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Effect of Openings on the Behaviour and Strength of R/C Beams in Shear

M. A. Mansur

Department of Civil Engineering, National University of Singapore, 10 Kent Ridge Crescent, 119260 Singapore, Singapore

Abstract

The effects of introducing a transverse opening on the behaviour and strength of reinforced concrete beams under predominant shear are presented and discussed in this paper. On the basis of observed structural response, some guidelines are suggested to classify the opening as "large" or "small". For small openings, two types of diagonal tension failure have been identified, and a method of design using the current codes of practice is proposed. The method is illustrated by a numerical example. © 1998 Elsevier Science Ltd. All rights reserved.

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INTRODUCTION

Transverse openings through beams are often required for the passage of utility ducts and pipes. These openings may be of different shapes and sizes[1], and are generally located close to the supports where shear is predominant. Although numerous shapes are possible, circular and rectangular openings are the most common ones. Circular openings are required to accommodate service pipes, such as for plumbing, while rectangular openings provide the passage for air conditioning ducts that are generally rectangular in shape.

With regard to the size of openings, many researchers use the terms "small" and "large" without drawing any clear-cut demarcation line. Mansur and Hasnat[2] have defined small openings as those circular, square or nearly square in shape. Whereas, according to Somes and Corley[3], a circular opening may 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. The author however considers that the essence of classifying an opening either small or large lie 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, test data reported in the literature[4–7,1,8–10] have shown that beam-type behaviour transforms into a vierendeel action as the size of opening is increased. Since the behaviour of a beam depends on the size of opening, small and large openings need separate treatment.

The effects of transverse openings on overall response of a reinforced concrete beam in shear are considered in this study. Based on a survey of available literature, the behaviour and design of such beams are presented and discussed. For small openings, two different failure modes are identified, and a method of design using the current code provisions is proposed and illustrated by a design example. The need for further research is also highlighted.

BEAMS WITH A LARGE RECTANGULAR OPENING

Consider a reinforced concrete beam with a large rectangular opening in the web, the opening being located in a region subjected to predominant shear (Fig. 1). This type of beam has been the subject of many investigations conducted in the past[4–7,1,8,11,10]. When no additional reinforcement is provided in the members above and below the opening (chord members), tests conducted by Siao and Yap[11] have shown that the beams fail prematurely by sudden formation of a diagonal crack in the compression chord. However, if a suitable reinforcement scheme comprising additional longitudinal bars near the bottom and top faces of the top and bottom chords, respectively, and short stirrups in the chords (Fig. 2) over and above those needed for a solid beam is employed, then the failure occurs in a gradual manner. In such a case, the experimental observations of the effects introducing an opening on the overall response of a beam as reported in the literature[4–7,1,8,10] may be summarised as follows:

1. Introduction of an opening in the web of a beam leads to early diagonal cracking, and the load at first crack decreases with an increase in either the length or the depth of opening.
2. Unless additional reinforcement is provided to restrict the growth of cracks, the opening corners are liable to exhibit wide cracking.

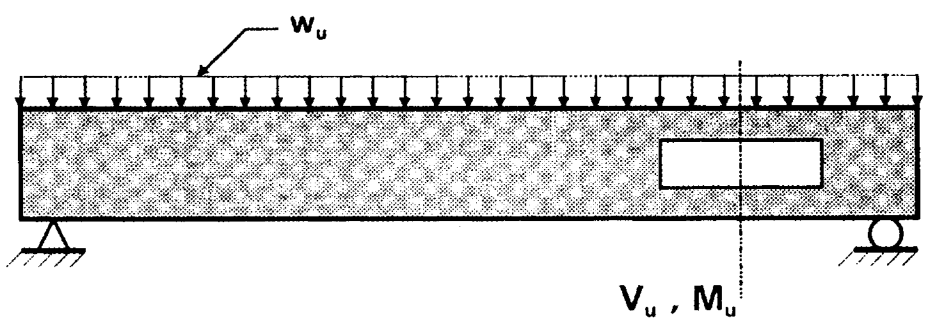

Fig. 1. Beam with a large opening in the predominant shear zone.

