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Design concept of reinforced concrete beams with large web openings

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Abstract. This paper presents numerical investigations in studying large web openings. Based on the previous guidelines, the web openings in reinforced concrete beams are being investigated. The simple verification design procedure is followed by ACI-318. In general, web openings have to consider a certain position so that each chord sides imply a sufficient area to expand the ultimate compression in flexure and give the appropriate reinforcement. In this case, two openings are placed nearly to one-half from support on each side. The analysis follows the recommended procedure for elastic bending moments and shear forces while the deflections are evaluated both in the short and long-term periods. It is found that the beam with a large web opening meets the required standard in all aspects, but it is indicative of having a large moment.

1. Introduction

In most of the tall buildings, utilities of pipes and ducts are accommodated in the space within the floor ceiling and beams. Implementing these utilities through transverse openings in the floor beams saves a significant amount of headroom and result in a more compact and economical design [1]. The total height also can be reduced due to the presence of the transfer openings that allow the passage of service utilities [2], [3]. However, the design provision with a hole in flexural members changes their simple mode behavior to a complex and indeterminate mode. In general, the evaluation of members with a different type of openings becomes underhanded and requires much effort and time which may not be justified in many projects. In this particular case, research work will give a reasonable procedure for the analysis and design of flexural members with different web openings.

The previous studies have been proposed for the strength design of beams with large web openings under various conditions. Mansur, et al [1], [4] investigated the large rectangular of web openings reinforced concrete (RC) under pure tension within a different of opening sizes and their locations. This study was also carried out by Tan et al [5] which analyzed the behavior of large openings based on different reinforcement criteria and design assumptions. The assumption of a typical free body diagram is presented in Figure 1. In addition, Rodríguez, et al [6] and Alsaeq [7] evaluated the effect of opening shape on the RC beams by using numerical analysis. The previous research works concluded that the opening locations have more effect on the structural strength than the opening shape. Notwithstanding, these methods require the magnitudes of forces and moments at the center of the opening to be predetermined and can, therefore, be readily applied to statically determinate beams only. In continuous beams that generally occur in practice, reduction in stiffness due to the provision of openings through webs causes a redistribution of internal forces and moments, the amount of which needs to be evaluated



before a design can proceed. To support the strength and deformation of the openings some modifications into RC beams are also necessary such as adding fiber reinforce concrete [8], [9] and engineered cementitious composite [10]–[13]. Another simulation is also conducted to verify experimental works [14]

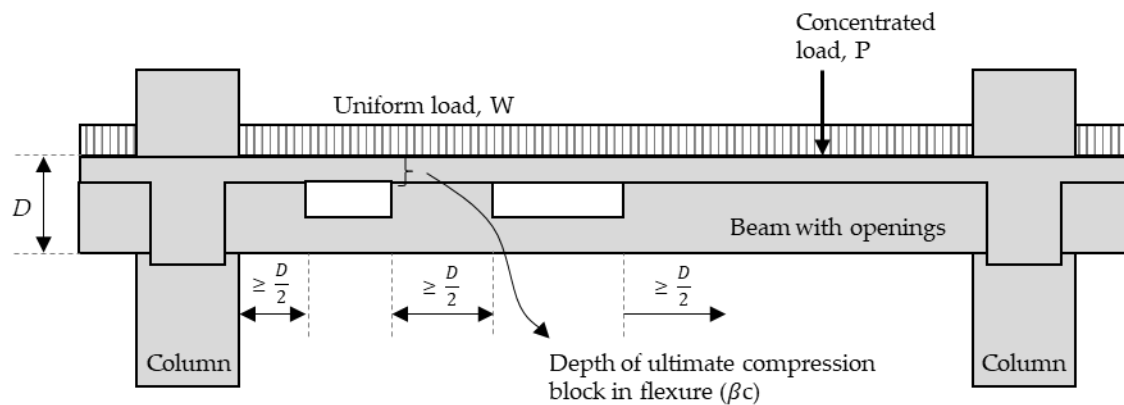


Figure 1. Typical condition of the beam with openings considering guidelines of Tan and Mansur [5]

1.1. Research Significance

This paper provides a case study within the implementation procedure to complete analysis and design the RC beam with the large web openings. General information for the placement of openings is given and supported by the numerical analysis. The procedure check for the ultimate strength, flexure, and shear. It also ensures that the capacity of the section fills the short and long-term deformation.

