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Investigation of structural behavior of reinforced concrete deep beams with regular geometric openings using finite element method

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ABSTRACT

Reinforced concrete deep beams have begun to be widely used in the design and production of reinforced concrete structures today, thanks to their contribution to structural behavior. Since the height and span values of the deep beams are close to each other, there are situations where openings are left in the deep beam body for the installation of electricity, water, sewage, communication, heating and ventilation installations of the buildings. Due to the placement and geometric shape of these openings left in the beam body, much more complex changes in structural behavior are observed, and nonlinear approaches come to the fore in stress and strain calculations. In this study, the modification of the structural behavior of a deep beam in the presence of regular geometric openings is investigated using the finite element method. The study was carried out in four phases and in the first phase, the appropriate size and material properties of the deep beam elements with regular openings were determined. In the second stage, the deep beam elements whose dimensions, material properties and reinforcement details were determined were modeled with ABAQUS software using finite element modeling technique. In the third phase, the load arrangement to be applied to the deep beam was determined, and in the last phase, the displacement-controlled static analysis of the deep beam was performed depending on the determined loading arrangement. The aim of the study is to determine the impact of regular geometric spans in the deep beam web on the collapse behavior, maximum load carrying capacity, ductility and stiffness of the beam.

I. INTRODUCTION

Although the definition of a deep beam varies depending on the scientific literature and building codes of different countries, according to ACI 318-19 [1], beams that meet at least one of the M<4D or k<2D (M: beam net span, D: ultimate depth of beam, k: shear span) conditions are defined as deep beams. Today, deep beams are used in industrial, port and offshore structures, in header beams in pile foundation applications, as partition walls in high-rise buildings, in transferring loads to the support in large-area halls, warehouses and silos, and are one of the building elements whose usage area is growing day by day (Figure 1).

Reinforced concrete deep beams are quite different from conventional beams in terms of both structural and dynamic behavior. In this respect, all parameters affecting the structural and dynamic behavior of deep beams should be considered in the design of deep beams. This is because, even in the case of only simple bending in reinforced concrete deep beams, the Bernoulli-Navier that plane sections remain plane after bending, which is valid for conventional beams, loses its validity. Conclusion, the stress and strain distribution in the elevation direction in deep beams, which behave as a vertical plate loaded in-plane, is not uniform as in conventional beams, but varies. Stress distributions in conventional beams and deep beams under load are shown in Figure 2. Therefore, it is clear that the stresses calculated by conventional methods are not useful in the analysis of deep beams. Thus,

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in deep beam analysis, the problem should be considered as a two-dimensional plane stress problem and appropriate methods should be used for realistic results [2].

In addition, since the ratio of the shear span to the useful height is very small in such beams, the bending effect loses its importance and the shear effect comes to the fore in the behavior, causing the amount of tensile reinforcement to remain at low values. Therefore, there is a need to take precautions against lateral buckling in the nonlinear behavior of deep beams and winding problems for tension reinforcement. Three collapse situations that need to be taken into consideration when sizing and reinforcing deep reinforced concrete beams without openings can be explained as follows [3]: a) If the horizontal and vertical body reinforcements reach the limit state, the inclined cracks caused by the principal tensile stresses may cause collapse. b) The beam may lose it carrying capacity due to the principal compressive stresses that cause concrete to crush, c) If sufficient reinforcement is not used, the clamping in the support area may be lost and the support may crush.

Figure 1. Application areas of reinforced concrete deep beams

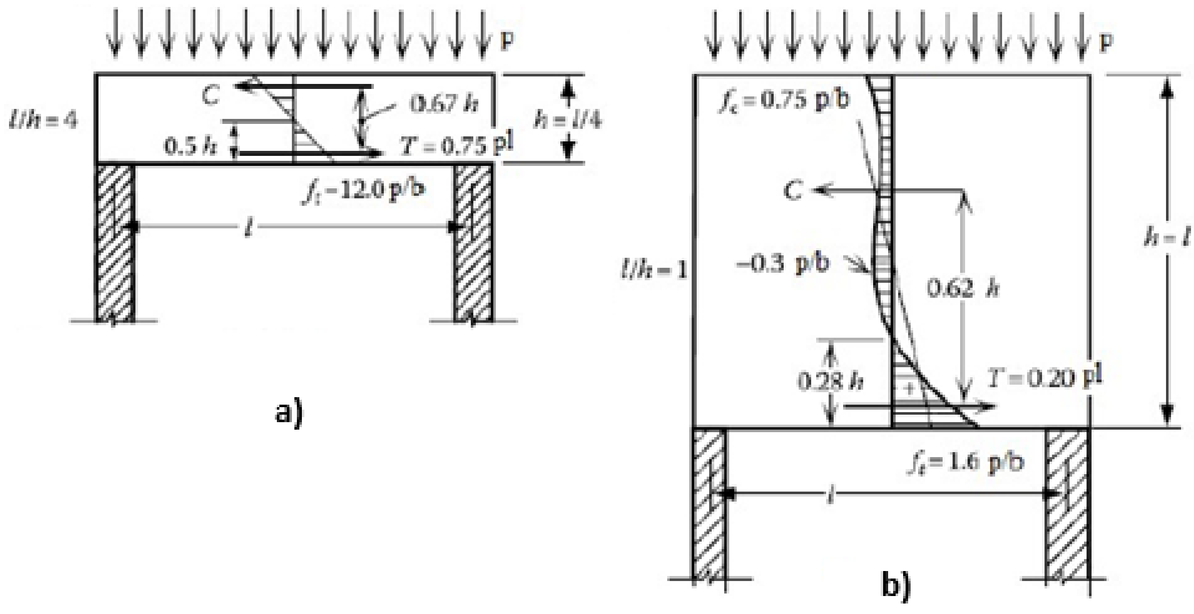


Figure 2. Stress distributions in beams a) conventional beam b) deep beam

Figure 3a shows the main trajectories in deep beams loaded from above. The solid and dashed lines show the distribution of tensile and compressive stresses, respectively. Large and heavy loads acting on concrete create vertical cracks as seen in Figure 3b. Vertical cracks are perpendicular to the principal tensile stresses and parallel to the stress trajectories indicated by the dashed line. The grid reinforcement arrangement placed within the reinforced concrete section meets these principal stresses. In addition, the flexural reinforcement that counteracts the tensile effects must be present up to 1/5 of the beam depth (Figure 3a).

