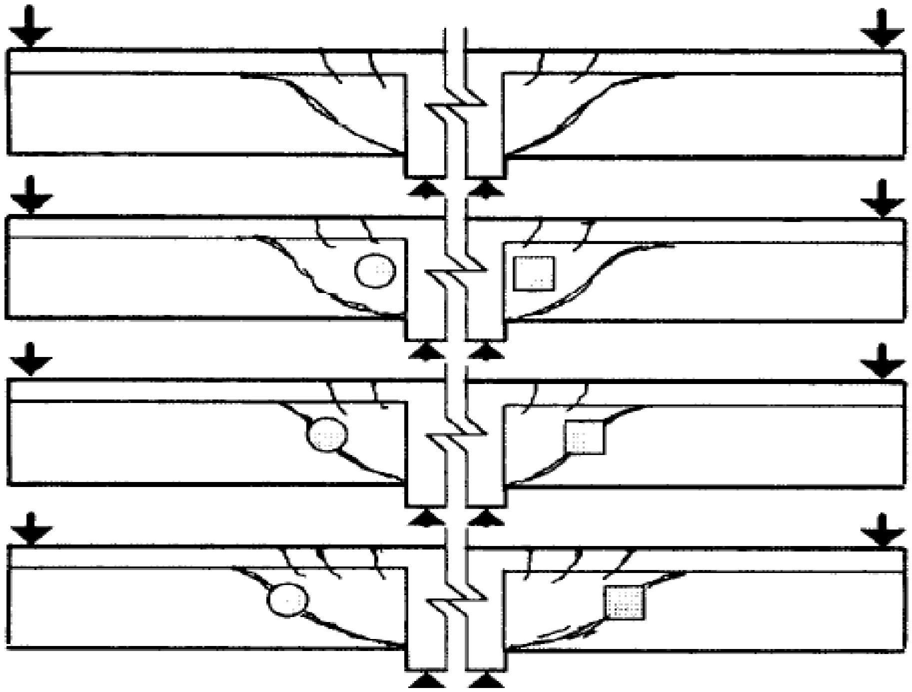

Figure (2.1) Typical shear failure of a beam with small openings without shear reinforcement, (Hanson, Somes, and Corley *et al*., 1969)[2]

Salam [3] Carried out a study on perforated beams with rectangular cross section and loaded by two symmetrical point loads. His study aimed to eliminate the weakness of beams due to the provision of opening and restore its strength using a suitable scheme of reinforcement. Based on this study he suggested that longitudinal reinforcement above and below the opening and full depth stirrups by its sides are necessary, when sufficient reinforcement is provided to prevent a failure along a diagonal crack passing through the centre of the opening and traversing the entire depth, then the failure is precipitated at the minimum section.

Hemdan [4] Studied experimentally and analytically the behavior of reinforced concrete beams with end rectangular openings under static and repeated loadings. A set of fourteen rectangular reinforced concrete beams with opening were tested; eleven beams were tested under static loading, while the other beams were tested under repeated loading. The main parameters were: opening length, opening height opening location, and the amount of reinforcement around the opening. The author revealed that: the provision of end rectangular openings at shear zone of a rectangular reinforced concrete beam causes change in the behavior of beam: increases the deflection, reduces both the cracking load and ultimate strength, changes the mode of failure of beam, and completely changes the distribution of elastic stresses in the end zones. Increasing the opening dimensions (either length or height)

lead to increase the central deflection and elastic stresses. Deflection and grows of cracks increase successively by repeated loading. Beams tested statically after one million cycles of repeated loading have greater stiffness, and less number of cracks with smaller widths than those occurs at the same load in beams tested directly under static loads. The ultimate static load at a maximum load level of 50% was the same of beams tested statically, while an increase of about 10% was noticed at a maximum load level of 80%.
The mode of failure of beams tested statically after one million cycles is the same as that of the beams tested directly under static loads. Finally the author suggested that: its better to exchange the central opening which have a large height which greatly affects the compression zone of the reinforced concrete beams by two end openings, one at each end. Beams with large opening must be reinforced as a vierendeel panel, at opening location, vertical reinforcement are to be provided as close as possible to the vertical edges of the opening to resist the tensile stress concentration due to opening.

