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# Finite element analysis of reinforced concrete deep beam with large opening



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## Abstract

**Background:** A series of nonlinear finite element (FE) analyses was performed to evaluate the different design approaches available in the literature for design of reinforced concrete deep beam with large opening. Three finite element models were developed and analyzed using the computer software ATENA. The three FE models of the deep beams were made for details based on three different design approaches: (Kong, F.K. and Sharp, G.R., Magazine of Concrete Res\_30:89-95, 1978), (Mansur, M. A., Design of reinforced concrete beams with web openings, 2006), and Strut and Tie method (STM) as per ACI 318-14 (ACI318 Committee, Building Code Requirements for Structural Concrete (ACI318-14), 2014). Results from the FE analyses were compared with the three approaches to evaluate the effect of different reinforcement details on the structural behavior of transfer deep beam with large opening.

**Results:** The service load deflection is the same for the three models. The stiffnesses of the designs of (Mansur, M. A., Design of reinforced concrete beams with web openings, 2006) and STM reduce at a load higher than the ultimate design load while the (Kong, F.K. and Sharp, G.R., Magazine of Concrete Res\_30:89-95, 1978) reduces stiffness at a load close to the ultimate design load. The deep beam designed according to (Mansur, M. A., Design of reinforced concrete beams with web openings, 2006) model starts cracking at load higher than the beam designed according to (Kong, F.K. and Sharp, G.R., Magazine of Concrete Res\_30:89-95, 1978) method. The deep beam detailed according to (Kong, F.K. and Sharp, G.R., Magazine of Concrete Res\_30:89-95, 1978) and (Mansur, M. A., Design of reinforced concrete beams with web openings, 2006) failed due to extensive shear cracks. The specimen detailed according to STM restores its capacity after initial failure. The three models satisfy the deflection limit.

**Conclusion:** It is found that the three design approaches give sufficient ultimate load capacity. The amount of reinforcement given by both (Mansur, M. A., Design of reinforced concrete beams with web openings, 2006) and (Kong, F.K. and Sharp, G.R., Magazine of Concrete Res\_30:89-95, 1978) is the same. The reinforcement used by the STM method is higher than the other two methods. Additional reinforcement is needed to limit the crack widths. (Mansur, M. A., Design of reinforced concrete beams with web openings, (2006)) method gives lesser steel reinforcement requirement and higher failure load compared to the other two methods.

**Keywords:** Transfer beam, Non-prismatic, Finite element, STM, Deep beam

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## 1 Background

Designs of many of the new tower buildings include transfer beam elements with depths equal to a full floor depth to achieve the architectural requirements for both parking and upper floors. In many situations, the full beam depth cannot be utilized for the full span due to the presence of openings and space restrictions. In such cases, the structural engineer utilizes the available solid zone developing non-prismatic beams with different shapes and depths. These particular shapes create a challenge to understand the load transfer mechanisms and to estimate ultimate strengths and reinforcement details.

El-kareim et al [1] studied the strength and behavior of deep beams with openings. They reported experimental tests on flanged deep beams with different shear spans and openings. They considered the effect of flange on the behavior of these beams in terms of cracking, reinforcement strains, and deformations. They made a finite element model to predict the experimental behavior. El-kareim et al. [1] calculated the deep beams' capacities using design equations. The finite element model was able to predict the experimental behavior. Hassan et al. [2] studied self-compacted high-strength concrete deep beams with opening. They conducted experimental tests to study the effect of location, size, and shape of opening. Hassan et al. [2] commented on crack patterns, absorbed energy, and deflection. Yang et al. [3] analytically and experimentally evaluated the influence of web openings in reinforced concrete deep beams. They studied the effects of shear span-to-depth ratio, depth and width of opening, and concrete strength. Their tests indicated that the effect of concrete strength on the shear capacity decreased for deep beams with openings compared to solid deep beams. Campione and Minafo [4] analytically and experimentally studied the effect of openings of circular shape in deep beams of low shear span-to-depth ratio. The tested beams had different opening positions and reinforcement arrangements. Their study revealed that the benefit of reinforcement depends on its arrangements. They predicted the shear strength and corresponding deflection. Mohamed et al. [5] performed finite element analyses for deep beams with opening and without opening to study the effect of reinforcement pattern. They recommended avoiding web openings crossing the expected compression struts and limiting the opening depth to 20% of the deep beam depth. El-Kassas et al. [6] studied deep beams with longitudinal opening for mechanical and electrical services. In their experimental work, they changed the opening size, shape, and location. They recorded crack patterns, load capacity, and deflection. The experimental work revealed that increasing the opening size decreases the beam capacity while changing its shape has a slight effect. Placing the opening in the compression zone gives more reduction in the load-carrying capacity. Tseng et al.

[7] developed an analytical method to evaluate the shear strength of deep beams with openings and obtain the failure mode. The proposed method is based on the strut-and-tie analysis. This method is used to study deep beams with different reinforcement ratios, concrete strengths, sizes of web openings, and span-depth ratios. The results proved that the proposed method is simple and accurate.