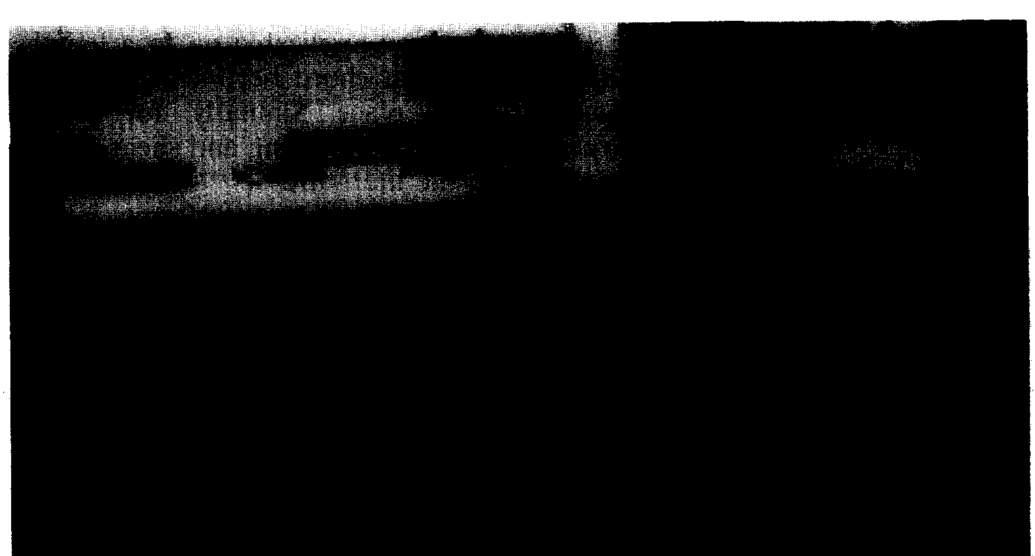

Fig. 2. A suitable reinforcement scheme to avoid sudden failure.

3. Provided that the same amount and scheme of reinforcement is used[5,6,10], an increase in the opening size either by increasing the length or the depth of opening decreases the strength as well as stiffness of the beam. The eccentricity of opening, however, has only a marginal effect on both strength and stiffness.
4. The chord members above and below the opening behaves in a manner similar to the chords of a vierendeel panel with contraflexure points located approximately at midspan of the chords. Final failure occurs by the formation of a mechanism with four hinges in the chords, one at each corner of the opening as shown in Fig. 3.

Observation 4 as listed as above has been the main ingredient of a method of strength analysis[5] and a number of design proposals[4,12,13,7,8,14]. Although the assumption that the contraflexure points occur at midspan is strictly valid only when the chord members are symmetrically reinforced[5], such an assumption considerably simplifies the design and yields an output very close to what would have been obtained by a more rigorous method[12,13]. The local forces and moments acting in the chord members may then be represented as shown in the free-body diagram of Fig. 4. Obviously, the global moment, M_u at the centre of opening is resisted by the normal stress resultants in the two chords. Similarly, the global shear, V_u, is shared by the shear stresses developed in the two chords. Provided the amount of shear carried by each chord is known, the forces and moments acting at the critical end-sections of the chord members may be determined from statics alone, and the chords be designed independently as eccentrically loaded tension and compression members with significant shear by following any of the current codes of practice.

There are, however, three schools of thought regarding the distribution total shear between the two chords. The first, as proposed by Lorensten[15], assumes that the compression chord carries the entire shear. This is probably true in case of a beam where the opening is located near the tension face without the use of any short stirrups in the tension chord. The second, which according to Nasser *et al.*[7] and Regan and Warwaruk[8], distributes the total shear between the chord members in proportion to their cross sectional areas, and the third by Barney *et al.*[4] distributes the shear force in proportion to the flexural stiffness of the chord members. In their recent design proposal for a continuous beam containing a large opening, Tan and Mansur[14] incorporated the third proposal because of its rationality when large openings are involved.