Mahmoud [5] Conducted experimental and analytical study similar to Hemdan's work, except he exchanged the rectangular openings by circular openings. The major parameters considered in the study were: opening size, opening location in horizontal and vertical direction, opening shape, multiplication of the openings, and type of loading. Generally it was found that the results were similar to Hemdan's conclusion. Finally, he recommended the following: use of circular opening in shear zone of beams is preferable and better than any other shape. The diameter of such openings must not exceed half the effective depth of the beam. Using inclined and vertical stirrups in both sides as well as adequate short stirrups in both top and bottom chords of the hole in addition to sufficient circular steel are recommended for improving the behavior of beams. Using multiple openings is more preferable than a single one of the same area and multiple openings should be divided by posts of width not less than the greater from the hole radius or 8 cm.

Nassef [6] Studied the effect of the provision of openings at shear zone on the behavior of reinforced concrete beams. Twelve beams with two symmetrical shear openings except one was solid beam (without openings as a reference) were tested experimentally. Some of these beams had rectangular cross-section and the other have T-section, all beams were tested under two concentrated loads at the third points. The main parameters considered in this study were: the opening shape, top flange width, and reinforced details around the openings. The test results of this work showed that, rectangular-shaped openings with fillet corners and diagonal steel bars improved the crack distribution around the corners of openings and increased the shear strength of the beam nearly equal to those corresponding to beam without openings. The authors recommended that exchanging the large rectangular openings by two smaller holes, by creating a vertical post, increased the beam capacity in shear, failure of this beam was due to shear in the vertical post. They also found that in beams with the same opening area, the horizontal rectangular-shaped opening led to higher strength in comparison with other investigated shaped opening (square & circular). T-beams in this investigation showed that the presence of compression flange reduced considerably the effect of opening and controlled the failure to be due to flexure. However, increasing the width of this flange more than those familiar limits hasn't tangible effect on the behavior of beam. The investigators recommended that the beam with one large web opening should be treated as a vierendeel panel at the opening location.

Architectural Institute of Japan (AIJ) [7] Suggested a formula for structural calculation of reinforced concrete structures to evaluate the shear capacity V_n of beams which contain a small opening. This empirical formula, in equation (2.1), is considered similar to the traditional approach where the total shear resistance is provided by both concretes and the steel crosses a 45° failure plane passing through the centre of the opening as shown in Figure (2.2). The formula given is as follows:

$$V_n = \left[\frac{0.092\mathrm{KuKp}\ (\grave{f_c}+17.7)}{\frac{M}{V_d}+0.12}\left(1-\frac{1.61\mathrm{do}}{\mathrm{h}}\right)+0.846\sqrt{\rho'_w\, f_{yv}}\right]\mathrm{b}\,\mathrm{d_v} \qquad (2.1)$$

where $k_p = 0.82\ (100As/bd)^{0.23}$, d_o is the diameter of the circular opening or diameter of the circumscribed circle in the case of a square opening, which should be taken as less than or equal to h/3; h is the overall depth of the beam, and M/(V_d) is taken as less than or equal to 3. The term K_u is a function of the effective depth d to account for the size effects in shear and has a value of between 0.72 and 1.0 as shown in Figure (2.3). f_{yv} , is the yield strength of web reinforcement. Where d_v is the distance between the top and bottom longitudinal bars, the term ρ'_w refers to the ratio of web reinforcement placed within a longitudinal distance $^{d_v}/_2$ from the centre of the opening as shown in Figure (2.2), and can be calculated according to eq. (2.2) as:

$$\rho'_w = \frac{A_v\ (\sin\alpha+\cos\alpha)}{b\ d_v} \qquad (2.2)$$

Where, A_v is the area of web reinforcement.