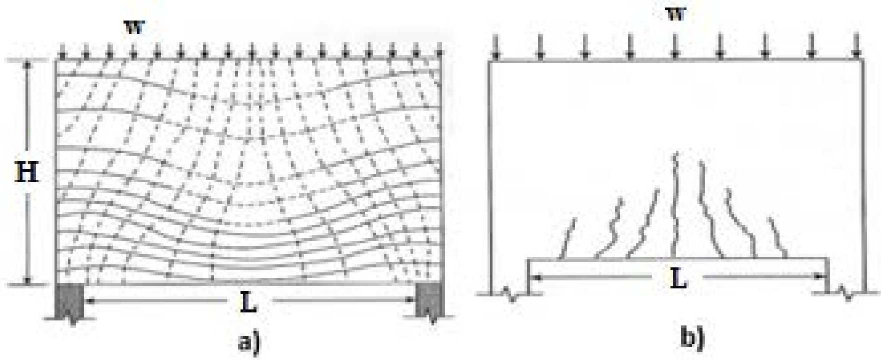


Figure 3. Stress distributions in deep beams a) solid lines for tension, dashed lines for compression b) Crack distribution [4]

In many studies in literature, different problems that cause collapse in deep beams have been discussed in detail. These are properties related to section geometry, concrete strength class, steel reinforcement ratio, presence of openings and geometrical properties of openings. However, when the above-mentioned failures of deep beams are considered, it is understood that the shear strength has a great effect on the failure. In this case, it is obvious that the openings to be left in the body of deep beams will cause a major decrease in the shear strength of the beam but will greatly affect the structural behavior. In the literature, there are extensive and numerous studies on the effect of shear strength on the structural behavior of deep beams with and without openings. [5-9]. However, the number of studies on deep beams with regular openings is quite limited [10]. Ashour and Rishi (2000) [11] concentrated their research on deep beams with rectangular-shaped openings. In the study, the location of the openings and the properties of the opening cross-section were considered as variable parameters. Depending on this, it is determined how the behavior will change. As a conclusion of the study, it was determined that the resistance of the deep beam against shear stresses depends more on the reinforcement arrangement in the vertical direction and the location of the opening on the deep beam is more effective in determining the deformations that occur. They also noted that the location of the openings has a major influence on the collapse mode. Özkal (2017) [12] determined that circular openings are more favorable in terms of stress concentrations than quadrilateral openings in his study on opening deep beams. In addition, in his study, he determined that if the body cavity is rectangular, the stiffness value is high. However, in this study, the structural behavior in the case of one or more openings in the deep beam body is investigated. The presence of one or more openings causes the stresses to be concentrated around these openings, thus causing fractures to occur with the loss of shear bearing strength before reaching the bending bearing strength. Since shear fractures are an extremely unfavorable and undesirable type of brittle fracture, it is necessary to design opening designs to prevent shear fracture in deep beams with openings. Hu et al. (2007) [13] subjected six deep beams with simple bearings to four-point bending tests in their study. In these tests, the openings on the deep beams were trapezoidal in cross-section and the beam spans varied. When the position of the opening in the deep beam is between the beam support and the point where the bending load is applied and does not prevent the formation of the upright assumed to be formed, there is no major decrease in the strength of the beam. In this case, a meaningful comparison can be made with the deep beam with no opening. Nair and Kavitha (2015) [14] analyze seven deep beams with opening with dimensions of 200 x 400 x 800 mm and different dimensions and cross-sectional properties under a monocentric force using ANSYS software. The reduction in the carrying capacity of the reinforced concrete deep beam was calculated as 3% for the deep beam with circular or rectangular openings, 19% for the deep beam with circular openings close to the support, 23% for the deep beam with rectangular openings close to the support and 38% for the deep beam with circular openings close to both supports with respect to the deep beam without openings. Kadhim and Kadhim (2021) compared 14 deep beams in which rubber was used instead of aggregate in terms of shear behavior. It was determined that the deflection increased but the carrying capacity decreased by 32% in the deep beam produced by using rubber instead of 20% of the large and fine aggregate volume. In addition, a 37% improvement in ductility was determined in the deep beam. Al-Mahbashi et al (2023) [16] carried out a study on five two-span deep beams using high strength concrete in which opening shape and location were considered as variable parameters. Circular and rectangular openings with the same height and area were used in the study. In the experimental and numerical studies carried out in accordance with the four-point bending test setup, the location of the opening was chosen as the region where the deep beam is most vulnerable to shear effects. As a result of the study, it was determined that if there are two openings in the same span, the collapse load decreases by 38% compared to the deep beam without openings, regardless of the shape of the opening. In the case of an opening in each span, it was determined that there was a 41% decrease if the opening shape was circular and a 45% decrease if it was rectangular.

In addition to the studies mentioned above in the previous literature, many studies have been carried out on the location and geometric structure of the openings to be left on the reinforced concrete beam with conventional structure. In such a case, the reinforced concrete deep beam may crack even under the effect of service load. In her study, Quadri [17] conducted an experimental study for reinforced concrete deep beams with and without openings loaded monotonically from three points. Eight reinforced concrete deep beams with a shear span to depth ratio of 1.04 were used in the study. Three of these deep beams are designed to have no openings, while the others are designed to have one opening each at the support and in the middle span. At the conclusion of the study, it was determined that the shear reinforcement used to meet shear stresses increased the deep beam carrying capacity and ductility by 70% - 300%.