The preceding discussion deals with what may be termed as the "mechanism approach" in the treatment of a beam with web openings. The method is simple and is compatible with the global analysis[14] and current design practices. Other methods available for the design of the opening region alone include truss model[16,17]

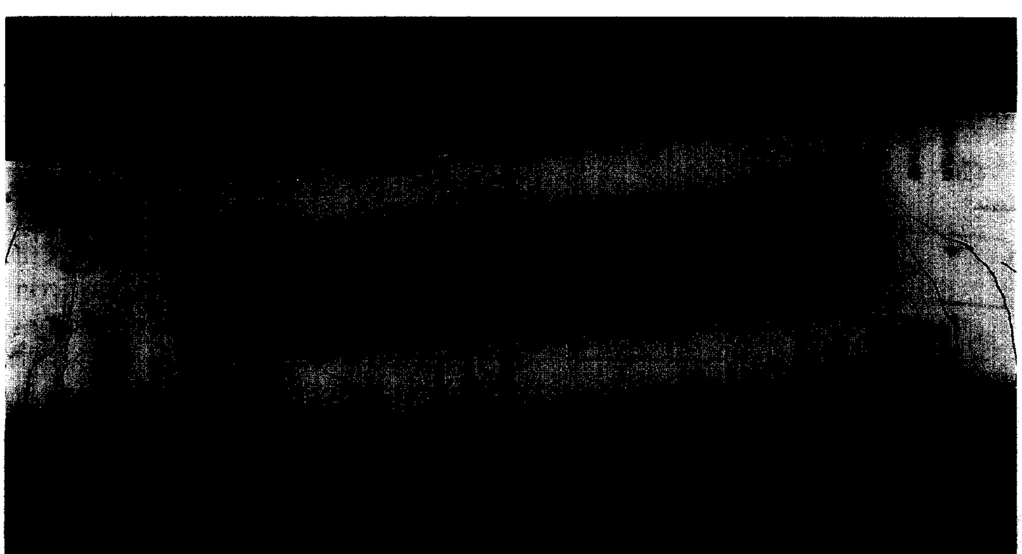

Fig. 3. Typical failure mode of a beam with a large rectangular opening.

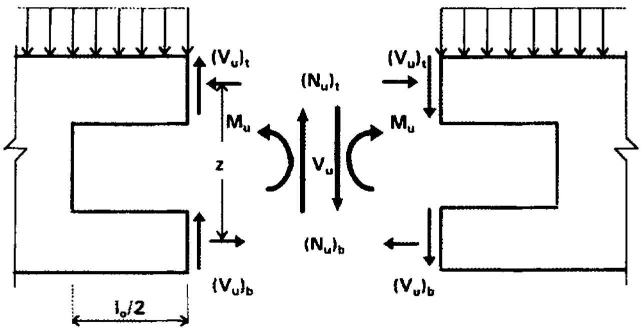

Fig. 4. Forces acting in the chord members.

and strut-and-tie model[18]. For brevity, these methods are not included in the present discussion.

DEFINITION OF SMALL AND LARGE OPENINGS

In addition to providing a simple design method, observation 4 also furnishes some clues for classifying the size of an opening as either large or small. It is obvious that for large openings subjected to combined bending and shear, vierendeel action prevails and failure occurs by the formation of a four-hinge mechanism. Referring to Fig. 3, it may be reasonable to assume that these hinges form in the chord members at a distance $h/2$ from the vertical faces of the opening as shown in Fig. 5, where h is the overall depth of a chord member, and the subscript t and b refer to the top and bottom chords, respectively.

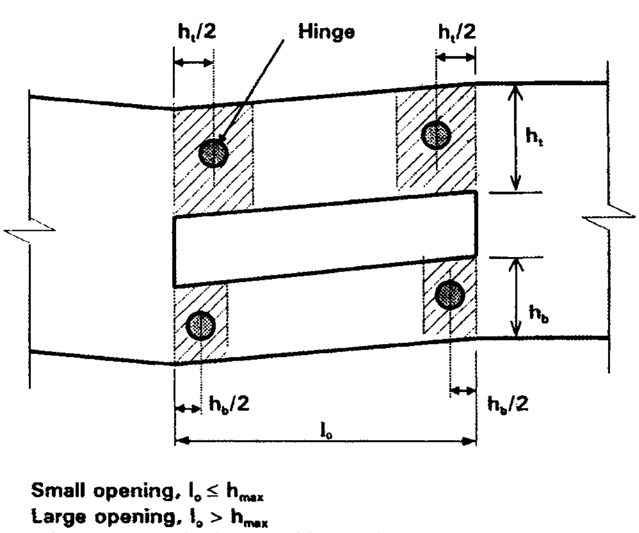

Fig. 5. Definition of large and small openings.