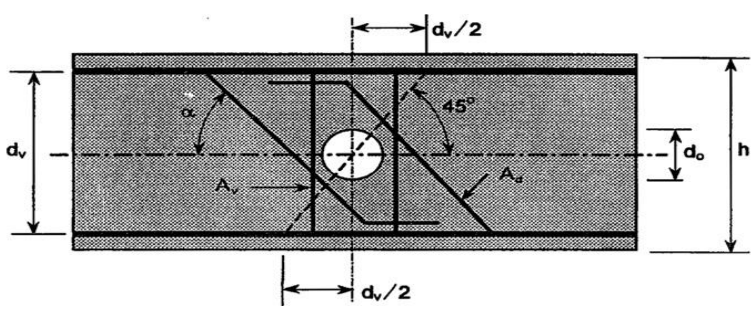

Figure (2.2) Effective web reinforcement for opening, (AIJ *et al.*, 1998)[7]

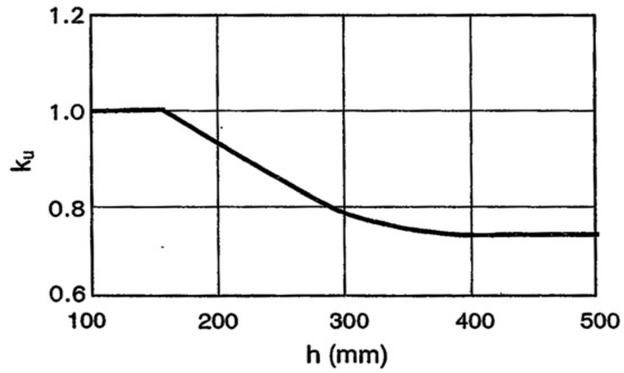

Figure (2.3) Determination of Ku, (AIJ *et al*., 1998) [7]

Mansur, Tan, and Huang [8] conducted an experimental program on 15 reinforced concrete continues T-beams with large web opening. The main parameters were the size and location of openings. From the test results, the authors revealed that:
The presence of web opening leads to decrease both the cracking and ultimate strength. Performance of beam with multiple openings is more desirable for strength and serviceability. The thickness of the post between adjacent openings should not be less than one-half the overall beam depth and should be adequately reinforced to avoid premature failure. A continuous T-beam which containing a large rectangular opening behaves similarly to a vierendeel panel at the opening segment. The total applied shear may be distributed between the top and bottom chord according to their flexural stiffness, based on their gross or cracked transformed section.

Mansur [9] Classified the size of an opening large or small, that for large openings subjected to combined bending and shear, vierendeel action prevails and failure occurs by the formation of a four-hinge mechanism. The formation of hinges can be assume in the chord members at a distance h/2 from the vertical faces of the opening, where h is the overall depth of a chord member as shown in Figure (2.4). Considering that the length of opening is decreased, a stage will then be reached when the two hinges in a particular chord will merge into a single one, and vierendeel action will obviously vanish. Since the formation of a three-hinge mechanism is not possible, this length, which equals the maximum of the two h's, may be taken as the lower limit of a large opening. That is, when the length of opening, $l_o$is less than or equal to h_{max}, the opening can be defined as a small opening. While for large openings, $l_o > h_{max}$.