In addition to the above-mentioned literature, there are many studies investigating the change in the behavior of conventional reinforced concrete beams depending on the opening shape and location. Amiri and Masoudnia (2011) [18] formed two circular openings on a conventional reinforced concrete beam span with dimensions of 250 x 150 x 2000mm (height x width x span). The relationship between the bearing capacity of the beam and the size of the opening was investigated using numerical methods. These investigations using Ansys software showed that leaving an opening in each shear span does not significantly affect the bearing strength of the beam for cases where the diameter of the circular opening is less than 48% of the beam height. However, the fact that this study is limited only to conventional beams, the lack of a variety of opening geometry and the creation of the openings only in the shear span limit the study in this sense. Dündar (2008) [19] investigated in detail the behavior of reinforced concrete beams with many regular circular, rectangular and triangular openings along the span. In this study, it was determined that the use of diagonal reinforcement significantly improves the behavior of reinforced concrete beams with regular openings. In addition, it was determined that it contributed significantly to the ductility and energy absorption capacity of the beam. However, since the study was carried out on conventional beams, it could not be determined whether the use of diagonal reinforcement would have the same positive effects for deep beams. Aykaç and Yılmaz (2011) [20] experimentally investigated the behavior of reinforced concrete continuous beams with regular body openings under uniform loads. In the experimental study, it was determined that conventional beams with low and normal tensile reinforcement ratios showed sufficient strength and ductility, but no sufficient success was obtained for conventional beams with highly reinforcement. For this reason, studies should be continued according to different reinforcement arrangement techniques in highly reinforced conventional beams. Considering that a similar situation may be encountered in reinforced concrete deep beams, it is necessary to determine a reinforcement arrangement in which sufficient strength and ductility can be provided in a highly reinforced condition. Kalkan (2014) [21] investigated the in-plane bending behavior of conventional reinforced concrete beams with regular openings and their deflections under service loads. Analytical values obtained from the formulae available in the literature were compared with the test results of specimens with various reinforcement arrangements. However, the study was conducted only on conventional beams. The interpretations and evaluations made for conventional beams do not apply to deep beams. Because the structural behavior of deep beams and conventional beams are very different from each other.

As can be clearly seen from the literature given so far, many studies have been carried out and continue to be carried out on the change in the behavior of conventional reinforced concrete beams and deep beams depending on the opening geometry and location. In these studies, the change in the behavior by placing an opening in any part of the beam has been discussed. This causes stresses to accumulate around this opening and inconsistencies in the behavior of the beam. However, studies on reinforced concrete deep beams with regular openings and the effect of opening geometry on the behavior of these beams are very limited. From this point of view, it is aimed to make an important contribution to the literature on how the effect of regular geometric openings to be formed on the deep beam on the lateral load carrying capacity, stiffness and energy consumption capacity of the beam will change the behavior. In this study, the effect of the reduction in the lateral load carrying capacity, energy absorption capacity and flexural stiffness due to regular openings in deep beams on the ratio and shear behavior will be investigated.

In buildings where deep beams are used, it is very common to carry out installations such as plumbing, waste water installation, electrical and telephone cables, heating pipes and ventilation ducts from the ceiling. In these applications, instead of installing the installation around the deep beam, it is also common in these applications to manually create an opening in the deep beam body. It is obvious that such applications in the beam body will have unfavorable static results. Since the position of the regular openings to be left on the deep beam will be investigated with this study, it is thought that this unfavorable and inappropriate application will be eliminated.

II. MATERIALS AND METHOD

In this research paper, deep beams without voids and deep beams with voids of various cross-sections and dimensions are considered. Figure 4 and Figure 5 show the size and cross-sectional properties and reinforcement arrangement of the deep beams without and with voids, respectively. The six deep beams with voids are compared with a reference deep beam without voids. The control deep beam and all other deep beams are designed in accordance with ACI 318-19 [1, 16].

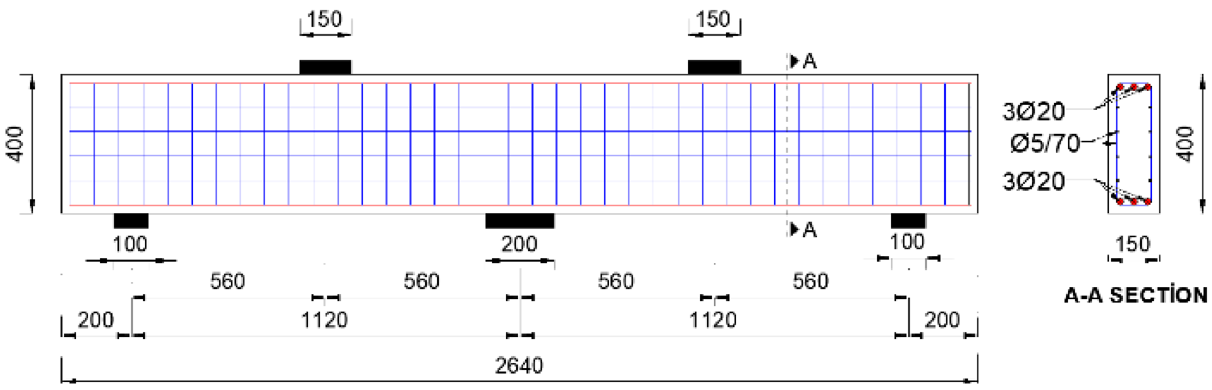
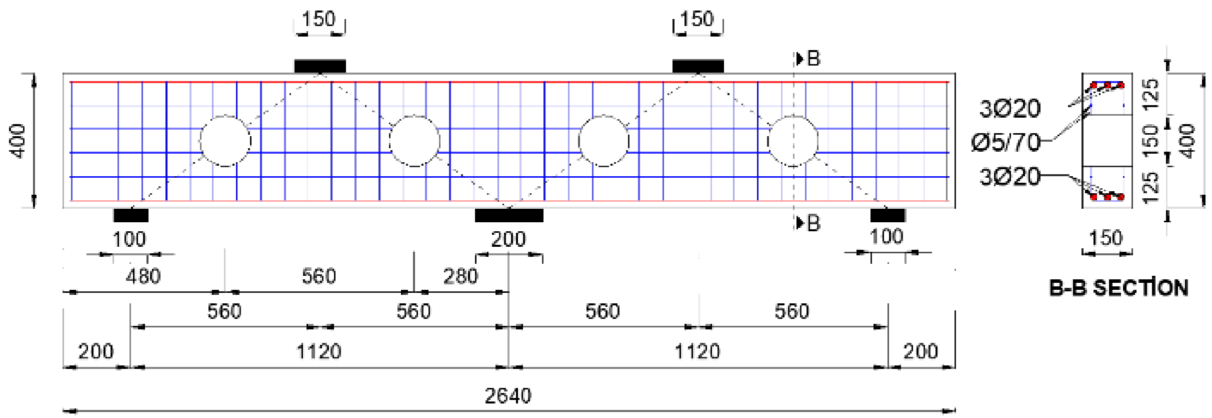


Figure 4. Control deep beam (RCDB-R) size and cross-sectional properties with reinforcement arrangement (Unit: mm)