Now, consider 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 larger of the two h's, i.e., h_{max}, may be taken as the lower limit of a large opening or, in other words, the upper limit of a small opening. That is, when the length of opening, l_o is less than or equal to h_{max}, it may be defined as a small opening. For large openings, $l_o > h_{max}$. In this definition, it is assumed that the members above and below the opening have adequate depth to accommodate the reinforcement scheme as shown in Fig. 2. In the case of circular openings, the circle should be replaced by an equivalent square for the determination of the value of h_{max}.

BEHAVIOUR OF BEAMS WITH SMALL OPENINGS IN SHEAR

When a small opening is introduced in the web of a beam, unreinforced in shear, test data reported by Hanson[19], Somes and Corley[3] and Salam[9] indicate that the mode of failure remains essentially the same as that of a solid beam. However, as the opening represents a source of weakness, the failure plane always passes through the opening, except when the opening is very close to the support so as to bypass the potential inclined failure plane. Figure 6 shows schematically some typical shear failures of beams containing square and circular openings as reported by Hanson[19] and Somes and Corley[3], respectively.

Hanson[19], at PCA laboratory, tested a series of longitudinally reinforced T-beams representing a typical joist floor. The specimens contained square openings and were tested to simulate the joist on either side of a continuous support. The major parameters considered in the study were the size and horizontal and vertical locations of the opening. Somes and Corley[3] reported a similar study but, in this case, the openings were circular in shape.

In both cases, it was found that an opening located adjacent to the centre stub (support) produced no reduction in strength. As the opening is moved away from the support, gradual reduction in strength occurs until it levels off to a constant value. Test data suggest

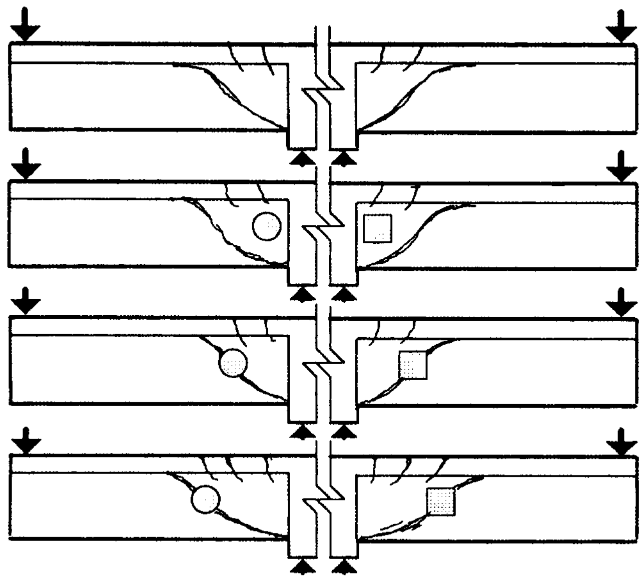

Fig. 6. Typical shear failure of a beam with small openings containing no shear reinforcement[19,3].

that the vertical position of opening has no significant effect, while an increase in the size of opening leads to an almost linear reduction in strength. However, there appears to be a size of opening below which no reduction in shear strength occurs. This size corresponds to about 25% of the beam depth for square openings and 33% of the beam depth for circular openings. They have also noted that the strength of such a longitudinally reinforced beam may be fully restored by providing stirrups on either side of the opening.

Salam[9] conducted an investigation on perforated beams of rectangular cross section tested under two symmetrical point loads. The study was mainly aimed at devising a reinforcement scheme suitable to restore the strength to the level of a corresponding solid beam. He found that, in addition to the longitudinal reinforcement above and below the opening and full depth stirrups by its sides, short stirrups in the members both above and below the opening are necessary to eliminate the weakness due to the provision of opening.

In his study, Salam[9] noted that 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. In such a case, formation of two independent diagonal cracks in the members above and below the opening split the beam into two separate segments. Figure 7 shows the sketch of the cracking pattern of the beam that failed in this manner.