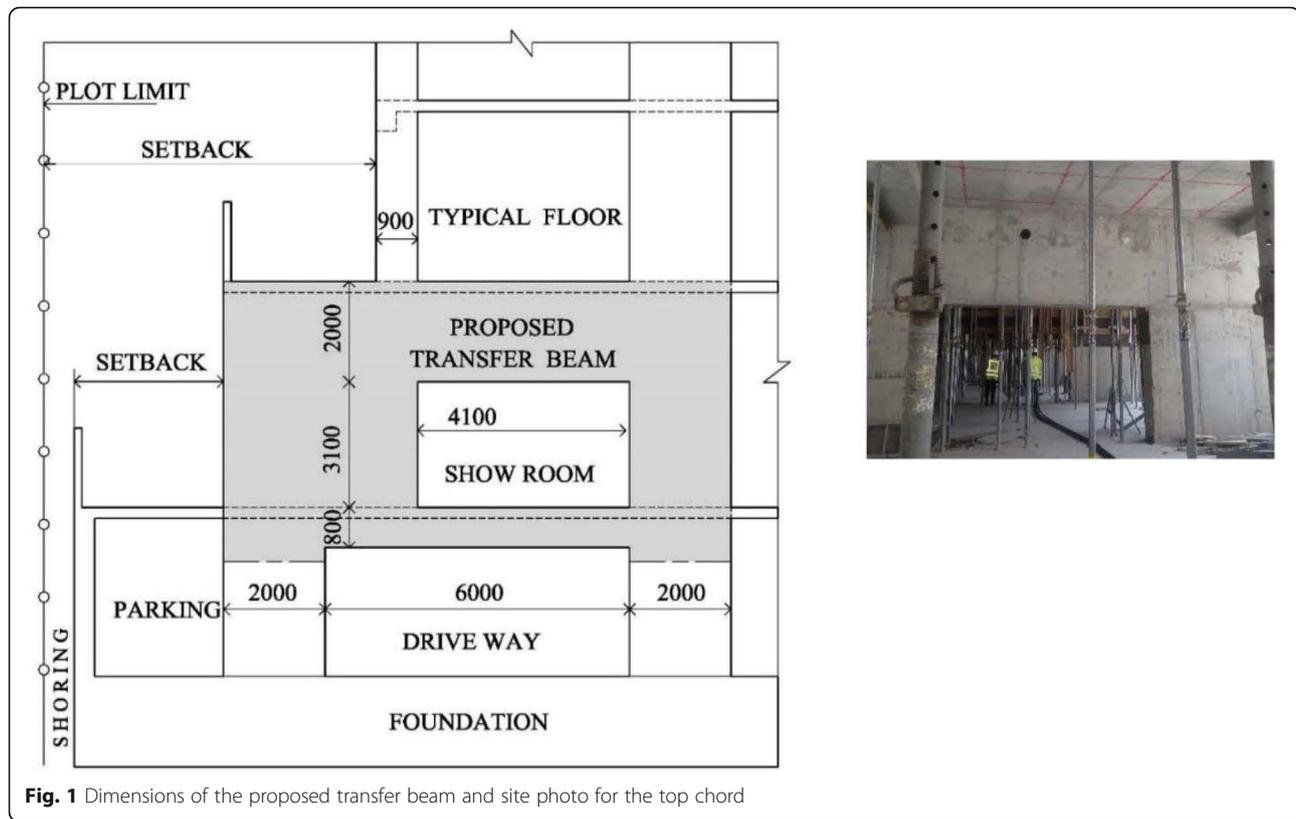
Studies on deep beams with web openings are generally limited and international codes do not include provisions for the design of these elements. Other previous studies such as the works of Maxwell and Breen [8], Kong and Sharp [9], Kong and Sharp [10], Ray. D. P [11], Ashour and Rishi [12], Ray [13], and Tan et. al. [14] have developed formulas to calculate the ultimate strength of deep beams using the modified Mohr-Coulomb's criterion and the shear friction theory. Kong. F. K [15] provided recommendations for applying his method with limitations on the opening size and location. A simplified procedure was also suggested by Mansur [16] which proposed an equivalent stiffness of the beam opening segment based on the analysis of a continuous beam with large web openings. Another alternative for designing deep beams with web openings is the use of strut-and-tie (STM) models. The complex stress flow in a cracked concrete structure is approximated with simple truss model that can be analyzed and designed by structural mechanics (Tan *et al.* [14]). The ACI 318-14 [17] code substituted the use of empirical equations for predicting the shear strength of deep beams by the use of the Strut and Tie (STM) method.

## 2 Methods

The objective of this paper is to compare the mechanical behavior such as cracking, yielding of reinforcement, and deflection of transfer deep beam with large opening designed according to three different approaches. This is to decide on the merits of each design approach. To the writers' knowledge, this type of comparison and evaluation of merits of the three design models is not done in the literature. The finite element software ATENA Program Documentation [18] is used in the analysis. This software can simulate the actual behavior of concrete elements including cracking and plasticity phases. The software is validated previously using laboratory research carried by El Maaddawy and Sherif [19] for deep beams with openings and Markou and AlHamaydeh [20] for deep beams without shear reinforcement.

## 3 Details of beam geometry and reinforcement

A typical transfer beam in a high-rise building consisting of two levels for basement and ground and fourteen typical floors was analyzed for this study. The beam was introduced from ground to first-floor level to take the columns' location which was restricted in the basement by the driveway and in the



first floor by the setback, as shown in the cross-section in Fig. 1. Reinforced details were provided using the three selected approaches by Kong. F.K [15], Mansur [16], and Strut and Tie method (STM) as per ACI 318-14 [17]. The dimensions of the beam were based on the maximum allowed shear value and the possible concrete dimensions that meet architectural conditions. The beam was designed for a concentrated factored load of 10 MN. The cubic concrete strength ( $f_{cu}$ ) is assumed to be 50 MPa, and both flexural and shear reinforcement bars were assumed to have a yield strength  $f_y$  of 460 MPa. The provided reinforcements in the support zones were similar in all approaches to prevent failure in these zones.

The beam was considered as a simply supported deep beam with overall dimensions of 10,000 × 5900 × 500 mm (length × depth × width) with a large opening of 4100 × 3100 mm. The transfer load was applied at shear span to overall depth ratio of 0.25.

### 3.1 Beam reinforcement using the Kong. F.K [15] approach

#### 3.1.1 Flexural

The beam was analyzed as a simple beam in which the internal forces were obtained. The ultimate flexural strength for the beam was calculated using the formula

proposed in the CIRIA (Construction Industry and Research Information Association), CIRIA Guide 2 [21] for a beam with a solid web as explained in the section below.

$$A_{st} = \frac{M}{0.85 f_{ys} z}$$

where  $A_{st}$  is the flexural reinforcement,  $M$  is the design moment at ultimate state, and  $z$  is the lever arm for a single span. For preliminary design, it is recommended to use  $z = 0.6D$ , where  $D$  is the overall depth and  $f_{ys}$  is the yield strength of longitudinal steel reinforcement. Therefore, the reinforcement will be distributed over a height of 0.2D, which was taken as 800 mm due to the presence of an opening. The equation above is applicable for beams with openings; however, a capacity reduction factor of 0.65 is recommended (Ray, [13]). The principal reinforcement is calculated and rounded to the nearest significant figure.

The area of reinforcement required to be concentrated around the opening is based on the reduced tensile capacity of the opening,  $a * b * f_t$  where,  $a$  is the half dimension of the opening perpendicular to reinforcement direction considered,  $b$  is the beam thickness,  $f_t$  is the

cylinder-splitting tensile strength of the concrete,  $f_t = 0.5 \sqrt{f_{cu}}$ , and  $f_{cu}$  characteristic strength of concrete.

### 3.1.2 Shear strength

The ultimate shear equation proposed by Kong, F.K [15] is based on the shear resistance of a solid deep beam and is a function of the concrete resistance and the tension and web reinforcements. The effect of web opening on the concrete shear strength is accounted by the constants  $\lambda_1$ ,  $\lambda_2$ , and  $\lambda_3$ , as follows:

$$\frac{V_u}{bD} = 0.1f'_c [\lambda_1 \lambda_2 \lambda_3] + 0.0085\psi_s\rho_s f_{ys} + 0.0085\psi_w K_w \rho_w f_{wy}$$

where  $\lambda_1$  is a failure mode parameter that mainly depends on the shear span as follows:

$$\lambda_1 = \left[1 - \frac{1}{3} \left(\frac{K_1 X_N}{K_2 D}\right)\right] \text{ for } \frac{K_1 X_N}{K_2 D} \leq 1, \text{ and } \lambda_1 = 2/3 \text{ for } \frac{K_1 X_N}{K_2 D} \geq 1$$

in which  $K_1 X_N$  and  $K_2 D$  are the dimensions from the edge of the practical region to the opening center as shown in Fig. 2.

$\lambda_2$  is a constant that accounts for the interception of the opening into the natural path load (critical diagonal crack) that can be expressed as:

$$\lambda_2 = (1 - m)$$

in which  $m$  is the ratio of the path length intercepted to the total path length along the natural path.