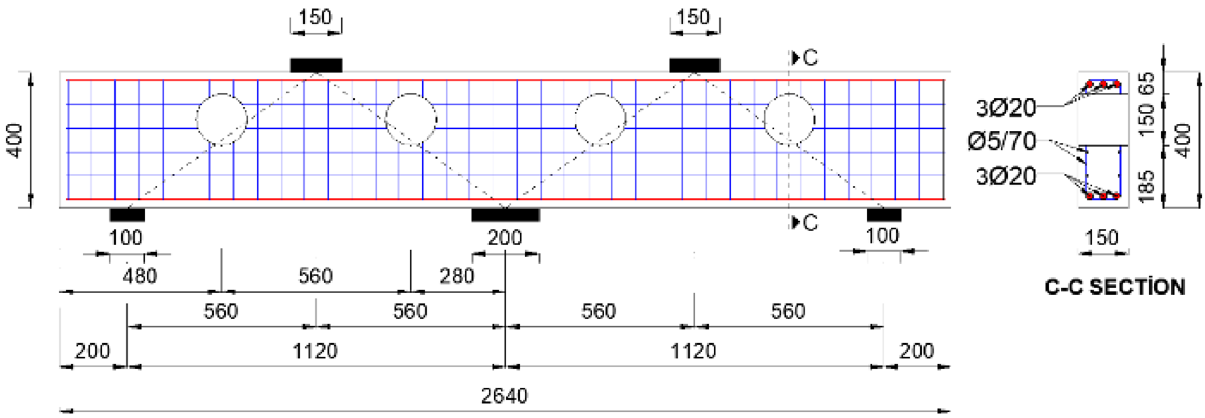
All deep beams in the study have a rectangular cross section of 150 x 400 mm and a length of 2640 mm. C30/37 strength concrete was used in all deep beams. Longitudinal 3Ø20 reinforcement was used at the upper and bottom of the deep beam and transverse reinforcement was placed throughout the entire length of the beam in both vertical and horizontal directions to conform to the minimum requirements of ACI 318-19 [1]. All transverse reinforcements were arranged with 70 mm spacing in vertical and horizontal direction to meet the maximum spacing and minimum reinforcement percentage of ACI 318-19 [1]. The mechanical properties of all reinforcement and concrete are shown in Table 1.

In deep beams with two spans, each opening is in the center of the shear spans along the deep beam. Two different span positions were considered. In the first one, in the middle of the shear spans, 125 mm from the beam geometric center to the top and bottom surfaces of the beam, and in the second one, in the middle of the shear spans, 65 mm from the beam geometric center to the top surface and 185 mm to the bottom surface (Figure 5). The locations considered include the most critical possible scenarios for deep beams with two spans. The openings in all deep beam elements are of circular and rectangular geometry with the same area (17663 mm^2).

In addition, the positioning of the openings is intended to make the best use of the ceiling heights in buildings with deep beam elements.



(a)



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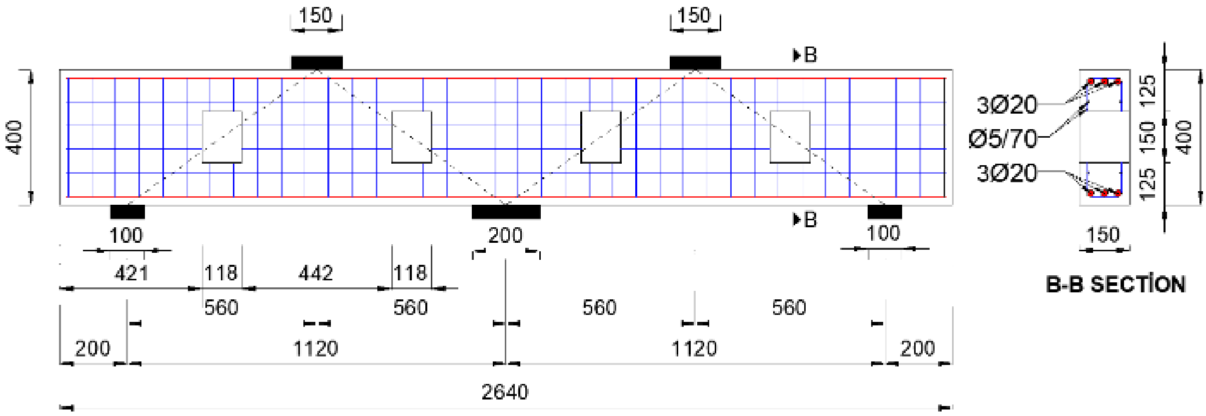

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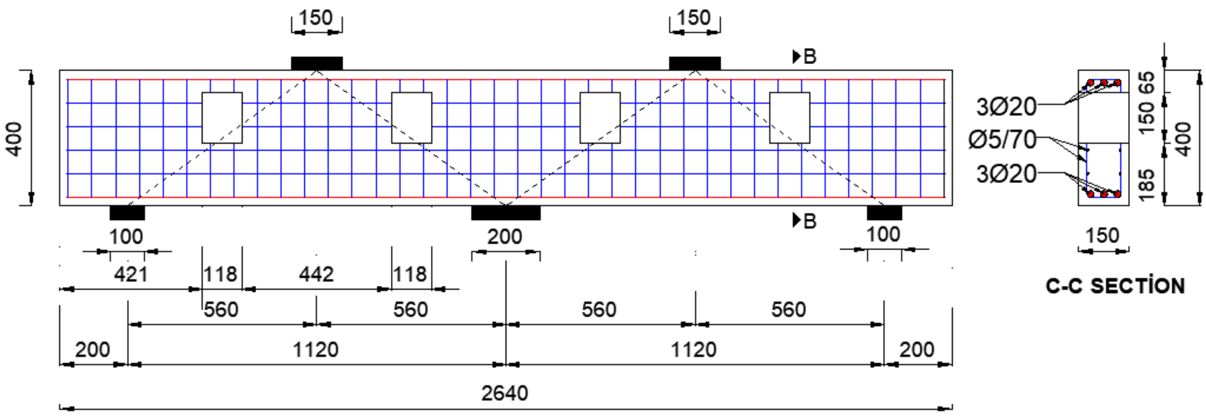


(d)

Figure 5. Dimensional and cross-sectional properties with reinforcement arrangement of regular opening deep beams: a) RCDB-1 b) RCDB-2 c) RCDB-3 d) RCDB-4 (Unit: mm)

2.1 Creation of Deep Beam Finite Element Models

Finite element models of deep beam elements were created using ABAQUS [22] package program. The dimensions of the element to be modelled in numerical analyses and the finite element mesh dimensions to be used directly affect the time and result of the analyses to be performed. In this direction, to shorten the analysis time and to accurately identify both crushing and cracks that may occur in the concrete, the finite element mesh is composed of 100 x 100 mm elements. Figure 6 and Figure 7 show the finite element models generated using the ABAQUS [22] package for the deep beam elements.