PROPOSED DESIGN APPROACH

According to the current design philosophy, bending moment and shear force are treated separately. A section subjected to combined bending and shear is therefore designed first for bending. The longitudinal reinforcement thus arrived at is then taken into account in the design of transverse reinforcement for shear because it indirectly contributes to the shear resistance. The total resistance to shear is considered to be supplied by two components, concrete and transverse reinforcement. The former combines the shear resistance provided by the concrete compression zone, aggregate interlock action and dowel action of longitudinal bars through an inclined crack. It is generally taken as the strength of a beam without shear reinforcement. When the factored shear force exceeds the resistance provided by the concrete, reinforcement is provided using a 45° truss model to take care of the balance. A similar approach is proposed herein for beams containing a small opening.

Beams without shear reinforcement

In the absence of any method for quantitative assessment of the shear strength of a longitudinally reinforced concrete beam with small openings, an attempt has been made here to find if the ACI simplified equation[20] with some modification, be applied to such beams. It is proposed that the effective depth, d in this equation be replaced by the net depth, $(d-d_o)$, irrespective of vertical and horizontal location of an opening where d_o is the diameter/depth of an opening. The nominal shear strength of a beam without shear reinforcement, but containing a small opening thus becomes

$$V_c = \frac{1}{6}\sqrt{f_c^1}\, b_w(d-d_o) \quad (1)$$

The predictions of eqn (1) are calculated and compared with the test data reported by Hanson[19] and Somes and Corley[3] in Fig. 8. Since most of the beams were made of light-weight aggregate concrete, a reduction factor of 0.8 was assumed as suggested in the ACI Code[20].

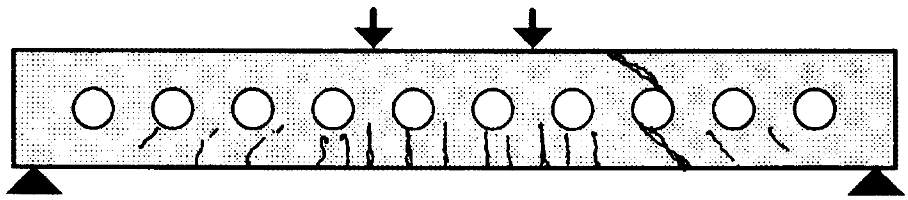

Fig. 7. Shear failure of a beam at the throat section[9].

Also, as the beams had variable web width, the minimum width of web was used as proposed by Hanson for solid beams. It may be seen in Fig. 8 that eqn (1) gives a conservative prediction of shear strength for the entire range of test data. Although, the specimens with openings closer to the supports exhibited strength considerably higher than the prediction of eqn (1), such an enhancement in shear strength is generally ignored in design. Therefore, eqn (1) may conservatively be used for shear strength prediction of a longitudinally reinforced concrete beam containing a small transverse opening.

Beams with shear reinforcement

The traditional approach for the design of a beam in shear is to consider that the total nominal shear strength, V_n is the sum of two components:

$$V_n = V_c + V_s \quad (2)$$

in which V_c is the shear strength of the beam attributable to the concrete and V_s is that attributable to the shear reinforcement. Assuming a 45° failure plane, the expression for V_s may be easily derived for a beam without any opening.

However, when the beam contains a small opening, two types of diagonal tension failure are possible as discussed in the preceding section. The first type is typical of the failure commonly observed in solid beams except that the failure plane passes through the centre of opening. In the second type, formation of two independent diagonal cracks, one in each member bridging the two solid-beam segments, leads to the failure. These types of failure may be labelled as "beam-type" failure and "frame-type" failure, respectively, and require separate treatment for a complete design.

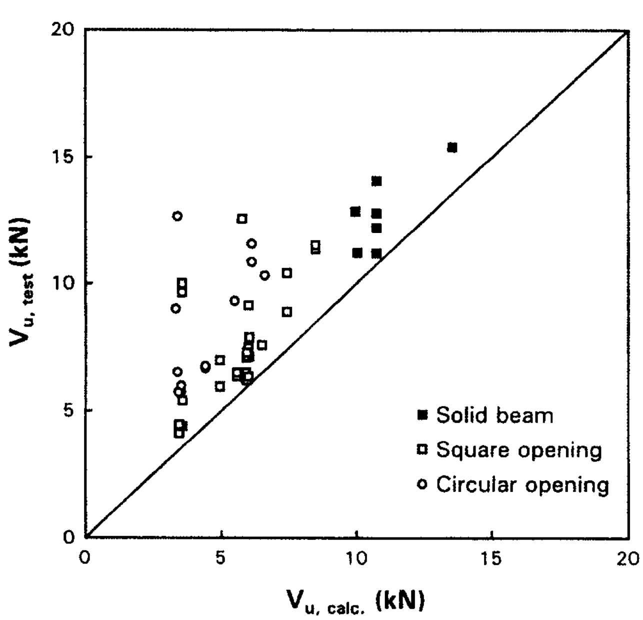

Fig. 8. Comparison of eqn (1) with test data[3,19].