$\lambda_3$  is a constant that accounts for the combined effect of the size of the opening with respect to its location as follows:

$$\lambda_3 = \left[0.85 \pm 0.3 \left(\frac{e_x}{X_{net}}\right)\right] \left[0.85 \pm 0.3 \left(\frac{e_y}{Y_{net}}\right)\right]$$

$$e_x \leq \frac{X_N}{4}$$

$$e_y \leq \frac{0.6D}{4}$$

$$X_{net} = (X_N - a_1 x)$$

$$Y_{net} = (0.6D - a_2 D)$$

$e_x$  and  $e_y$  are the eccentricity of the center of the opening in relation to the center point of the critical diagonal crack,  $X_{net}$  and  $Y_{net}$  are the dimensions of solid shear zone in the X and Y directions after subtracting the dimensions of the web opening in the respective directions, and  $a_1 x$  and  $a_2 D$  are the opening dimension in X and Y directions, respectively, measured as indicated in Fig. 2 a.

The sign convention adopted as negative when the opening is in the quarter where the load is applied and positive when is located in the quarter with no load. As shown in Fig. 2a the loaded quadrants are the regions located closer to the load and support bearing blocks.

$\psi_s$  and  $\psi_w$  are empirical coefficients assumed as 0.65 and 0.5, respectively.

$\rho_s$  ( $\rho_s = \frac{A_{st}}{bD \times 100}$ ) is the main steel ratio in the concrete deep beam, and  $\rho_w$  ( $\rho_w = \sum \frac{A_w}{bD \times 100}$ ) is the web steel ratio in the concrete deep beam.  $A_w$  is the area of individual web reinforcement either vertical, horizontal or inclined intersecting with the critical diagonal crack.

$K_w = 0.85$  for horizontal web reinforcement,  $Cot\beta$  for vertical web reinforcement, and 1.15 for inclined web reinforcement.

$\beta$  is the critical diagonal crack inclination angle with the horizontal axis.

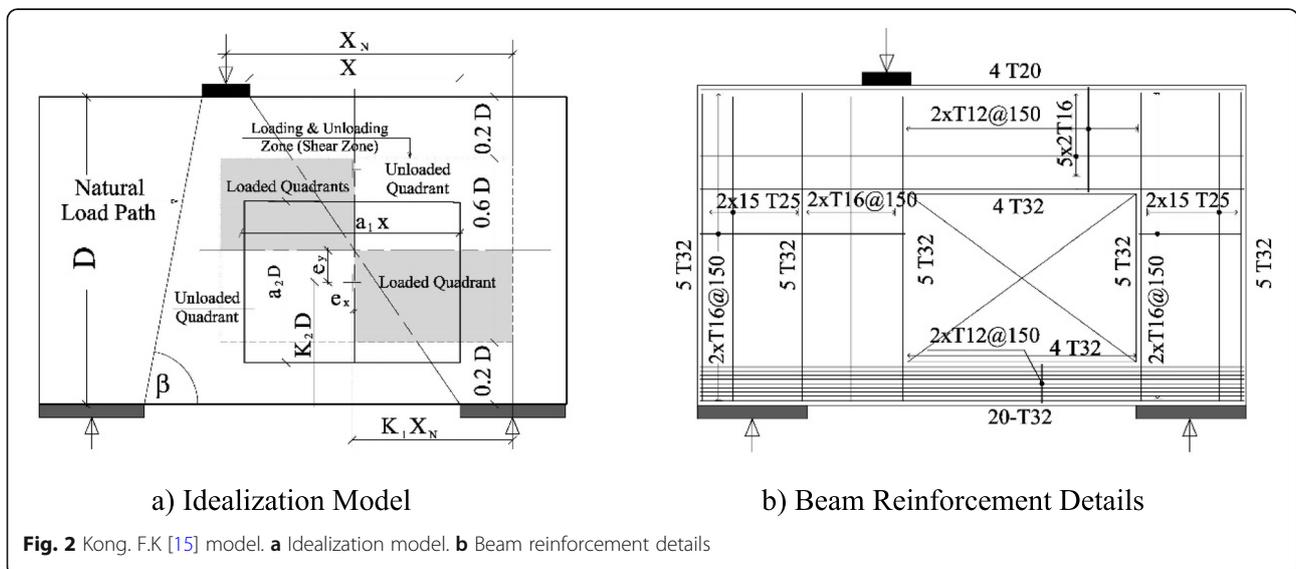


Fig. 2 Kong, F.K [15] model. a Idealization model. b Beam reinforcement details

Figure 2 presents the structural idealization and reinforcement details based on the empirical formula proposed by Kong, F.K [15].

The above equations represent the general relationship used for plain beams and for beams with and without web reinforcements. Ray [13] considered that this equation favors the design engineering practice.

A system of orthogonal web reinforcement is required with bars in each face where the minimum area of vertical and horizontal reinforcement are as follows:  $\frac{A_v}{(bs_v)} \geq 0.20$ , and  $\frac{A_h}{(bs_h)} \geq 0.20$

where  $S_v$  and  $AS_h$  are the vertical and horizontal reinforcement spacing, respectively.

**3.2 Beam reinforcement using the Mansur [16] method**

In this method, the beam is analyzed as a simple determinate structure in which the non-prismatic shape does not affect the straining action values. The design procedure for the opening segment is based on Vierendeel behavior of chord members at the opening. Contra flexure points are assumed at the mid span of the top and bottom chord members for which the axial load is obtained by dividing the moment at the center of the opening by the distance between the plastic centroids of the chord members, as follows:

$$C = T = \frac{M}{Y_{ct}}$$

where  $Y_{ct}$  is the distance between the plastic centroids of the bottom chord and top chord and  $M$  is the ultimate bending moment at the middle of the opening.

The shear force at the center of the opening,  $V$ , is distributed between the top chord  $V_t$  and the bottom chord  $V_b$  according to their relative flexural stiffness. The

moments at the ends of the top chord,  $M_t$ , and the bottom chords,  $M_b$ , are calculated using statics as follows:

$$M_t = \frac{V_t L}{2} \text{ and } M_b = \frac{V_b L}{2}$$

where

$$V_t = V \frac{I_t}{I_t + I_b} \text{ and } V_b = V \frac{I_b}{I_t + I_b}$$

in which  $I_b$  and  $I_t$  are the gross moments of inertia at the bottom and top chords, respectively, and  $L$  is the opening length.

The critical sections were designed for bending, axial, and shear in the usual manner using the interaction diagrams. Figure 3 shows the free body diagram of the opening segment and the required reinforcement details.