Table 1. Mechanical properties of reinforcement and concrete

Concrete			
Density (kg/m^3)		2400.0	
Compressive strength (MPa)		30.0	
Poisson ratio		0.2	
Elastic modulus (MPa)		26400	
Steel rebars	**Ø20**	**Ø5**	**Plates**
Density (kg/m^3)	7849	7849	7849
Poisson rate	0.3	0.3	0.3
Elastic modulus (GPa)	200	200	200
Yield stress (MPa)	553	526	240
Ultimate stress (MPa)	1338	0	0

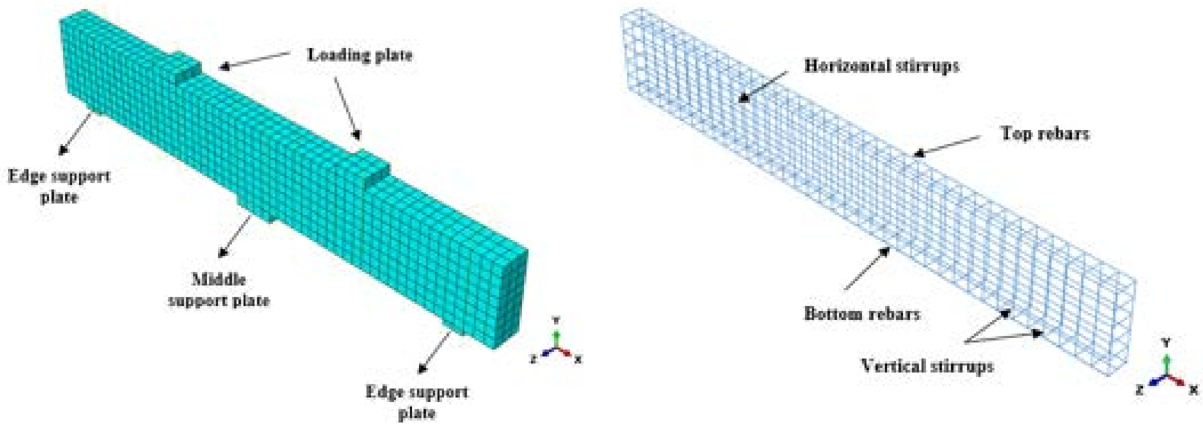


Figure 6. Finite element model of deep beam without openings (RCDB-R)

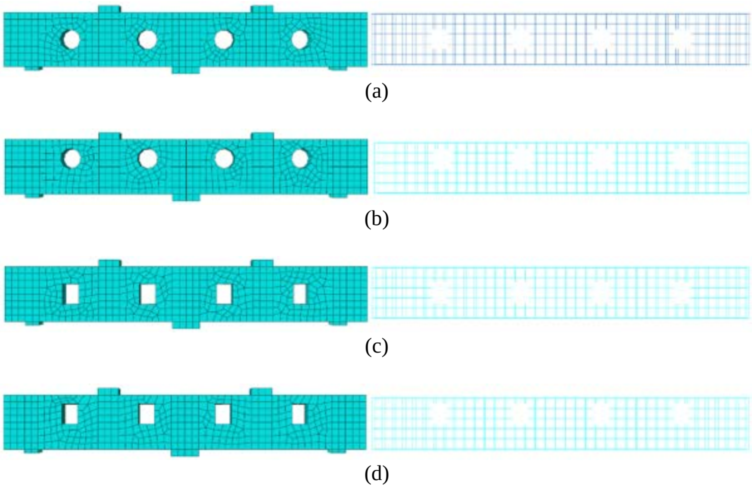


Figure 7. Finite element models of deep beams with regular openings: a) RCDB-1 b) RCDB-2 c) RCDB-3 d) RCDB-4

In order to obtain the correct structural behavior in finite element models of reinforced concrete deep beam elements, it is extremely important to simulate the actual behavior of concrete and steel reinforcement. In this direction, a 3-dimensional and 8-node continuous solid element (C3D8R) type was selected (Figure 8a), which best reflects the cracking and crushing behavior of the concrete material with load, displacement and plastic strain. Transverse and longitudinal reinforcements in the finite element model of the deep beam were modelled using a 3-dimensional bar element (T3D2) type with 2 nodes (Figure 8b).

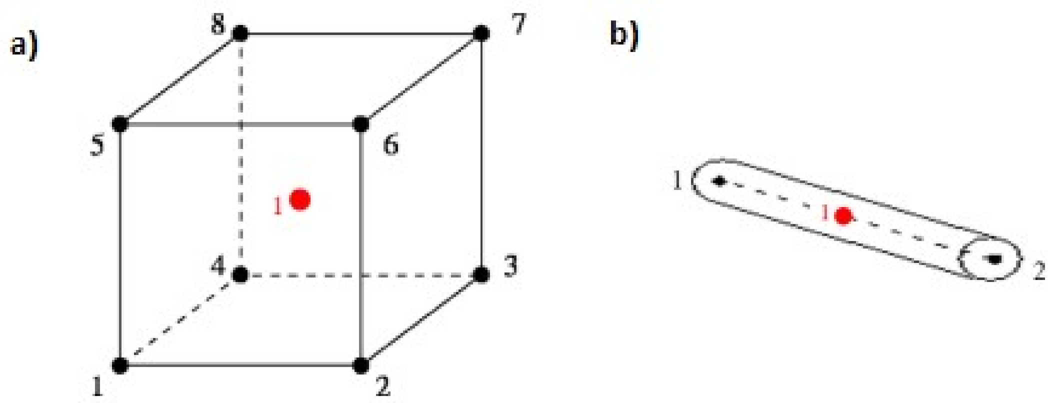


Figure 8. Element types used in finite element models of deep beams: a) C3D8R b) T3D2

In the finite element model of deep beams, the supports near the end of the beam are designed as movable (Centre of plate restrained against Y displacement) and the support in the middle of the beam is designed as fixed (Centre of plate restrained against X and Y displacement). In all models, the optimum element dimensions and mesh type were determined in order not to prolong the analysis times and to obtain meaningful data. Accordingly, the reinforced concrete deep beam components were modelled as a hexagonal mesh with side lengths of 0.1 m each.