Beam-type failure

In designing for this type of failure, a 45°-inclined failure plane may be assumed similar to a solid beam, the plane being traversed through the opening centre (Fig. 9). The component V_c should then be calculated by eqn (1).

For the other component V_s, reference may be made to Fig. 9. 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 longitu-

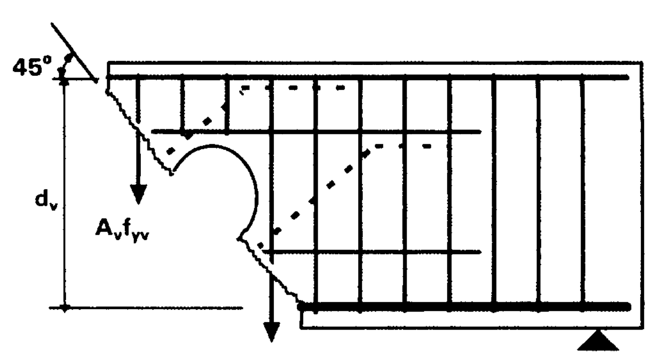

Fig. 9. Shear strength V_s provided by shear reinforcement at an opening.

dinal bars and d_o is the depth (or diameter) of opening. Thus, the expression for V_s becomes

$$V_s = \frac{A_v f_{yv}}{s}(d_v - d_o) \qquad (3)$$

in which A_v is area of vertical legs of a stirrup, s is the spacing of stirrups and f_{yv} is the yield strength of stirrup reinforcement.

The total amount of web reinforcement thus calculated should be contained within a distance $(d_v - d_o)/2$ on either side of the opening, and other restrictions with respect to usual shear design, that is, restrictions on minimum shear reinforcement, maximum spacing of stirrups and maximum shear at the section must be strictly adhered to. However, in the calculation of the maximum shear, $V_{u,max}$, the net cross sectional area through the opening, similar to eqn (1), should be used. A similar approach is included in the AIJ (Architectural Institute of Japan) Standards[16,21], but no consideration was given to the "frame-type" failure.

Frame-type failure

Frame-type failure occurs by the formation of two independent diagonal cracks, one in each member above and below the opening as shown in Fig. 7. From this type of failure, it appears that each member behaves as an independent entity similar to a member in a framed structure. In order to suggest a suitable approach for this type of failure, let us consider the free-body diagram at beam opening as shown in Fig. 10.

Clearly, the applied moment, M_u, is resisted by the usual bending mechanism, i.e., 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 statics subject to the restrictions imposed by the ultimate stress block in flexure on the concrete area available in the compression chord as

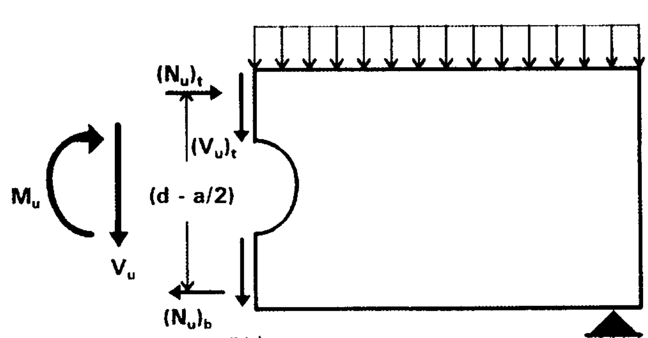

Fig. 10. Free-body diagram at beam opening.

$$(N_u)_t = \frac{M_u}{\left(d - \frac{a}{2}\right)} = -(N_u)_b \qquad (4)$$

In this equation, the subscripts t and b denote the top and bottom members of the opening.