**3.3 Beam reinforcement using the STM method as per ACI 318-14**

The deep beam was designed using the strut and tie method (STM) described in Chapter 23 of ACI 318-14. There can be many possible truss models for the given loading and geometry of the deep beams. However, the assumed theoretical STM for the applied loads is shown in Fig. 4. Selecting the truss model of the STM to use depends on the experience of the designer. The location of struts and ties represent the elastic flow of forces within the structural components. The tie is placed at the position of the bars centroid; the struts such as the horizontal struts along the top of the member are placed based upon the depth,  $a$ , of the rectangular compression stress block as determine from the typical flexural analysis as follows:

$$a = \frac{A_s f_s - A'_s f'_s}{0.85 f'_c b}$$

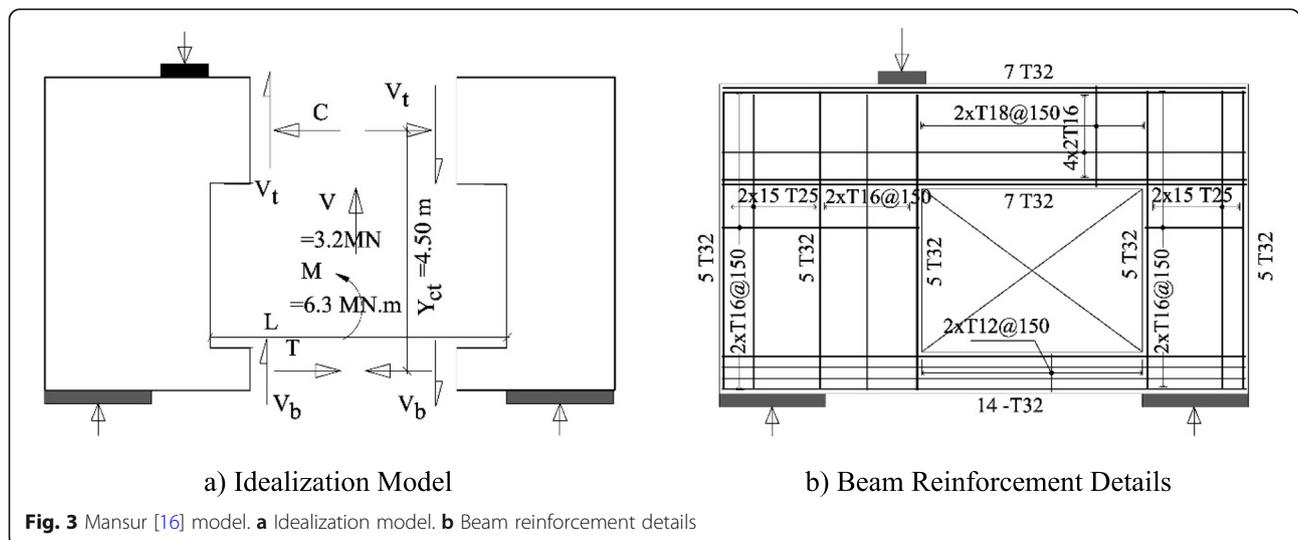
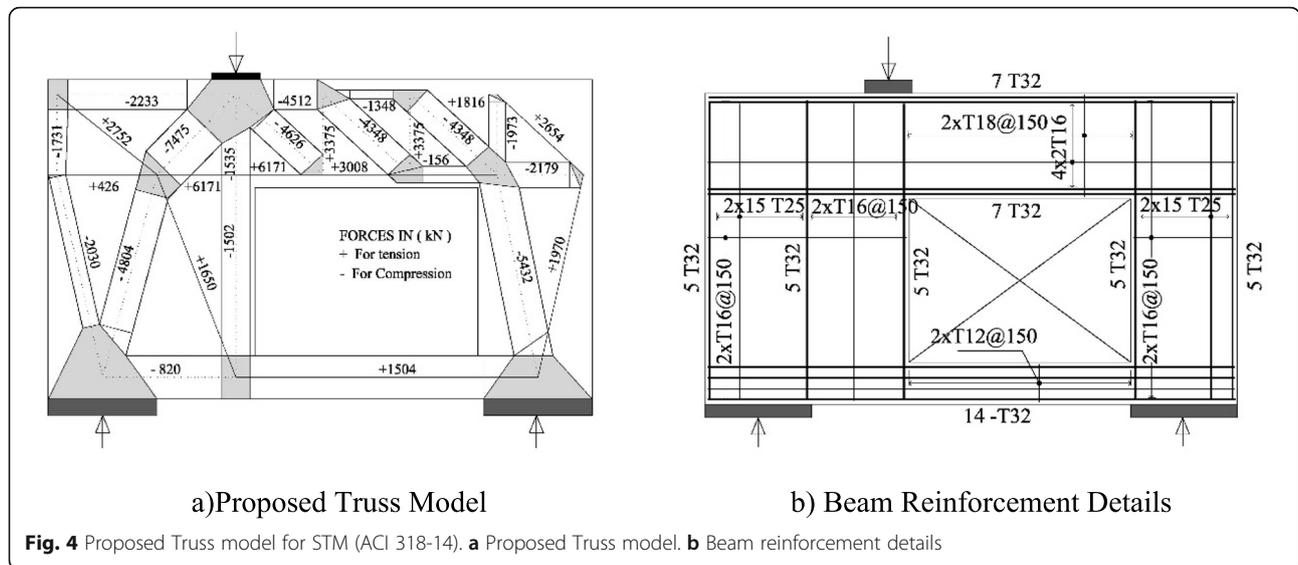


Fig. 3 Mansur [16] model. a Idealization model. b Beam reinforcement details



where

- $A_s$  = area of tension reinforcement in  $\text{mm}^2$ ,
- $A'_s$  = area of compression reinforcement in  $\text{mm}^2$ ,
- $f_s$  = stress in tension reinforcement in MPa,
- $f'_s$  = stress in compression reinforcement in MPa,
- $f'_c$  = specified cylinder compressive strength of concrete in MPa, and
- $b$  = width of member's web in mm.

### 3.3.1 Tie strength

$$A_{st} = \frac{F_u}{\Phi f_{ys}}$$

where

- $F_u$  = Factored ultimate force in the tie,
- $f_{ys}$  = yield strength of the steel, and
- $\Phi$  = resistance factor of 0.75.

### 3.3.2 Strength of the nodal zones

The nominal compression strength at the face of a nodal zone or at any section through the nodal zone shall be

$$F_{nn} = f_{ce} A_n$$

where  $A_n$  is taken as the area of the face of the nodal zone that the strut force  $F_u$  acts on,  $f_{ce}$  is the effective compressive strength of the concrete in the nodal zone and is calculated as  $f_{ce} = 0.85 \beta_n f'_c$ .

The coefficients  $\beta_n$  can be obtained from Table 23.9.2 in ACI 318-14 [17].

### 3.3.3 Strength of the strut

The nominal compressive strength of a strut without longitudinal reinforcement shall be taken as

$$F_{ns} = f_{ce} A_{cs}$$

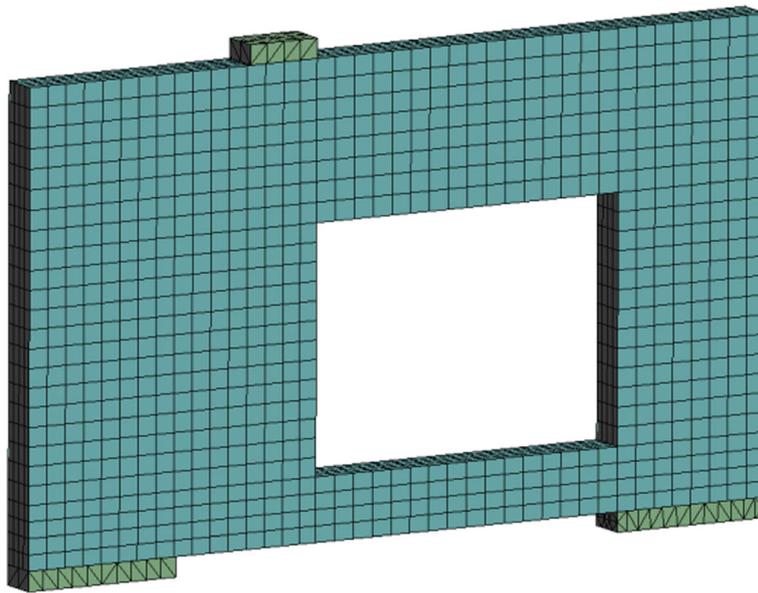
where  $A_{cs}$  is the cross-sectional area at the end of the strut that the strut force  $F_u$  acts on,  $f_{ce}$  is the effective compressive strength of the concrete in the nodal zone and is calculated as  $f_{ce} = 0.85 \beta_s f'_c$ .