2. Design Method

The guidelines procedure is taken from a brief review from several works of literature [8], [9], [15]–[17] which considers its behavior and strength from this case to facilitate the selection of the size and location of the openings. In this special condition, the flexural member is used as a rectangular beam. The openings are placed at mid-depth of the section and exercise to in precise dimension to provide sufficient concrete cover as the support of reinforcement for the chord members below and above the opening. This is concerned to have an acceptable concrete area in terms of developing the ultimate compression block in flexure and have adequate depth to give effective shear reinforcement.

Another procedure that should carry is openings location. The openings should omit the position which is closer than one-half the beam depth D to the supports to avoid the critical region for shear failure. Openings depth should also limit to fifty percent of overall beam depth. The factor that limits the length of the openings are the stability of the chord members, the compression chord, and the deflection based on the serviceability required criteria. In this case, the opening location is remained in the same position (single opening) with a variety of opening sizes.

Furthermore, the design procedure herein is used ACI-318 [18] which involves structural analysis, strength design, and serviceability design. All procedures are to determine the distribution of shear forces and moments due to ultimate loads, wherein the critical sections are designed for ultimate strength in bending and in shear. When it comes to serviceability, the performance level is used as a design parameter using direct displacement-based design to ensure the structure performs its intended functions satisfactory under the given loads.

2.1. Design of stiffness of beam segments

The member containing an opening is considered as a no prismatic beam. The beam with no openings is also considered into account as a parameter control. In this stiffness calculations, gross section of the

concrete is evaluated based on ACI-318 [18]. The modulus of elasticity of the concrete is according to Eq. (1a) where the shear modulus can be taken as Eq. (1b).

$$E_c = 4730 \sqrt{f'_c} \quad (1a)$$

$$G = \frac{E_c}{2(1 + \nu)} \quad (1b)$$

where f'_c is the cylinder compressive strength in MPa and ν is the Poisson's ratio which is taken 0.2 follows the recommendation by BS-8110 [19]. In the design parameter, the equivalent flexural stiffness of an opening segment is considered as $(EI)_{eq}$, the moment of inertia of concrete section minus the openings should be applied.

The equivalent of shear stiffness for an opening segment and the effective length of its openings can be obtained as Eq. (2a) and (2b).

$$(GA)_{eq} = \frac{12E_c (I_{gt} + I_{gb})}{l_e^2} \quad (2a)$$

$$l_e = \frac{l_o}{1 - \left(\frac{d_o}{D}\right)^{1.5}} \quad (2b)$$

Where I_{gt} , I_{gb} , l_o , d_o and D are the gross moment of inertia for top and bottom chord members, opening length, opening depth, and beam depth, in order. The shearing deformation of the solid segments is generally ignored.

2.2. Design of bending moment and shear force envelopes

The ultimate design bending moment M_m and shear force V_m at the middle of the opening segment from bending moment and shear force envelopes, and calculate axial forces N_t and N_b (positive for compression) acting, respectively, in the top and bottom chords which can be obtained from Eq. (3a) and (3b), where z is the distance between the plastic centroids of the top and bottom chords.

$$N_t = \frac{M_m}{l_e} \quad (3a) \quad N_b = -N_t \quad (3b)$$

Further, to distribute the applied shear between the top and the bottom chords are calculated in Eq. (4a-b), where I_{gt} and I_{gb} are the gross moment of inertia of the top and bottom chords, respectively. For the evaluation of moments at the ends of chord members, the analysis can refer to Eq. (5a-d). Where ω the uniformly distributed load acting directly on the top chord and M is a moment. Subscripts 1, 2, 3 and 4 designate the opening corners, as illustrated in Figure 2.