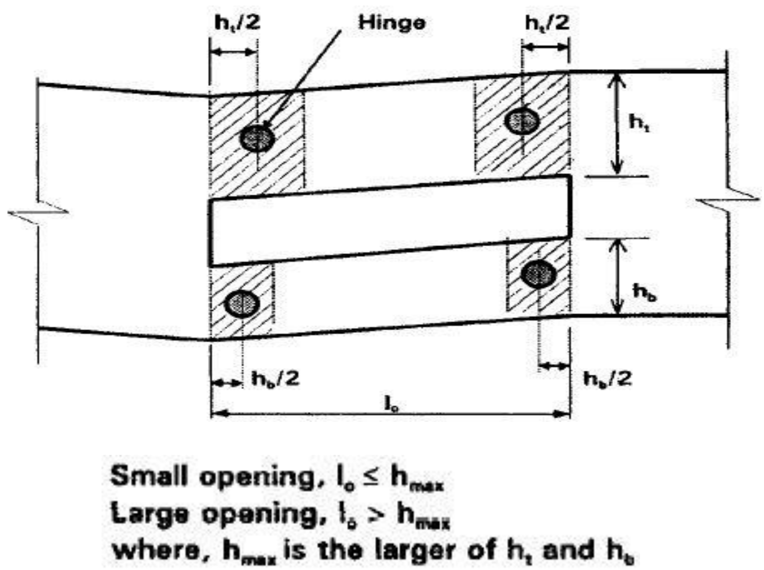

Figure (2.4) Definition of large and small openings, (Mansur *et al*., 1998)[9].

Mansur and Tan [10] Suggested guidelines to facilitate the selection of the size and location of web openings as illustrated in Figure (2.5). the authors recommended that: for T-beams, openings should preferably be positioned flush with the flange for ease in construction. In the case of rectangular beams, openings are commonly placed at mid-depth of the section, but must also be placed eccentrically with respect to depth. Care must be exercised to provide sufficient concrete cover to the reinforcement for the chord members above and below the opening. The compression chord should also have a sufficient concrete area to develop the ultimate compression block in flexure and should also have adequate depth to provide effective shear reinforcement. Openings should not be located closer than one-half of the beam’s depth to the supports to avoid the critical region for shear failure and reinforcement congestion. Similarly, the positioning of an opening closer than 0.5D to any concentrated load should be avoided. Depth of openings shouldn’t be exceeded 50% of the overall beam depth. The stability of the chord members, in particular the compression chord, and the serviceability requirement of deflection were the factors which limit the length of an opening. When the opening becomes bigger, it is preferable to divided it into multiple openings providing the same passageway instead of using a single opening, and the post separating two adjacent openings should not be less than 0.5D to ensure that each opening behaves independently.

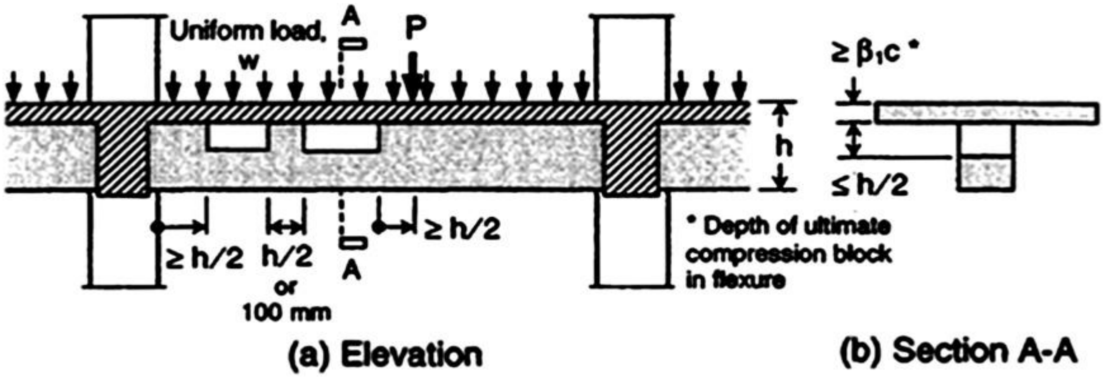

Figure (2.5) Guidelines for the location of openings, (Mansur and Tan *et al*., 1999)[10].