The coefficients  $\beta_s$  can be obtained from Table 23.4.3 in ACI 318-14 [17].

The verification of the strut and nodal zone strengths can be obtained by comparison of the available strut or nodal area against the required values. Generally, the thickness of the beam is assumed constant and verification can be provided by comparing the strut or nodal width,  $w_{prov}$  with the required value  $w_{req}$ . The critical nodes and struts have been manually checked for this deep beam however the whole truss is analyzed and checked using cast software.

## 4 Finite element model

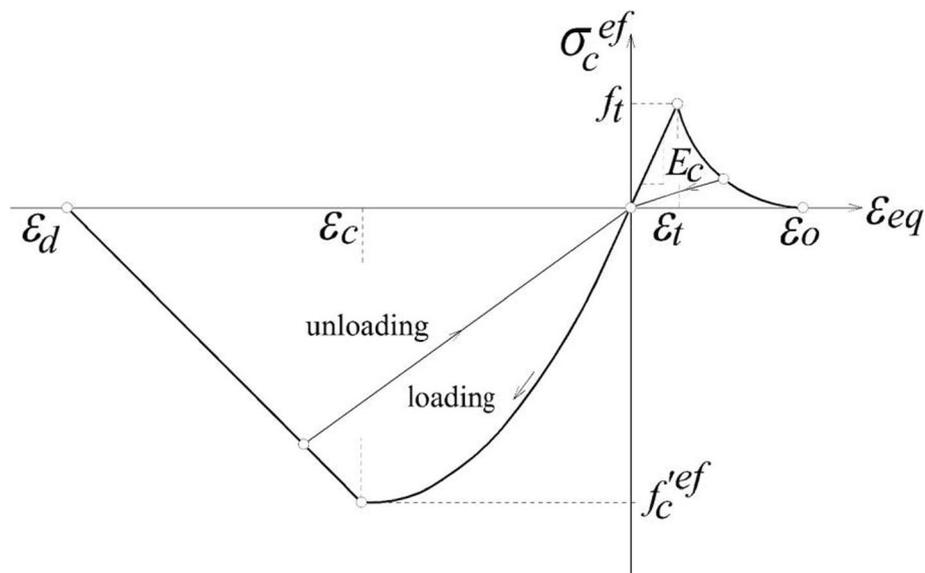
The previously verified finite elements program ATENA [18] is used in this research. Three-dimensional (3D) finite element (FE) models were developed for the analysis of the transfer deep beam. All the models had the same material properties with different reinforcement arrangements and quantities according to the designs of the three methods. The concrete was modeled using 3D solid brick elements with CC3DNonLinCementitious2 Model of the ATENA program. The steel bars were modeled as discrete reinforcement of bilinear stress-strain relationship using truss elements. A sensitivity



**Fig. 5** Finite element model

study was performed to analyze the effect of mesh size. Large size was chosen for the mesh and a finite element run was performed. The mesh size was then reduced in successive runs until the stresses obtained from the successive runs showed no significant change. Finally, it is selected to use four elements for the beam width as recommended by ATENA manual to capture the flexural behavior and to use an element length of 25 cm. The finite element model is shown in Fig. 5. The steel loading plates used in the FE model covered the entire width of

the beam. The model is supported on two plates, one at each end. One end support plate is restrained from movement in the vertical direction ( $Z$ ) and in the out of plane direction ( $Y$ ) with a point support placed at the bottom center of the plate. The other support is restrained in all directions ( $Z$ ,  $X$ , and  $Y$ ) to maintain the model stability and prevent out of plane distortion. A displacement-controlled incremental loading method is employed in the analysis. The iterative solution procedure is based on the Newton-Raphson method.



**Fig. 6** Stress-strain constitutive relationship in the CC3DNonLinCementitious2 Model of ATENA (reference [18])

**Table 1** Material parameters for concrete (reference [18])

Material property	Explanation
$E$ [GPa]	Young's modulus (initial value): $E_0 = (6000 - 15.5f_{cu})\sqrt{f_{cu}}$
$f_t$ [MPa]	Tensile strength: $f_t = 0.24f_{cu}^{2/3}$
$f_c$ [MPa]	Compressive strength: $f_c = 0.80f_{cu}$
$\mathcal{E}_{cp}$	Plastic strain at compression edge: $\mathcal{E}_{cp} = f_c/E_0$
$G_F$ [Pa]	Fracture energy: $G_F = 0.000025f_t$
$w_d$ [m]	Critical compressive displacement = $-0.0005$ m
$\mu$ [-]	Poisons ratio = 0.20
$r_c^{lim}$ [-]	$f_c$ reduction due to lateral tensile strain = 0.80

**4.1 Constitutive model for structural concrete**

Two stages describe the nonlinear behavior of concrete in the case of static loading. The initial stage is prior to the crack initiation where the material is modeled using a linear-elastic relationship. After cracking, several constitutive relationships can describe the 3D nonlinear behavior of structural concrete such as elastic-plastic, fracture-plastic, and smeared-crack failure.

The nonlinear behavior is to be modeled using the fracture-plastic model (CC3DNonLinCementitious2) which can describe all phases of concrete including cracking, crushing, and plastic behavior. This model combines the constitutive relations for tensile (fracture) and compressive (plastic) responses as shown in Fig. 6.

The input parameters of the finite element (FE) model have been used as the default calculated according to EuroCode2 (EC2) and CEP-FIP MC90 [22] model code expressions as indicated in Table 1.

**4.2 Reinforcement constitutive model**

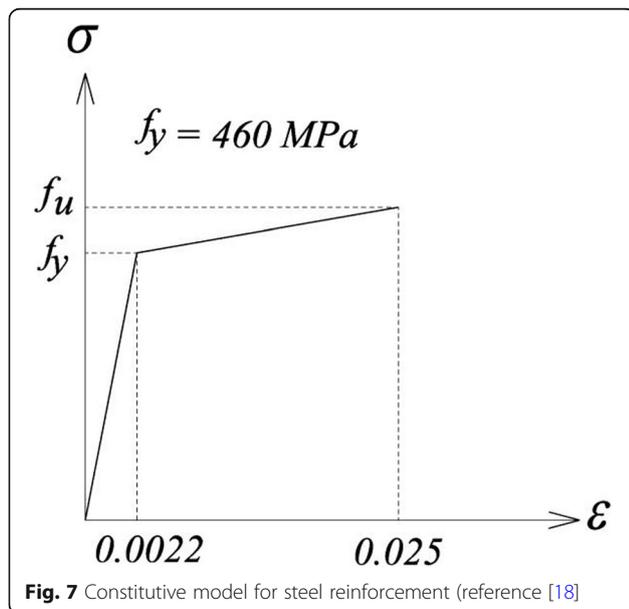
In this work, discrete bar elements were used to model the reinforcement assuming a bilinear stress-strain relationship that considers strain hardening which allows the stresses to increase after yielding. The input data for the bilinear constitutive model are shown in Fig. 7 where the yield stress is 460 MPa, the ultimate stress is 560 MPa, and the ultimate strain is 0.025.

