Behaviour of Reinforced Concrete Beams with and Without Web Openings using Direct Displacement Based Design

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Abstract. This paper describes analysis at the reinforced concrete building that contain web openings at the beam element in certain location. In the analytical modelling, the beams are treated as structural members comprising several segments which has a different dimension, and the equivalent stiffness of the opened beams has been derived. The whole structure including the beams are then analysed by the direct displacement based designed method. As the result from three analytical modelling within the variety of web openings and literature studies are compared with the evaluation of deflections and support reactions under service load. A numerical modelling is also supported the study to corroborate findings. In general, a good agreement has been obtained.

1. Introduction
There is expanding trend in the most of tall building toward erasing the extra space nearly to ceilings by setup the utilities or ducting pipe through openings underneath the floor beams. This concept provides a significant space in particular of the effective height of building. This design also offer compact usable room in term of effectivity and economical reason [1]. However, when the openings are positioned in the web of reinforced concrete (RC) beam, it will lead to inducing high stress concentration around the opening area, reducing stiffness of beam and altering the simple concept of beam behaviour into the complex one. Consequently, while on these terms, arranging the opening on the web of beam element, the responses on the ultimate strength and service load behaviour of the beam must be accurately accounted for in design.

The influence of large or closely spaced web openings on the behaviour of RC beam is relatively complex. There are many factors that may control failure which also should be carefully taken care of such as the position of the openings whether in high shear or a high bending zone, the type of loading category as uniform or pointed loading, the shape of the openings e.g., rectangular, circular or elongated both rectangular and circular and the spacing of the openings which correlated to the slenderness of the web [1]–[3]. As the matter of fact, beams both with or without openings should be designed satisfy the design requirements as the ultimate and the service ability states referring to the construction and erection method. The failure modes that may happened around the condition of the large openings are illustrated in Figure 1[4].

Extensive research from various researcher in the past had been conducted on the capacity concerned on the ultimate strength and its behaviour as well as RC designing and prestressed concrete beams providing large web openings [5], [6]. In comparative, a small amount of research having attention toward to insuring adequate service load behaviour such as the deflection aspect of the beams.
at service loads. One of the related researches had been studied by Mansur et al. [1]–[3], [7]–[9] under the modification of the beam with various section opening of the beam, the deflection provide analytical calculation based on the performance capacity approach. In this study, the concept of finite element technique was proposed on the truss model predicting the load-deflection response of concrete T-beams with variety of openings. The result testified the accuracy within the experimental program. However, the method is only concerned under a simple increment of loading based on the experimental program.

Another research activities also completed by Pertiwi [10] within the concept of RC beam under large web opening. In some point, the use of material will also participate to the changing behaviour [11]–[15]; the supportive research will enhance the information to determine the type of opening or to improve the RC beam section within the concept numerical modelling based on performance design [16]–[19], e.g. added the supplementary materials [11], [12], [20], tailored by engineered cementitious composite [14], [21]–[23] or used a bamboo as the alternative confinement materials [24].

The main objective of the work reported here was to give the evaluation based on the simple method by using numerical analysis with the concept of direct displacement-based design (DDBD) to predict the service load deflection of RC beam that contain a large web opening. Since most design of structure now having such opening and the easiest way for analysing structure, the method should be handily compared to existing software such as SAP2000 to imply its practical value.

![Figure 1. Element of RC beam structure that typically having a web openings [8]](image)

2. Research Significance
The calculation of the method is referred to the Mansur et.al., limiting the equivalent stiffness for the RC beam with opening segment. The formulation is taken by numerical analysis using SAP2000, it should provide a satisfactory service load behaviour to the deflection of RC beam contain a large web opening.
3. Theoretical Analysis

A model or RC beam that contain web opening within its deflected condition is illustrated in Figure 1. The correlated illustrated taken by the study Mansur [8]. It presents that the RC beam change both in flexure and shear response. The flexure relatively changes due to composite bending of concrete and reinforcement and for the shear is frame racking action, which results from the opposite condition of flexure in the chord members above and the below opening.

Considering the opening that the continuous chord members are displaced by an equivalent continuous medium, the RC beam may be had a condition as a structural member comprising a number of uniform segments, as illustrated in Figure 2. However, for the opening area, it is mandatory to draw of flexural equivalence and shear rigidities such as $EI$ and $GA$ to equate the behaviour of the actual opening.

The design procedure that is used according to ACI-318 [25] which compromise the total fully structural analysis such as, strength, and serviceability. The design procedures are to actuate the distribution of the ultimate loads both of moment and shear condition. To identify the serviceability, the method of DDBD is implied to ensure the structure performance.