Mansur, Tan, and Wei [11] Explored the adequacy of the ACI Code approach for shear design of a beam with circular openings. Seven T-beams with circular web openings were designed from moderate to high shear force. They were tested in an inverted position to simulate the conditions that exist in the negative moment region of a continuous beam. The results of the test indicated that crack control and preservation of ultimate strength are achievable through providing reinforcement around the opening. It was found that diagonal bars decrease the high stress in the compression chord and avoid premature crushing of the concrete. However, the provision of transverse openings alters the simple beam behavior into a more complex behavior. The provision of openings produces discontinuity in the normal flow of stresses and results in stress concentration and early cracking around the opening. The ultimate strength of the beam may also be seriously affected. Hence, special reinforcement should be provided around the opening to contain the width of cracks and to prevent possible premature failure of the beam. Diagonal bars are essential to control the cracks around the opening and the amount of diagonal bars should be sufficient enough to carry at least 50% of the applied shear. Figure (2.6) shows stirrups and diagonal bars.

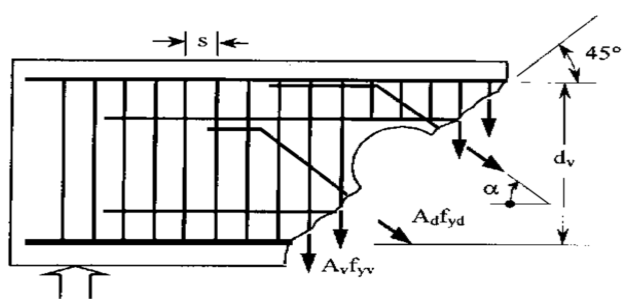

Figure (2.6) Shear resisted by stirrups and diagonal bars, (Kiang-Hwee *et al*., 2001)[11].

Javad VA, Morteza HA. [12] Studied the effect of small circular opening on the shear and flexural behavior and ultimate strength of reinforced concrete beams using normal and high strength concrete. The testing beams have been loaded as simple beam with two concentrated and symmetrical load. The main factors of this test are the changes of diameter, the position of opening and the type and location of reinforcement around the opening and changes in the strength of concrete. According to this study the author observed that, for beams with normal concrete, when the diameter of opening exceeded the 0.3 of depth of the beam, the reduction of ultimate strength increased and patterned of cracking as well as mode of failure of the beam changed, in order to control the cracks and restrain their width, it is better to use diagonal shear reinforcement. For increasing the ultimate shear strength of the beam usage of diagonal reinforcement and stirrups in top and bottom of opening is recommended.

M.A. Mansur [13] Studied the analysis and design of reinforced concrete beams that contain transverse small circular or large rectangular openings through the web and are subjected to pure bending or combined bending and shear (circular and large rectangular openings are treated separately), Practical situations of drilling an opening in existing beams, The special design considerations for beams with multiple openings are also briefly discussed. In his study he considered that the opening is considered small if it enough to maintain the beam-type behavior or, in other words, if the usual beam theory applies, then the opening may be termed as small opening. In contrast, large openings are those that prevent beam-type behavior to develop. Thus, beams with small and large openings need separate treatments in design (Mansur and Tan, 1999).

i. Beams with Small Opening

Openings that are circular, square, or nearly square in shape may be considered as small openings 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, a beam with small openings may follow the similar course of action as that of a solid beam. In the case of pure bending, the ultimate moment capacity a beam is not affected by the presence of an opening as long as the minimum depth of the compression chord, hc, is greater than or equal to the depth of ultimate compressive stress block, that is, when

$$hc \leq \frac{As\, f_y}{.85\, fc`b} \tag{2.3}$$

Where, A_s : Area of tensile reinforcement; f_y : yield strength of tensile reinforcement; f_c': cylinder compressive strength of concrete; b: width of the compression zone. The effects on maximum crack widths and deflection under service load have been found to be only marginal, and may safely be disregarded in design. In the case of beam subjected to combined bending and shear, test data reported by Hanson (1969), Somes and Corley (1974), Salam (1977), and Weng (1998) indicate that the beam may fail in two distinctly different modes. The first type is typical of the failure commonly observed in solid beams except that the failure plane passes through the center of the opening (Figure 2.7a). In the second type, formation of two independent diagonal cracks, one in each member bridging the two solid beam segments, leads to the failure (Figure 2.7b). Labeled respectively as beam-type failure and frame-type failure (Mansur 1998), these modes of failure require separate treatment.