**5 Results of crack patterns and failure modes**

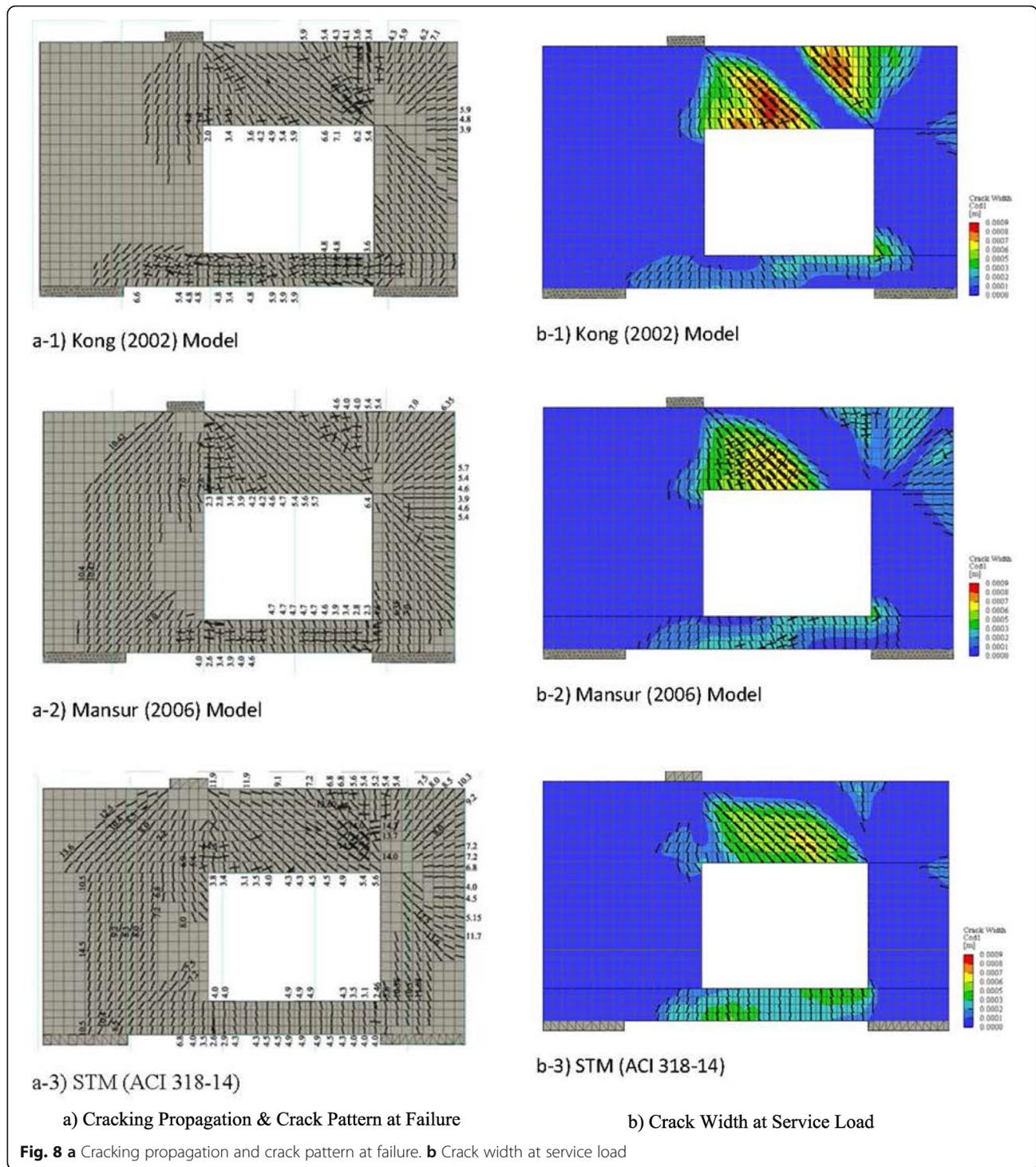
In this part, the output from the finite element models is used to evaluate the three design approaches and determine the most efficient design method for a transfer deep beam with large opening.

Failure modes and cracking patterns varied among the specimens. The location and amount of the main flexural and shear reinforcement change from one approach to another which affect the cracks' initiation, crack pattern at failure, and failure mode. Generally, the cracks initiate at the chord which does not contain the main flexural reinforcement. Figure 8 and Table 2 show the crack propagation with the load and crack width at service load for the three design approaches: Kong. F.K [15], Mansur [16], and STM, respectively. Figure 9 and Table 3 show principal concrete compression strain at failure, and steel tensile stress at failure resulted from the numerical analysis for the three approaches.

The empirical approach suggested by Kong. F.K [15] produces main reinforcement at the bottom chord as shown in Fig. 2. At an approximate load of 2 MN, a vertical crack starts to develop at the top left corner of the opening below the point of load application. At an approximate load of 3.4 MN, more cracks were developed at the beam top right surface and near the bottom right corner of the opening. With the load increase, diagonal cracks start to form and spread over the top chord. The failure of this specimen mainly occurred due to extensive shear cracks present at the top chord on the right side. At a load of 9.8 MN, the reinforcement starts yielding at the top left corner of the opening and the top right surface of the beam. Most of the shear