$$V_t = V_m \left(\frac{I_{gt}}{I_{gt} + I_{gb}} \right) \quad (4a)$$

$$V_b = V_m \left(\frac{I_{gb}}{I_{gt} + I_{gb}} \right) \quad (4b)$$

$$M_1 = -\frac{\omega l_o^2}{8} - \frac{V_t l_o}{2} \quad (5a)$$

$$M_2 = -\frac{\omega l_o^2}{8} + \frac{V_t l_o}{2} \quad (5b)$$

$$M_3 = -\frac{V_b l_o}{2} \quad (5c)$$

$$M_4 = \frac{V_b l_o}{2} \quad (5d)$$

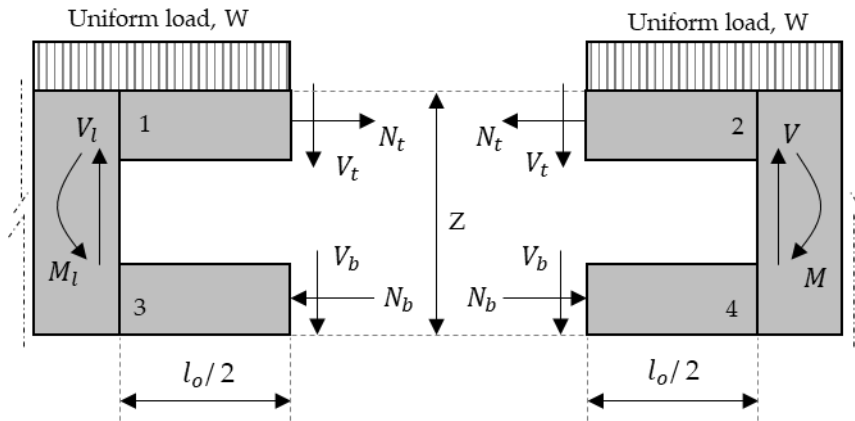


Figure 2. Detail of opening section [5]

2.3. Design of longitudinal and shear reinforcement

The longitudinal reinforcement in the bottom and the top of the section adjacent to the opening should be continued throughout the opening segments. Additional reinforcement required to resist the combined moment and axial force in each chord member is design considering idealized column interaction diagrams using the strain compatibility method. All combinations of bending moment and axial load should be evaluated within the appropriate interaction diagram to ensure sufficient reinforcement. As well as the capacity of flexure on the top chord. On the other hand, an updated reinforcement is necessary.

The shear forces transmitted to the bottom and the top chords are given by Eq. (4a-b). The condition to design is based on the knowing forces that are typically as same as to RC beam and slabs. Nonetheless, according to ACI-318 [18], the effects of axial forces in the chord members must be evaluated in design.

2.4. Design of deflections

The indirect way of satisfying the serviceability following the required deflection is by limiting the effective span depth ratio but it is not accurate for a beam with openings. Hence, the count of the actual service load deflection is necessary. In this case, the beam at the ultimate load may be used for the analysis since the detail of reinforcements is obvious. Then, the identical shear stiffness of the openings following the Eq. (2a-b) can be used.

3. Result and Discussion

One type, RC beam containing a web opening in the interior span is illustrated in Figure (3a). This represents a typical feature of a residential building (apartment) in which utility ducts run along the corridor between the rows of rooms. The full RC without opening will also be evaluated as the parameter control. The beam carries a dead load G_k , not including a self-weight of 10.66 kN/m of the and a uniformly imposed load Q_k of 3.75 kN/m. The material properties are $f'_c = 30$ MPa. Longitudinal and transverse steel, f_y , 400 MPa, and 240 MPa, respectively. The parameter location is cited in Surabaya with typically hard soil sites with the spectrum design $S_s = 0.705$ and $S_I = 0.305$. Following the proposed method using DDBD for the beam with particular openings is given as follows.

3.1. Structural analysis

From previous Eq. (1a-b), $E_c = 2600$ MPa and $G = 10800$ MPa. Then the following section information to support the evaluation are obtained respectively, $I_{gs} = 9.81 \times 10^9 \text{ mm}^4$, $I_{gt} = 4.22 \times 10^8 \text{ mm}^4$, $I_{gb} = 3.91 \times 10^8 \text{ mm}^4$ and the effective length of the opening $l_o = 1114.5$ mm. The cross-section area of solid segment $A_{so} = 3.6 \times 10^5 \text{ mm}^2$ and $E_c I_{gs} = 2.67 \times 10^5 \text{ mm}^2$ and $GA_{so} = 3.89 \times 10^9 \text{ N}$ whereas for the opening one $(EI)_{eq} = 2.54 \times 10^{14} \text{ Nmm}^2$ and $(GA)_{eq} = 2.03 \times 10^8 \text{ N}$. All the calculations are referred to Eq. (2a-b).