In numerical studies, it is necessary to use material models that reflect idealized states of the real properties of many materials such as concrete and reinforced concrete steel. ABAQUS [22] package program allows the definition of 3 different material models for concrete materials. These material models are concrete plasticity damage model, diffuse concrete crack model and brittle concrete crack model. Reinforced concrete deep beam element is subjected to both compressive and tensile effects during two-point bending loading. Crushing behavior due to compressive effects and cracking behavior due to tensile effects were modelled using the CDP (Concrete Damage Plasticity Model) material model in the ABAQUS package (Figure 9).

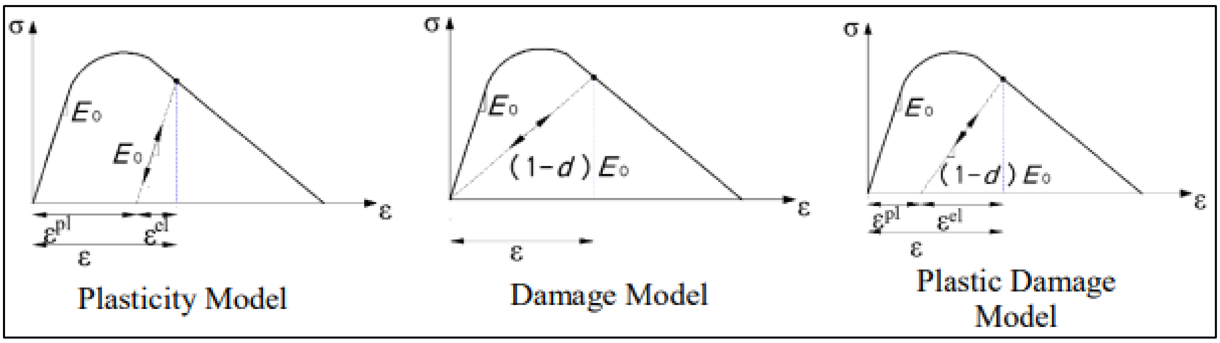


Figure 9. Concrete material models depending on damage and plasticity [23]

Stress - strain relations of the concrete material used to depend on the compressive and tensile effects defined in the CDP material model are given in Figure 10.

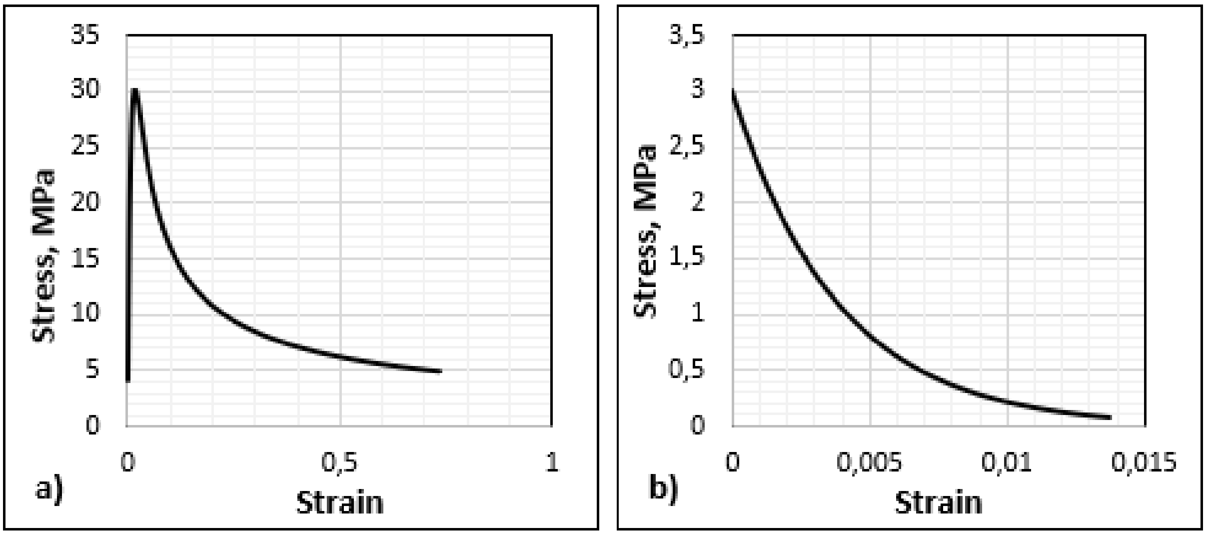


Figure 10. Stress-strain curve of concrete according to finite element model a) for axial compression b) for axial tension

Cracks occurring in concrete due to load effects also cause stiffness losses. In ABAQUS package programme, stiffness reduction parameters, *dc* for compression and *dt* for tension, were defined to represent the reductions in the stiffness of concrete. The variation of stiffness reduction parameters depending on inelastic strain is shown in Figure 11.

In many studies in the literature [24, 25, 26], it is seen that elastoplastic and bilinear material models are widely used in the modelling of reinforced concrete steel. Current study, elastoplastic material model is used for deep beam transverse reinforcement, while bilinear material model is preferred for longitudinal reinforcement. In the bilinear material model, after the steel reinforcement reaches the yield stress, stress increase occurs and plastic strains continue (Table 1). For the CDP material model used in the modelling direction, the parameters defined as dilation angle (ψ), eccentricity (e), viscosity (μ), f_{bo}/f_{co} the ratio of the yield stress in the biaxial loading case to the yield stress in the uniaxial loading case must be entered into the ABAQUS package program.