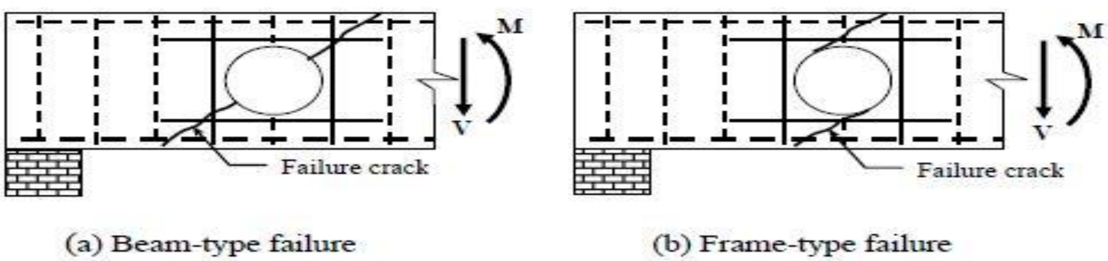

Fig (2.7) The two modes of shear failure at small openings, (Mansur *et al*., 2001) [13].

Similar to the traditional shear design approach, equation (2.4) can be used, it may be assumed in both the cases that the nominal shear resistance, V_n is provided partly by the concrete, V_c, and partly by the shear reinforcement crossing the failure plane, V_s. That is,

$$V_n = V_c + V_s \tag{2.4}$$

For the first type (beam-type failure) following the simplified approach of the ACI Code (1995), the shear resistance V_c provided by the concrete may be estimated (Mansur, 1998) by considering the net concrete area available as

$$V_c = \frac{1}{6}\sqrt{fc'}\, b_w\,(d - d_o) \tag{2.5}$$

Where, b_w : web width; d : effective depth; and d_o : diameter of opening.

For the contribution of the shear reinforcement, V_s, reference may be made to Figure (2.8). It may be seen that the stirrups available to resist shear across the failure plane are those by the sides of the opening within a distance (d_v - d_o), where d_v is the distance between the top and bottom longitudinal bars, and d_o is the diameter (or depth) of opening, as shown. Thus,

$$V_s = \frac{Av\,fyv}{s}\,(d_v - d_o) \tag{2.6}$$

In which, Av : area of vertical legs of stirrups per spacing s; fyv: yield strength of stirrups.

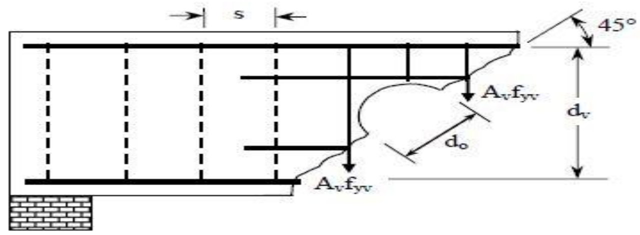

Fig (2.8) Shear resistance, V_s, provided by shear reinforcement at an opening, (Mansur *et al*., 2001) [13].

Knowing the values of V_c and V_s, the required amount of web reinforcement to carry the factored shear through the center of the opening may be calculated in the usual way. This amount should be contained within a distance $(d_v - d_o)/2$.