Conventional force-based design analysis of the structure uses the concept of elastic stiffness member. By using this concept significantly error value may occur. Under the DDBD, relative stiffness of members at the peak displacement will represent the prominent behaviour. It will adequately reduce the elastic stiffness of all beams by the system displacement ductility level. The same behaviour is also informed for beam with openings but with different factor of ductility.

$$OTM = \sum F_i \times H_i$$

$$OTM = T \times L_{B} + \sum M_{cj}$$

$$OTM = \sum V_{Bi} \times L_{base} + \sum M_{cj}$$

![Figure 2. Seismic moments from DDBD lateral forces](image)

3.1. Equivalent of flexural and shear rigidity

The equivalent both of flexure and shear are needed to solve the opening members. The equivalent flexural rigidity $(EI)_{eq}$ is based on the net section through the opening. The assumption coming through both chords section act the same way that cracked in flexure. For the moment of inertia, $I$, is counted using the transformed concept reflected to the opening condition. The value of modulus elasticity, $E$ and shear modulus, $G$, according to the Equation 1 and 2 followed the specification of ACI-318 [25]. Where is related to the $f'_c$ as the value of cylinder compressive strength (MPa) and the Poisson’s ratio, $\nu$ is used to identify the shear modulus. According to the BS-8110 [26], the value of $\nu$ normally taken 0.2.
$E_c = 4730 \sqrt{f_c}$ (1)  

$G = \frac{E_c}{2(1+v)}$ (2)

Then, the equivalent shear rigidity $(GA)_\text{eq}$ is related to the $(EI)_\text{eq}$ which is connecting to the chord members and the $l_e$ as the effective length of the opening. It may be obtained by the following Equation 3 and 4. As the information from the Equation, $I_{gt}$ is implied as the gross moment of inertia of top member and $I_{gb}$ as the bottom chord members. $l_o$ implied as the length of the opening and $d_o$ and $D$ are respectively for the depth of the opening and beam depth.

$$(GA)_\text{eq} = \frac{12E_c (I_{gt} + I_{gb})}{l_e^2}$$ (3)  

$$l_e = \frac{l_o}{1-(d_o/D)^{1.5}}$$ (4)

### 3.2. Member stiffness and transfer matrix

To calculate the shear deformation, the shear rigidity has to be incorporated into the member of stiffness matrix. The matrix is considered to be taken by Tan et. Al., [25] that include the effect of shearing deformation derived by the flexibility and inform as $S_M$ as the following Equation 5 which is equal as the Equation 6. Typically, the transfer matrix can also be obtained by Equation 7 as $T_{ML}$ in which $\alpha$ and $\beta$ are the distances of the applied point load or moment in a member from the left and right supports, respectively, as shown in Figure 4.

$$S_M = \frac{EI}{1+2g} \begin{bmatrix} \frac{12}{L^3} & \frac{6}{L^2} & \frac{-12}{L^2} & \frac{6}{L^2} & \frac{12}{L^2} & \frac{6}{L^2} \\ \frac{6}{L^2} & \frac{4}{L^2} & \frac{6}{L^2} & \frac{-12}{L^2} & \frac{6}{L^2} & \frac{12}{L^2} \\ \frac{6}{L^2} & \frac{2}{L^2} & \frac{1}{L^2} & \frac{6}{L^2} & \frac{2}{L^2} & \frac{6}{L^2} \end{bmatrix}$$ (5)  

$$g = \frac{6 EI}{L^2 GA}$$ (6)

$$T_{ML} = \frac{1}{1+2g} \begin{bmatrix} \frac{\beta^2}{L^3} \left[ 3\alpha + \beta + 2\beta (L/\beta)^2 g \right] & \frac{6\alpha\beta}{L^3} \\ \frac{a\beta^2}{L^3} \left[ 1 + (L/\beta)^2 g \right] & \frac{\beta}{L^2} (2\alpha - 2gL) \\ \frac{\beta a^2}{L^3} \left[ 1 + (L/a)^2 g \right] & \frac{a}{L^2} (2\beta - 2gL) \end{bmatrix}$$ (7)

### 3.3. Reinforcement design

The reinforcement for longitudinal section area both of top and bottom chord follow the condition of the opening. It should continue and connect one to another as illustrated in Figure 4. Additional reinforcement follow the required standard according to ACI-318 [25]. The reinforcement should resist the combined load including the moment capacity that interact with the compatibility method. Based on the evaluation of the bending moment and axial load, it should imply appropriate reinforcement for RC beam as well as the capacity of flexure and shear. Further, in the matter of serviceability, the limiting of effective span has to be considered before adding the opening. The deflection is needed to be controlled carefully as the attachment of the large opening.
4. Method of Analysis

The analysis is modified based on the stiffness and the matrixes of the preceding research using direct stiffness method before evaluating into a numerical modelling using SAP2000. The RC beam with web opening is taken into account from the real structure. The load and the capacity of the elemental structure without the openings have to meet the required standard as the parameter control. Then implied the RC beam with opening as the investigation concern. Specification for the building is illustrated in Figure 4 having 31.5 m width, 14.5 m length with 8 stories. The response of modification follows the criteria of the building as residential building or apartment. The combination of the loading scheme is followed the instruction of SNI 1727-2019 [27]. The building location is in Surabaya with the soil’s sites classified as class SC with the spectrum design $S_s = 0.705$ and $S_f = 0.305$. After the whole structure is modelled using SAP2000 (see Figure 3-4), the capacity of beam has been identified then The RC beam with opening is treated as a non-prismatic member with two sections with different cross-sectional properties, i.e., the solid section and the equivalent opening section.