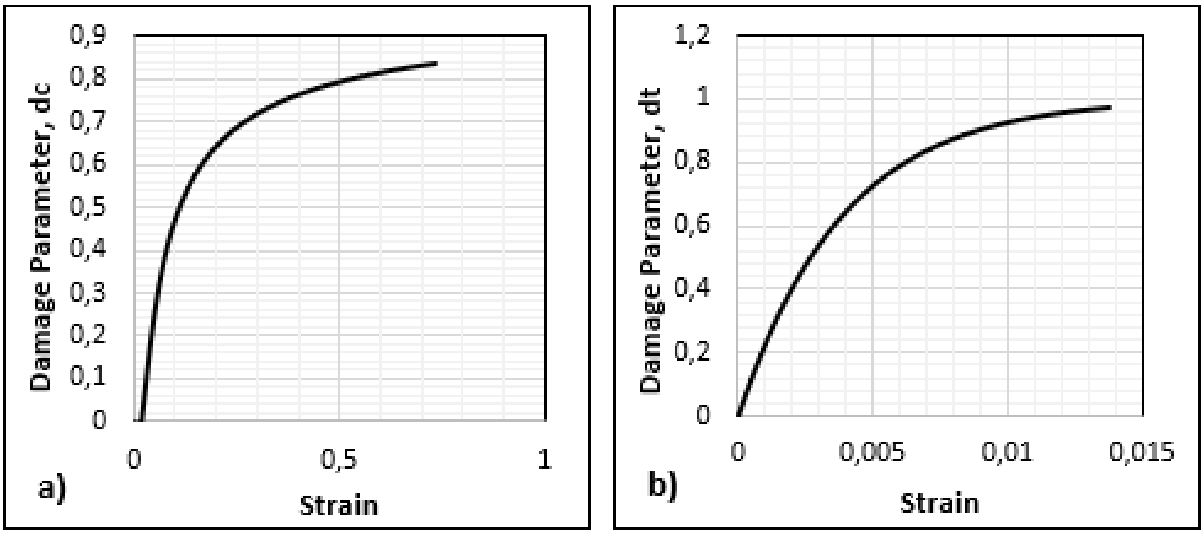


Figure 11. Variation of stiffness reduction parameter depending on inelastic strain a) for compression b) for tension

The dilation angle (ψ) is a numerical expression of the volumetric change in the material under shear stress or shear strain. The variation of the dilation angle may result in more rigid or more elastic material behavior under the same displacements. In many studies in the literature [27, 28, 29], the dilation angle was selected between 5° and 45° to be compatible with experimental studies. Çolakoğlu and Hüsem [31] performed many parametric studies with different values of the dilation angle and investigated the change in behavior. Accordingly, the dilation angle was taken as 35° in this study.

The eccentricity (e) is a small positive parameter that quantifies the rate at which the hyperbolic flow potential approaches its asymptote [22]. In accordance with previous studies in the literature [24, 26, 30], the eccentricity value adopted in this study is 0.1.

f_{bo}/f_{co} is expressed as the yield stress ratio in biaxial and uniaxial stress states. It is taken as 1.16 in the literature [32] and in this research paper.

Viscosity (μ), is the parameter that enables the concrete material equations to be arranged as visco-plastic in numerical analyses. Softening and stiffness losses occurring in the sections of the material models cause convergence problems in the analyses, and the viscosity parameter minimises such problems. In the studies in the literature [24, 25, 32, 33], the viscosity value is chosen between $1\,x\,10^{-7}$ and $667\,x\,10^{-3}$. In this study, the openings on the deep beam increase the convergence problems in numerical analysis. Therefore, in order to eliminate these problems and to complete the numerical analysis, the viscosity is taken as 0.007985 in this study.

III. RESULTS AND DISCUSSIONS

3.1 Total Load – Mid Span Deflection Relationship

The load-displacement graphs of five reinforced concrete deep beams for which nonlinear finite element analyses were performed are shown in Figure 12. In all deep beams with and not having regular cavities, the left and right center span displacements were obtained as equal due to the symmetrical property. Therefore, the left and right center span displacements are averaged and plotted in Figure 12.

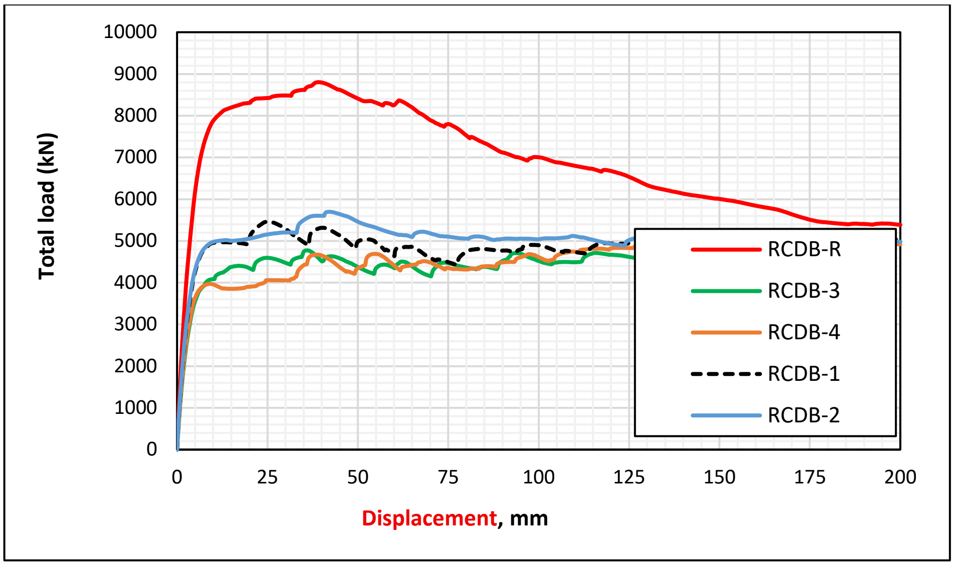


Figure 12. Load-displacement relations

It was determined that leaving regular openings in the deep beam reduces the shear resistance of the deep beam. Compared to the RCDB-R control deep beam without openings, the reduction in shear capacity in RCDB-1 and RCDB-2 specimens, where the regular openings have a circular geometry, was 38% and 35%, respectively.

In RCDB-3 and RCDB-4 specimens where the regular openings have rectangular geometry, the reduction in shear capacity was 44% and 42%, respectively. However, it is seen that this significant reduction in the shear capacity is due to the regular openings left on the deep beam interrupting the formation of diagonal compression supports. In fact, the reduction in shear capacity of RCDB-2 and RCDB-4 specimens, which affects the formation of diagonal compression supports less due to the location of their openings, is lower than RCDB-1 and RCDB-3.