The applied shear, V_u, is however shared by the two members. According to Nasser *et al.*[7], the applied shear may be distributed between the two members in proportion to their cross sectional areas, and this appears to be more appropriate for small openings. Thus,

$$(V_u)_t = V_u \left[\frac{A_t}{A_t + A_b}\right] \qquad (5)$$

and

$$(V_u)_b + V_u - (V_u)_t \qquad (6)$$

Knowing the factored shear and axial forces, each member can be independently designed for combined shear and axial forces by following the usual procedure for solid beams.

Design for crack control

The reinforcement designed as above would ensure adequate strength. However, due to sudden reduction in beam cross section, stress concentration occurs at the edge of the opening. Adequate reinforcement must therefore be provided and properly detailed to avoid wide cracking under service conditions.

To deal with crack control in beams with large openings, Nasser *et al.*[7] advocated the use of diagonal bars at each corner of the opening and recommended that a sufficient quantity should be provided to carry twice the amount of external shear. Lorensten[15] and Barney *et al.*[4] suggested the use of full-depth stirrups adjacent to each end of the opening to carry the entire shear, but without any magnification. By analysing test evidence, Mansur *et al.*[13] recommended a combination of both diagonal bars and full-depth stirrups. In their proposal, the shear concentration factor η should be taken as 2 and at least 75% of the shear resistance should be assigned to the diagonal bars. All these recommendations were, however, based on tests conducted on beams with a large rectangular opening where failure occurs by the formation of a four-hinge mechanism.

In case of small openings, the reinforcement requirement for crack control may not be that large. Since full-depth stirrups are already provided by the sides of the opening to ensure adequate strength, provision of diagonal reinforcement may be considered to restrict the growth of cracks along the failure plane. Subject to experimental confirmation, an amount of diagonal reinforcement that is sufficient to carry the total shear along the 45° failure plane (beam-type failure) may be recommended. Thus, the total area of diagonal reinforcement, A_d, through the failure surface (Fig. 9) is

$$A_d = \frac{V_u}{\phi f_{yd} \sin \alpha} \tag{7}$$

in which α is the inclination of diagonal reinforcement and f_{yd} is the yield strength of diagonal reinforcement. This amount should be distributed equally on either side of the opening and be placed normal to the potential failure surface. An equal amount should be placed perpendicular to this reinforcement to avoid confusion during construction and to take care of any possible load reversal.

Use of this amount of diagonal reinforcement solely for crack control corresponds to a stress concentration factor of about 2 and, on the basis of the experiences gained with large openings, this amount may be regarded as adequate. The method described above is illustrated by a design example in Appendix A.

CONCLUDING REMARKS

In this paper, the behaviour and design of a beam containing a transverse opening and subjected to a predominant shear are briefly reviewed. Based on the observed structural response of the beam, suitable guidelines are proposed for classifying an opening as small or large. For small openings, a design method compatible with the current design philosophy for shear is proposed and illustrated by a numerical design example.

In the method proposed, the maximum shear allowed in the section to avoid diagonal compression failure has been assumed to be the same as that for solid beam except for considering the net section through the opening. This assumption needs experimental verification. Also, the proposal for the calculation of reinforcement to achieve acceptable crack control should be checked. These aspects, together with the adequacy of the overall design method proposed herein, are currently being investigated at the National University of Singapore.

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APPENDIX A: DESIGN EXAMPLE

A simply supported rectangular beam 300 mm wide and 600 mm deep carries a total factored load of 90 kN m^{-1} on a span of 6 m. The beam contains a 200 mm-diameter circular opening located at mid-depth of the beam at a distance of 600 mm from the support. Design and detail the reinforcement for the opening segment of the beam. Assume $f_c^1 = 30$ MPa, $f_y = 460$ MPa, $f_{yv} = 250$ MPa.

Solution

Analysis

The global shear and moment at centre of opening,

$$V_u = 216 \text{ kN}, M_u = 146 \text{ kNm}$$

Therefore, eqns (5) and (6) give

$$(V_u)_t = 108 \text{ kN}, (V_u)_b = 108 \text{ kN}$$

Design for bending

Considering the beam as a whole, flexural design of the section through the centre of opening gives 3T16 tension rebars. Provide 2T12 bars on the compression side of the beam for anchorage of stirrups.