![Building with the position of web openings](image)

![3DModeling of structure using SAP2000](image)

**Figure 3.** Illustration of RC beam with opening – section, position & 3D model

![Internal forces diagram under numerical analysis using SAP2000](image)

(a) Axial forces  
(b) Shear forces  
(c) Bending moment

**Figure 4.** Internal forces diagram under numerical analysis using SAP2000

The section is analyzed as a member as shown in Figure 5-6. It is normally added two extra joints into the modelling as the position of the opening. For the solid segment the behavior can be cited as the normal beam section such as ignoring the shear deformation and for flexural rigidity is still based on the cracked transformation. As the matter of fact, RC beam with large opening eventually given bigger deformation and reduces to the rest of continuous beam problem.
Figure 5. Detail of RC beam with large web opening [unit: mm]

Figure 6. Simply derivation equivalence – shear rigidity

Figure 7. Reinforcement details under web opening of RC beam
5. Result and discussion

The opening segment that is implied to the RC beam structure is illustrated in Figure 7, including the position of reinforcement. This current situation is typically used for utilities to maximize the building function as residential. The RC beam without opening is also counted to be used as comparison. Based on the calculation as informed, the RC beam with and without opening carried the same loading, $G$, with the value 10.50 kN/m and also added with the uniform imposed load as $Q$, of 3.50 kN/m.

All beams on the structure were installed typical in rectangular shape, 450 mm wide and 650 deep. For reinforcement, eight bars arranged across the section and continued throughout the length with the modification nearly to the opening as shown in Figure 7 while the result summary is presented in Table 1. RC beams were designed for shear which is needed to be controlled the cracks at the corners of the openings. Before evaluating the structure, the beam without web opening is needed to be controlled. The unit weight of the beam without web opening is 4914 kg when the beam with opening is 4535 kg which is nearly to 8% lighter than beam without openings. The parameter of the material that inputted to the numerical analysis is limited as the information; $E_c=2600$ MPa and $G = 10800$ MPa, $I_{gs} = 9.81\times10^9$ mm$^4$, $I_{gt} = 4.22\times10^8$ mm$^4$, $I_{gb} = 3.91\times10^8$ mm$^4$. The cross-section area of solid segment $A_{so} = 3.6\times10^5$ mm$^2$ and $E_c I_{gs} = 2.67\times10^9$ mm$^2$ and $G A_{so} = 3.89\times10^9$ N whereas for the opening one $(E I)_{eq} = 2.54\times10^{14}$ Nmm$^2$ and $(G A)_{eq} = 2.03\times10^8$ N.

**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) | Torsion (kN) |
|-----------------------|------------------|---------------|--------------|-------------|-------------|--------------|
| Beam without WO       | 4914             | -             | -246.979     | -151.19     | 0           | 55.78        |
| Beam with WO          | 4535             | 7.78%         | -177.549     | -132.17     | 27.04       | 51.31        |

Figure 8. Displacement vs drift beam without openings

Figure 9. Displacement vs drift beam with openings
The result to this structural problem relies on the recognition that any structural analysis in approximate (compare the relative structural approximations involved in an initial stiffness and secant stiffness representation both of which valid at different levels of seismic response). Figure 8 and Figure 9 illustrate the behaviour of displacement vs drift of beam with and without openings. It can be seen that based the deformation and drift with beam openings implied a slightly bigger value than the structure without beam opening. In fact, from the analytical evaluation for both structure \( \rho' = 0.0038 \), then \( \lambda = 1.7 \). The distributed load is given \((1.0G_k + 0.2Q_k) = 14.6 \text{ kN/m} \) while the result of the calculation for the maximum deflection is \( 9.15 \text{ mm} \); hence, the long-term deflection is counted \( 10 + 1.55 \times 9.15 = 10.70 \). The result has to be compared to the allowable long-term deflection according to ACI-318 of \( L/240 = 3500/240 = 14.583 \text{ mm} \). It is concluded that the result is satisfactory. The confinement is still required to be improved to considered the factor of safety.

6. Conclusions
From this current research under numerical simulation informed that RC beam containing medium opening that rectangular to the position of the center beam is treated as a non-prismatic member by dividing beam under two different cross-sectional properties e.g., solid and opening sections. Different stiffness needs to be proposed for each segment related to the opening. DDBD concept is considered to be a proficient method to analyze the openings, the formulation is easily adaptable to the whole structural investigation. Under the comparison study beam with and without openings implied a slightly different value with the typical behavior one and another, but when the openings are wider the stiffness of structure need to be reevaluated using a different approach. In addition, the predicted deflection has a good agreement with the required code ACI-318. However, the confinement improvement is necessary.

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