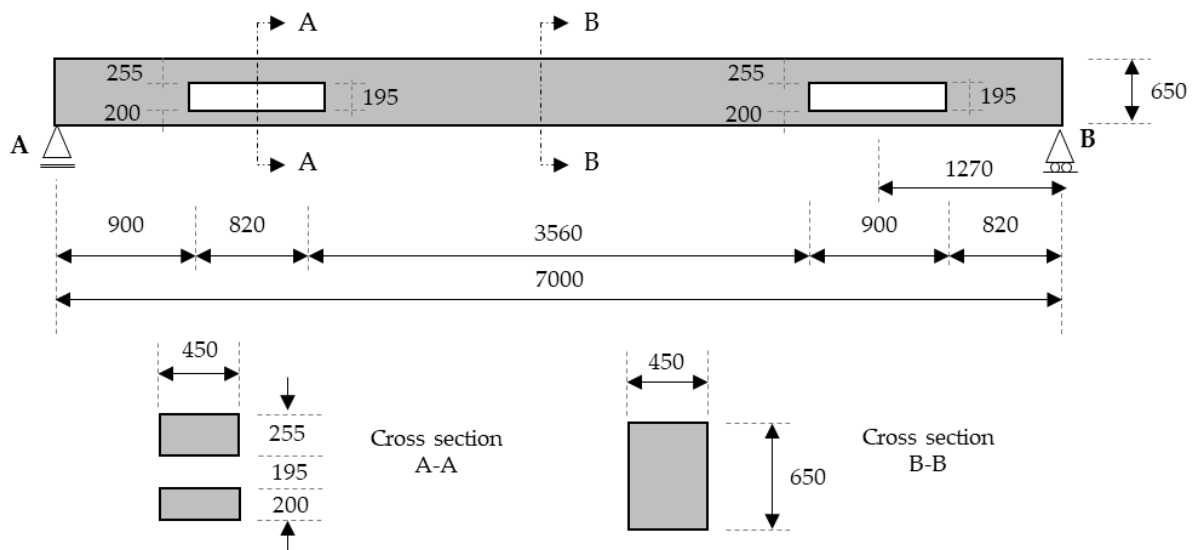


Figure 3. Detail of RC beam with large web opening

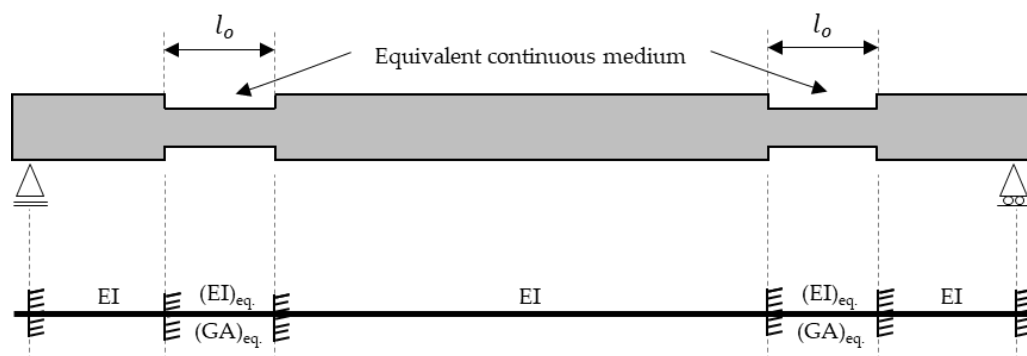


Figure 4. Equivalent beam with equivalent restrained structure scheme [unit: mm]

Table 1. Summary of design for critical sections – Beam with and without WO

Type of beam	Unit weight (kg)	Unit loss (%)	Moment (kNm)	Shear (kNm)	Axial (kNm)
Beam without WO	4914	-	- 294.76	-151.19	0
Beam with WO	297	6.04	- 243.31	151.12	27.04

The method of analysis to evaluate the load combinations is presented in Figure 4 and the segmented RC beams which are handed in the analysis are illustrated in Figure 5. Where the result is shown in Figure 6 as redistribution moment at the ultimate condition.

3.2. Strength design analysis

The result of the solid section was implemented in the usual manner. Both of RC with and without opening are summarized in Table 1. Furthermore, for the opening beam, the axial loads and shear forces referred to Figure 2 where bending moment M_m and shear force V_m at the center of the opening using Eq. (3a-b) and (4a-b). The result is shown in Table 2, considering $z = 400$ mm while the secondary moments using Eq. (5a-d).