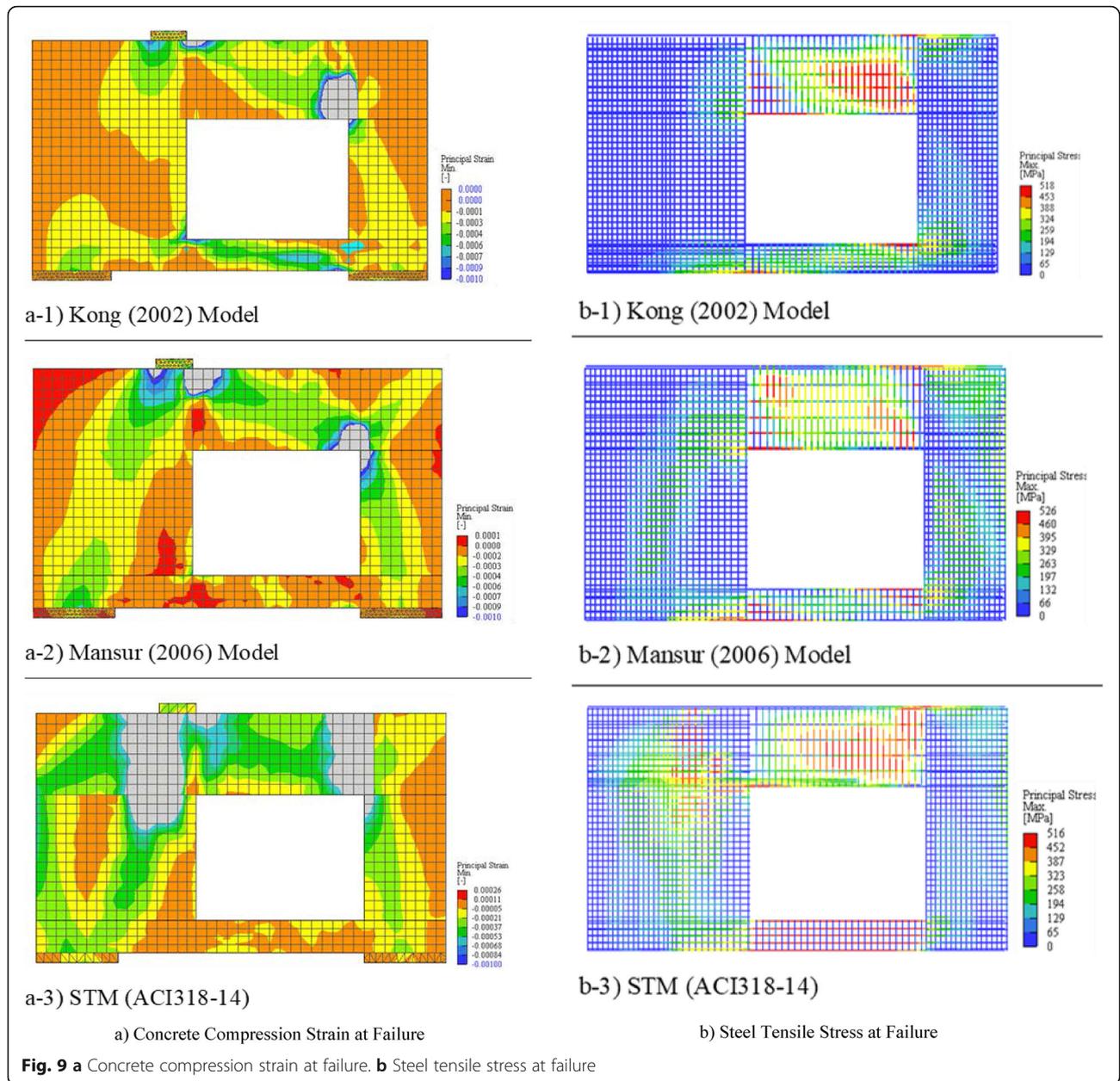
**Fig. 7** Constitutive model for steel reinforcement (reference [18])



**Table 2** Service loads and max. crack widths for the different models

Model	Service load (MN)	Maximum crack width (mm)
Kong, F.K [11]	6.0	0.8
Mansur [14]	6.0	0.6
STM (ACI 318-14)	6.0	0.6

reinforcement of the top chord reach the yield point at the same load. The bottom crack was narrow due to the presence of the main reinforcement. At the service load of approximately 6 MN (assumed to be 60% of the ultimate design load), the crack width at the top chord was about 0.8 mm while the crack width at the bottom



**Table 3** Max. concrete compressive strain and max. steel tensile stress at failure for the different models

Model	Maximum concrete compressive strain at failure	Maximum steel tensile stress at failure (N/mm <sup>2</sup> )
Kong. F.K [11]	0.0012	0.025
Mansur [14]	0.0015	0.025
STM (ACI 318-14)	0.0017	0.025

chord was 0.2 mm. Fig. 8b-1 and Table 2 show the crack width at service load.

In the specimen designed and detailed using the Mansur [16] method, the vertical cracks start at the top left and bottom right corners of the opening at an approximate higher load (compared to Kong, F.K [15] model) of 2.3 MN. At a load of 4.0 MN, diagonal cracks start to form at the top left corner of the opening in addition to the development of vertical cracks at the top right and bottom left surfaces of the beam. At the service load of 6.0 MN, the maximum crack width at the bottom chord was 0.3 mm while the one at the top was 0.6 mm as shown in Table 2. The yield point of the reinforcement starts at approximately 11.8 MN at the left upper corner of the opening. Failure occurs due to the presence of extensive shear crack at the left side of the upper chord.

The specimen detailed using the STM method starts to develop cracks at the lower chord at an approximate load of 2.5 MN. The cracks at the upper chord initiate at a higher load of 3.8 MN. At load of 14.81 MN, the concrete in the model reaches its tensile strength cracking at the right section of the upper chord and some sudden deflection occurs resulting in a redistribution of the forces. Finally, more reinforcements undergo yield. Parts a-3 and b-3 of Fig. 9 and Table 3 show the steel stress and concrete strain at the ultimate load. The crack width at the service load for the bottom chord is 0.3 mm while the one at the top chord is 0.6 mm. The yield point of the reinforcement at the lower chord starts at an approximate load of 9.0 MN while at the upper chord, the reinforcement starts yielding at a higher load

of 14 MN. The location of the yielded reinforcement is at the left part of the tie and stirrups on the right. It can be observed that the model details using the STM method are capable to develop and spread the yield of reinforcement over a large area in both shear and bending.

## 6 Deflection results

The load-deflection curves resulted from the numerical analyses for the three design approaches are presented in Figure 10. The failure loads, deflection at service and ultimate loads, and crack widths are summarized in Table 4. From the load-deflection curves it can be observed that the deflection is approximately the same for all the three models at the service loads. At loads close to the ultimate design value of approximately 9 MN, the stiffness of the beam reduces and exhibits faster deflection for the specimen designed and detailed using the Kong, F.K [15] model with the failure occurring close to the ultimate design load. The other two specimens behave similarly up to the failure load. The stiffness is reduced at a load of 12 MN, which is higher than the ultimate design load.

## 7 Deflection discussion

After the failure, the load decreases suddenly for all specimens except for the specimen designed and detailed using the STM method. The specimen designed according to the STM method restores its capacity and develops more deflection after the initial drop and this indicates that the load can be redistributed and find

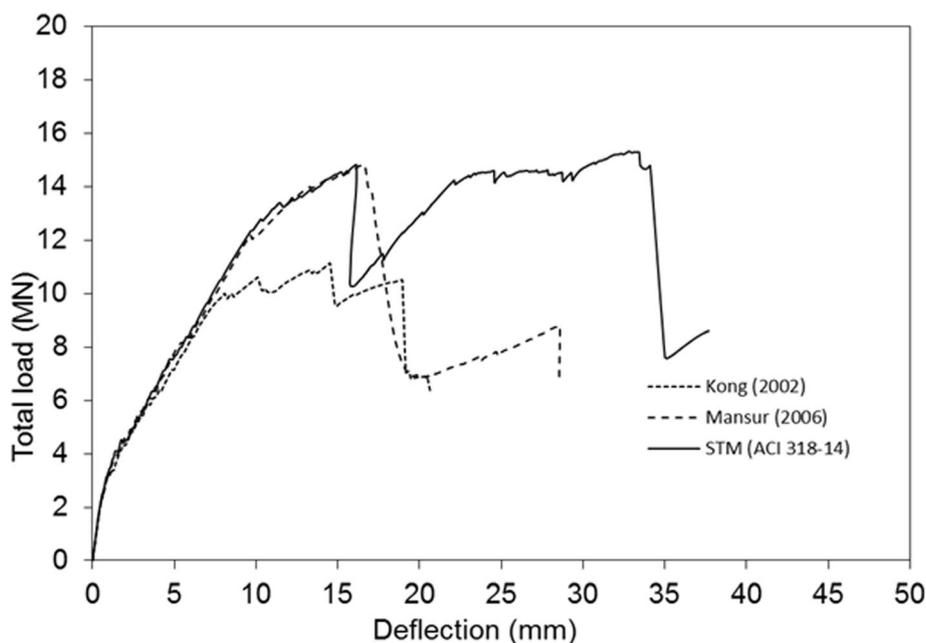


Fig. 10 Load-deflection curves of a transfer deep beam from the FE analyses for the designs of the three approaches

**Table 4** Results from the numerical models

Design approach	Ultimate load (MN)	Deflection at service load (mm)	Ultimate deflection (mm)
Kong. F.K [15]	10.93	3.68	16.14
Mansur [16]	14.81	3.39	16.72
STM (ACI 318-14 [17])	15.29	3.42	33.34

other alternative load paths after failure in any of its parts. The deflection value can be compared at the serviceability limit. The criterion for the deflection limit is the amount of displacement compared to the span over 500. All these designs satisfy the deflection serviceability limit.