For the second type (frame-type failure): the free-body diagram at beam opening, shown in Figure (2.9). Clearly, the applied factored moment, M_u, at the center of the opening from the global action is resisted by the usual bending mechanism, that is, by the couple formed by the compressive and tensile stress resultants, N_u, in the members above and below the opening. These stress resultants may be obtained by equation (2.7) as follows

$$(N_u)_t = \frac{M_u}{(d - \frac{a}{2})} = -(N_u)_b \quad (2.7)$$

In which, d : the effective depth of the beam, a: depth of equivalent rectangular stress block, and the subscripts t and b denote the top and bottom cross members of the opening, respectively.

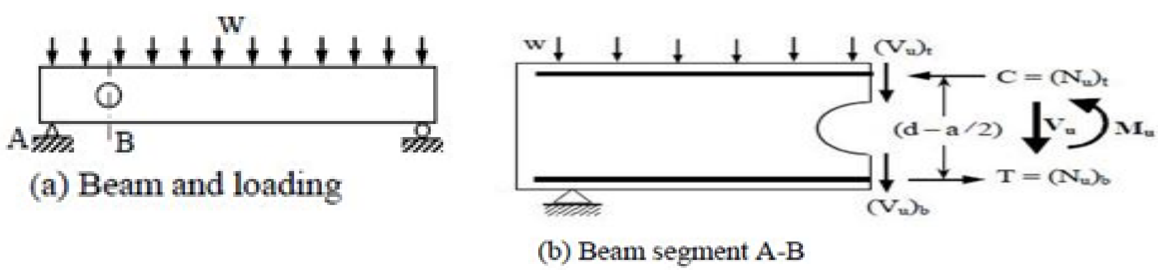

Fig (2.9) Free-body diagram at beam opening, (Mansur *et al*., 2001)[13].

Also, the applied shear, V_u, may be distributed between the two members in proportion to their cross-sectional areas (Nasser et al., 1967). Thus,

$$(V_u)_t = V_u \left[\frac{A_t}{(A_t - A_b)} \right] \tag{2.8}$$

And

$$(V_u)_b = V_u - (V_u)_t \tag{2.9}$$

Knowing the factored shear and axial forces, each member can be independently designed for shear by following the same procedure as for conventional solid beams with axial compression for the top chord and axial tension for the bottom chord. Consideration of beam-type failure will require long stirrups to be placed on either side of the opening, while that of the frame-type failure will need short stirrups above and below the opening. For anchorage of short stirrups, nominal bars must be placed at each corner, if none is available from the design of solid segments. This will ensure adequate strength. For effective crack control, nominal bars should also be placed diagonally on either side. The resulting arrangement of reinforcement around the opening is shown in Figure (2.10).

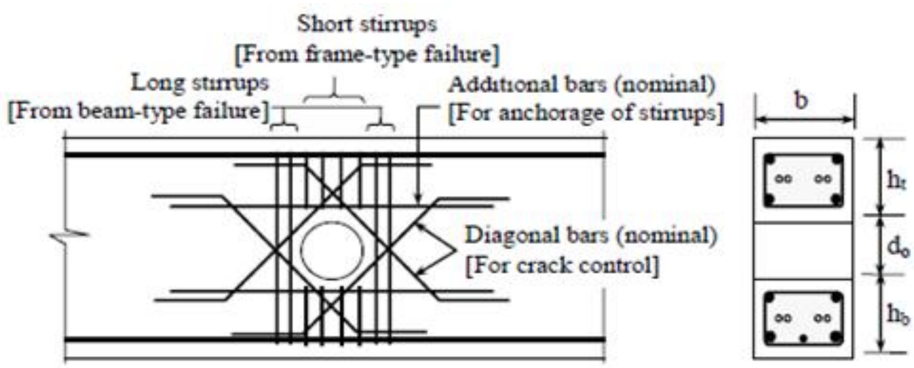

Figure (2.10) A suitable reinforcement scheme around a small opening, (Mansur *et al*., 2001) [13].

ii. Beams with Large Rectangular Opening

Beams with large openings was found similar to the beams with small openings, incorporation of a large opening in the pure bending zone of a beam will not affect its moment capacity provided that the depth of the compression chord is greater than or equal to the depth of ultimate compressive stress block, and that instability failure of the compression chord is prevented by limiting the length of the opening (Mansur and Tan, 1999).