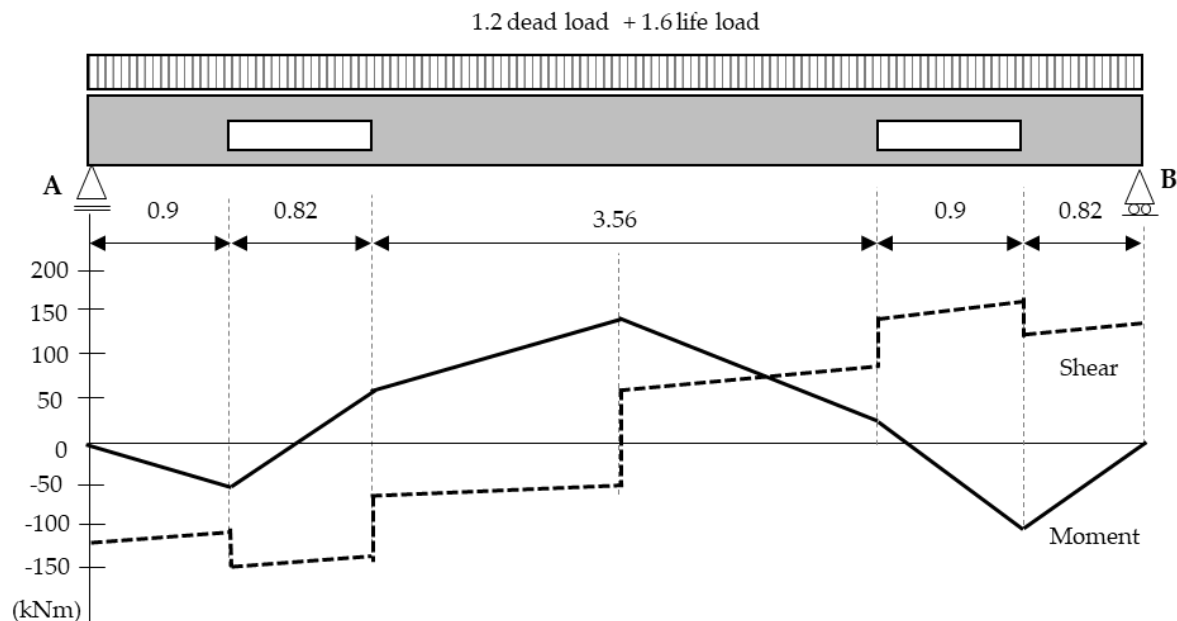


Figure 5. Redistribution of internal forces, moments, and shear in the beam with large web openings [unit: m]

From Table 1, the longitudinal reinforcement is informed. It is known that the solid beam adjacent to the opening is provided with 4D22 (four high-strength deformed bars of 22-mm diameter) and 2D22 (two high-strength deformed bars of 22-mm diameter). Hence, for the opening arrangement of reinforcement, the condition is illustrated in Figure 3 within 3D22 and 2D22 for the bottom and top chord.

The maximum shear of 95 kN at the opening center occurs and refer to Figure 4. Therefore, from Table 2, shear at top and bottom chord, respectively, $V_t = 49.8$ kN and $V_b = 45.8$ kN. The shear strength is evaluated by ACI-381 within the space limit is $d/2 = 192/2 = 96$ mm., therefore, provide stirrups of d10 (mild steel plain bars of 10-mm diameter) at 90-mm spacing.

$$\phi V_c = 0.85 \times 0.17 \left[1 + 0.073 \frac{(58)}{300 \times (250)} \right]$$

$$\sqrt{30} \times 300 \times 192 = 45.6 \text{ kN} < 45.9 \text{ kN}$$

3.3. Deflection

In the first parameter as a short-term deflection cracked moment is assumed from the inertia of the beam. The beam is evaluated using a service load of $(G_k + G_k) = 25.2$ kN/m. The maximum deflection is informed typically for bot side span AB and CB with a value of nearly 10 mm due to the combination of dead and life load. According to ACI-381, the allowable short-term deflection is likely to be designed as $L/360 = 7000/360 = 19.4$ mm > 10 mm; thus, the result is satisfactory.

In the following parameter, in long-term deflection (5 years period), the assumption is considered that 20 percent of the live load is sustained due to unpredicted conditions. Additionally, shrinkage and creep may also be determined following the indication of immediate deflection by a factor $\lambda = 2/(1+50\rho')$ where ρ' is the compression steel ratio at a maximum location when a deflection occurs. Seeing that $\rho' = 945/(300 \times 542) = 0.0058$, then $\lambda = 1.7$. On the other hand, the sustained load is given $(1.0G_k + 0.2Q_k) = 16.3$ kN/m while the result of the calculation for the maximum deflection is 8.15 mm; hence, the long-term deflection is counted = $10 + 1.55 \times 8.15 = 22.63$. The result has to be compared to the allowable long-term deflection according to ACI-318 of $L/240 = 7000/240 = 29.2$ mm. It is concluded that the result is satisfactory.

4. Conclusions

This study is indicated the calculation for large web openings in the RC beam. The calculation is made based on the previous investigation which is followed by the instruction guidelines. The investigated is made by a solid member and the opening member using the direct stiffness method. The predicted results found that deflection and support reactions have a good agreement with the required code ACI-318. The method also gives a reasonable data to be implemented the incorporating openings.

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