Shear design for beam-type failure

Assuming 30 mm clear concrete cover and M10 bars for stirrups,

$$d = 552 \text{ mm}, d_v = 504 \text{ mm}$$

Check adequacy of the section. Equation (1) gives

$$V_c = (1/6)\,(30)^{0.5}\,(300)\,(552 - 200)\,10^{-3} = 95.9 \text{ kN}$$

The maximum shear allowed in the section is given, according to the ACI Code[20], as

$$[V_u]_{max} = 5\phi\, V_c = 407.5 \text{ kN}$$

Since this value is less than $V_u = 216$ kN, the section is satisfactory to avoid diagonal compression failure.

Design of full-depth stirrups. $V_u = 216$ kN $> 0.5\ \phi\ V_c = 41$ kN, but is less than $3\phi\ V_c = 244.5$ kN. Hence shear reinforcement is required, and max. $s = 275$ mm.

$$\phi\, V_s = 216 - 0.85\,(95.9) = 134.5 \text{ kN}$$

Assuming that the shear resistance of the steel is provided by vertical stirrups only and that two-legged M10 stirrups are used, the required number of stirrups, n is

$$n = V_s/(A_v f_{yv}) = 158\,000/[(157)(250)] = 4.03$$

Use of two full-depth stirrups on either side of the opening at spacing of 100 mm would satisfy the requirements of maximum spacing and the positioning of stirrups, $(d_v - d_o)/2$.

Shear design for frame-type failure

Member below the opening (tension member). For this section, $d = 152$ mm, $V_u = 108$ kN. It is subjected to axial tension. Since $(V_u)_{max} = 174$ kN is less than V_u, the section is adequate to avoid diagonal compression failure. Neglecting the contribution of concrete, and using two-legged stirrups of M10 bars, we have

$$s = (\phi\, A_v f_{yv} d)/V_u = 0.85(157)(25)(152)/(108\,000)$$
$$= 46 \text{ mm}$$

As V_u is greater than $3\phi\ V_c = 104$ kN, the maximum s is $d/4 = 37.5$ mm. But these values are quite close. Considering the difficulty of achieving proper compaction of concrete, it is decided to use five short stirrups below the opening in between the full-depth stirrups giving a spacing of about 40 mm. Provide two nominal T12 longitudinal bars just below the opening for anchorage of stirrups.

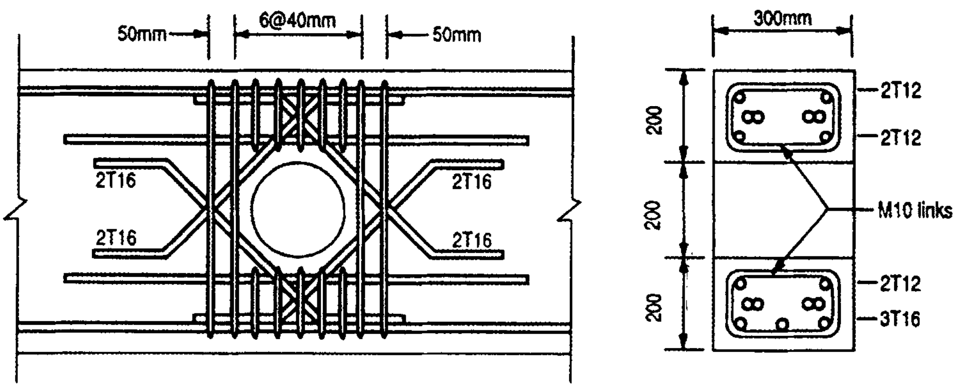

Fig. 11. Details of reinforcement around the opening.

Member above the opening (compression member). Since the section for this member has dimensions identical to those for the section below, and it is subjected to axial compression, use of the same spacing of stirrups would provide a conservative design.

Design for crack control

Diagonal reinforcement is used to achieve crack control under service load condition. Using eqn (7), and using $f_{yd} = 460$ MPa, the area of diagonal reinforcement required is

$$A_d = 216\,000/[(0.85)(460)\,(\sin 45°)] = 781 \text{ mm}^2$$

Use 4T16 diagonal bars in each direction.

Reinforcement details

Figure 11 shows the final arrangement of reinforcement in the opening region.