In practice, openings are located near the supports where shear is predominant. In such a case, tests have shown that a beam with insufficient reinforcement and improper detailing around the opening region fails prematurely in a brittle manner (Siao and Yap, 1990). When a suitable scheme consisting of additional longitudinal bars near the top and bottom faces of the bottom and top chords, and short stirrups in both the chords, as shown in Figure (2.11), is furnished, then the chord members behave in a manner similar to a vierendeel panel and failure occurs in a ductile manner. The failure of such a beam is shown in Figure (2.12). Clearly, the failure mechanism consists of four hinges, one at each end of the top and bottom chord.

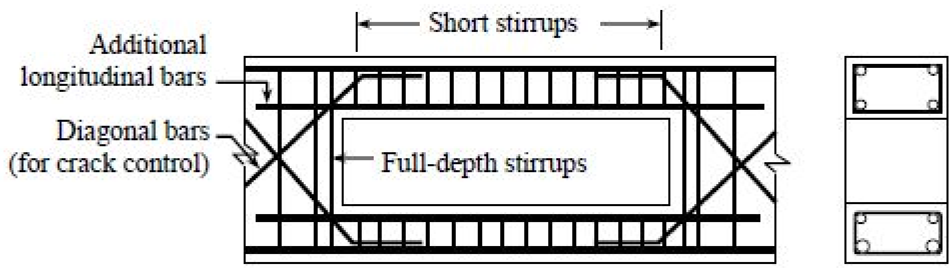

Figure (2.11) A suitable reinforcement scheme around a large opening, (Mansur *et al*., 2001) [13].

Figure (2.12) Ductile failure of a beam under combined bending and shear, (Mansur *et al*., 2001) [13]

A simply-supported beam subject to a single-concentrated load, P, at a solid section distant, X, from its right support, as shown in Figure (2.13), and the free-body diagram through the opening center and those of the chord members above and below it may be represented by Figures (2.13 a), (2.13 b), and (c), respectively.

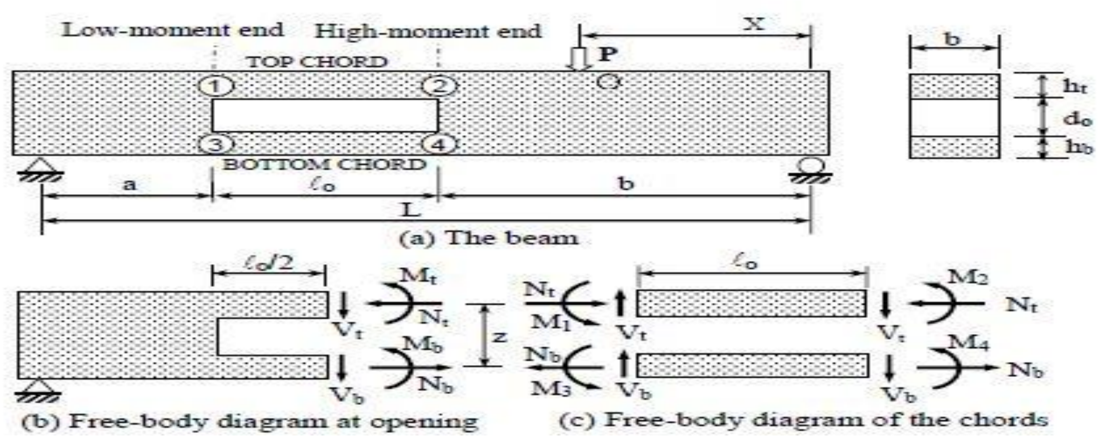

Figure (2.13) Beam with a large opening under bending and shear, (Mansur *et al*., 2001) [13].