## 8 Conclusions

- 1- The results of the finite element non-linear analyses of transfer deep beams with large openings show that the designs obtained with the three different approaches (Kong. F.K [15], Mansur [16], and the STM method (ACI 318-14 [17]) provide sufficient ultimate load capacity values.
- 2- At service load for all the three design models, the maximum width of cracks was observed near the mid-span of the top chord. The maximum crack width for beams designed according to Mansur [16] and STM (ACI 318-14 [17]) was approximately 0.6 mm and for beams designed according to Kong. F.K [15] was 0.8 mm. Additional reinforcement may be required to limit the crack width to the design value of 0.30 mm at the service stage.
- 3- The approach proposed by Mansur [16] may be considered efficient for the design of deep beams with large openings as it considers that the concrete members around the opening will follow a Vierendeel truss action and deals with chord members above and below the opening as an eccentrically loaded members. Designs using this method show considerable higher failure loads compared with the design ultimate load with cost-beneficial reinforcement ratios.
- 4- Comparing the Kong. F.K [15] and Mansur [16] approaches, it is observed that the amount of steel used in both approaches is approximately the same, with the difference in the arrangement of the steel.
- 5- The results from the analyses of the designs according to the STM method (ACI 318-14 [17]) and Mansur [16] method provide an adequate margin in the model capacity in which the numerical load/design load = 1.52 and 1.48, respectively. This indicates that placing the main reinforcement in the top chord in the present transfer beam was most effective in

transferring the loads to the supports. Further investigation is recommended to study various stiffness ratios between the top and bottom chords.

- 6- The reinforcement amount used in the STM method was approximate 25% more than the reinforcement utilized by the other two methods which had the same amount of reinforcement.
- 7- The deep beam designed according to STM method (ACI318-14) shows better ductility compared to the designs of the Kong. F.K [15] and Mansur [16] methods.
- 8- The three design models give deep beam which satisfy the deflection limit.
- 9- The current study considers transfer beams under static loads. Further investigations can be extended to consider the effect of cyclic loads.

### Abbreviations

FE: Finite element; STM: Strut and tie method

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### Authors' contributions

E.I.: acquisition, analysis. M.S.I.: acquisition, analysis. K.E.: drafted the work. All authors have read and approved the manuscript.

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### References

1. El-kareim A, Arafat A, Hassanin A, Atef M, Saber A (2020) Behavior and Strength of Reinforced Concrete Flanged Deep Beams with Web Opening. Structures 27:506–524
2. Hassan HM, Arab MA, El-kassas AI (2019) Behavior of High Strength Self Compacted Concrete Deep Beams with Web Openings. Heliyon 5:e01524
3. Yang K-H, Eun H-C, Chung H-S (2006) The Influence of Web Openings on the Structural Behavior of Reinforced High-Strength Concrete Deep Beams. Eng Struct 28:1825–1834
4. Campione G, Minafo G (2012) Behavior of Concrete Deep Beams with Openings and Low Shear Span-to-Depth Ratio. Eng Struct 41:294–306
5. Mohamed AR, Shoukry MS, Saeed JM (2014) Prediction of the Behavior of Reinforced Concrete Deep Beams with Web Openings using the Finite Element Method. Alexandria Eng J 53:329–339
6. El-Kassas AI, Hassan HM, Arab MA (2020) Effect of Longitudinal Opening on the Structural Behavior of Reinforced High-Strength Self-Compacted Concrete Deep Beams. Case Stud Constr Mater 12:1–10
7. Tseng C-C, Hwang S-J, Lu W-Y (2017) Shear Strength Prediction of Reinforced Concrete Deep Beams with Web Openings. ACI Struct J 114(6): 1569–1579

8. Maxwell BS, Breen JE (2000) Experimental Evaluation of Strut-and-Tie Model Applied to Deep Beam with Opening. *ACI Struct J* 97:142–149
9. Kong FK, Sharp GR (1977) Structural Idealization for Deep Beams with Web Openings. *Mag Concr Res* 29(99):81–91
10. Kong FK, Sharp GR (1978) Structural Idealization for Deep Beams with Web Openings: Further Evidence. *Mag Concr Res* 30(103):89–95
11. Ray DP (1966) An Investigation into the ultimate strength of reinforced concrete deep beams. *J Sci Eng Res India Inst Technol Kharagpur* 10:221–238
12. Ashour AF, Rishi G (2000) Test of Reinforced Concrete Continuous Deep Beams with Web Openings. *ACI Struct J* 97:418–426
13. Ray SP (1980) Behavior and Ultimate Shear Strength of Reinforced Concrete Deep Beams with and without Opening in Web. In: PhD thesis, Indian Institute of Technology, Kharagpur, India
14. Tan KH, Tong K, Tang CY (2003) Consistent Strut and Tie Modelling of Deep Beams with Web Openings. *Mag Concr Res* 55:67–75
15. Kong FK (2002) Reinforced Concrete Deep Beams. Taylor & Francis Books, Inc., New York
16. Mansur MA (2006) Design of Reinforced Concrete Beams with Web Openings. In: Proceedings of the 6th Asia-Pacific Structural Engineering and Construction Conference (ASPEC), Kuala Lumpur, Malaysia
17. ACI (American Concrete Institute, and International Organization for Standardization) (2014) Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary, Farmington Hills
18. ATENA Program Documentation (2009). Cervenka Consulting, Prague, Czech Republic.
19. Maaddawy TA, Sherif S (2009) FRP Composites for Shear Strengthening of Reinforced Concrete Deep Beams with Openings. *Compos Struct* 89(1):60–69
20. Markou G, AlHamaydeh M (2018) 3D Finite Element Modeling of GFRP-Reinforced Concrete Deep Beams without Shear Reinforcement. *Int J Comput Methods* 15.02(2018):1850001
21. CIRIA (Construction Industry and Research Information Association), CIRIA Guide 2 (1977) The Design of Deep Beams in Reinforced Concrete. In: Ove Arup and Partners, Construction Industry Research and Information Association, London, UK
22. CEB-FIP (Comité Euro-International du Béton) (1993) CEB-FIP Model Code 1990. In: Bulletin d'information, 213/214, Lausanne, Switzerland, pp 33–51

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