3.2 Stiffness – Mid Span Deflection Relationship

Stiffness - displacement curves obtained from finite element analyses of reinforced concrete deep beams are shown in Figure 13. The opening structure of the deep beam causes a significant reduction in its initial stiffness. In fact, as measured to the RCDB-R control deep beam without openings, the reduction in the initial stiffness of RCDB-1 and RCDB-2 specimens with circular geometry of regular openings was 24% and 22%, respectively. In RCDB-3 and RCDB-4 specimens where the regular openings have rectangular geometry, the reduction in the initial stiffness was determined as 35% and 32%, respectively.

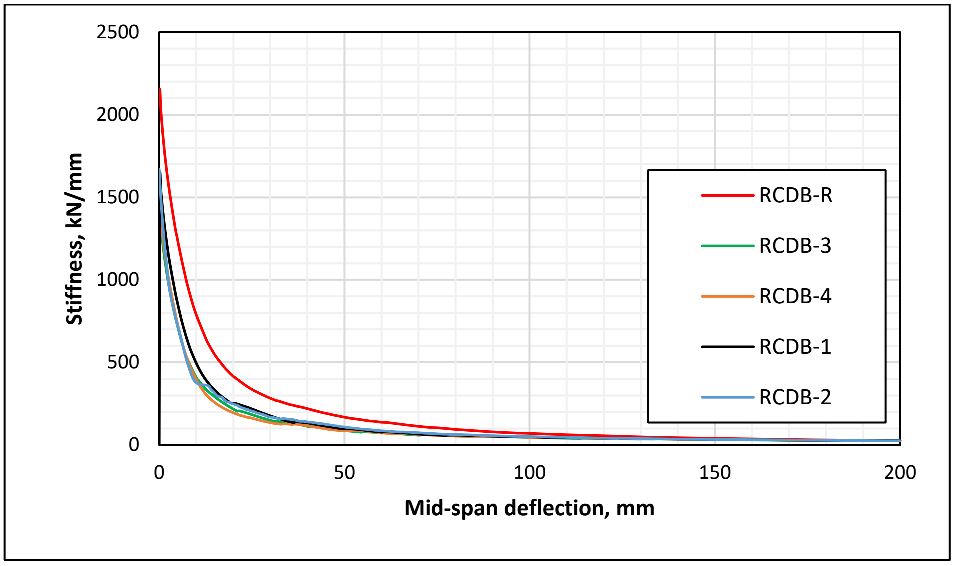


Figure 13. Stiffness - displacement relations obtained from finite element analysis

3.3 Moment – Curvature Relationship

The moment-curvature relationship can be used to reveal the behavior of a reinforced concrete section where only the bending moment or the axial force together with the bending moment is effective. In order to determine the M_i and K_i values that create this relationship between moment and curvature, it is necessary to use the equilibrium equations and compatibility equations [34].

If the cross section of any beam element is considered, various assumptions are made for the value of c until the equilibrium of forces is reached. The steel deformation ε_{si} is determined from an assumed value for ε_{ci}. Based on this value, the stress and force values of steel reinforcement are calculated. Based on this, the concrete compressive joint force F_c is found. After equilibrium is reached, M_i is found by calculating the moment of internal forces around the centre of gravity. The curvature is determined as specified in Equation 1 [34].

$$K_i = \frac{\varepsilon_{ci}}{c} \tag{1}$$

The curvature of the reinforced concrete deep beam, for which finite element analysis was performed, was calculated by taking the ratio of the displacement values in the y direction taken from the node points 1 and 2 shown in Figure 14 on the left or right center span A-A or B-B section, to the height of the beam as given in Equation 2.

$$K_i = \left(\frac{\Delta_{y1} - \Delta_{y2}}{L}\right) \tag{2}$$

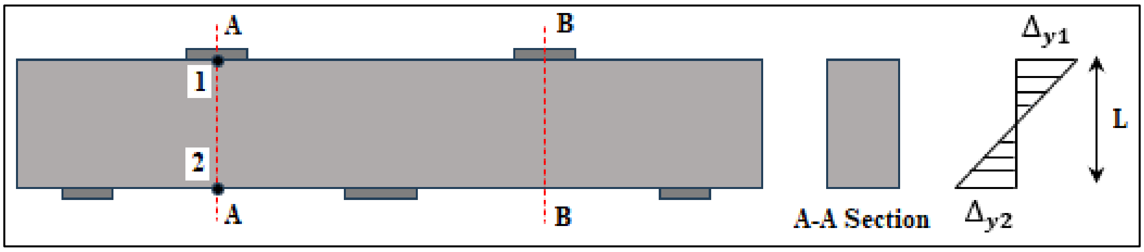
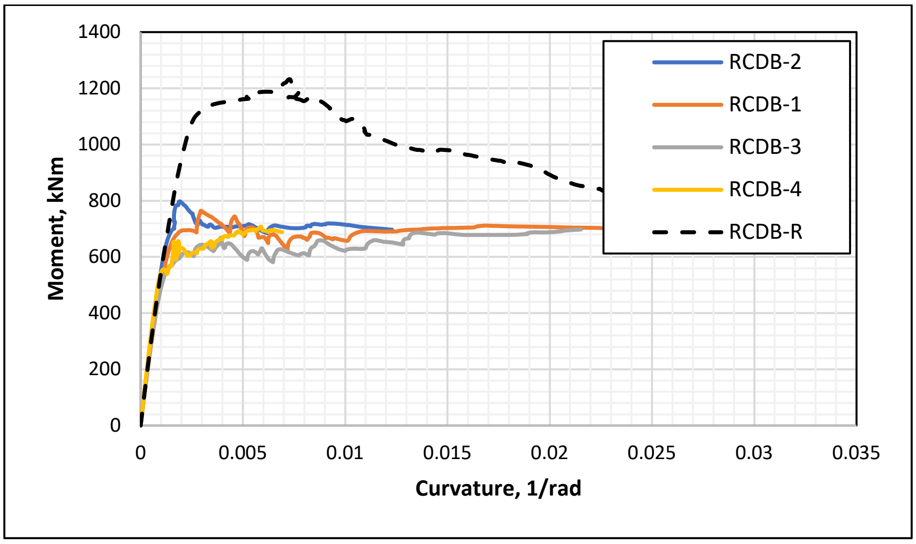


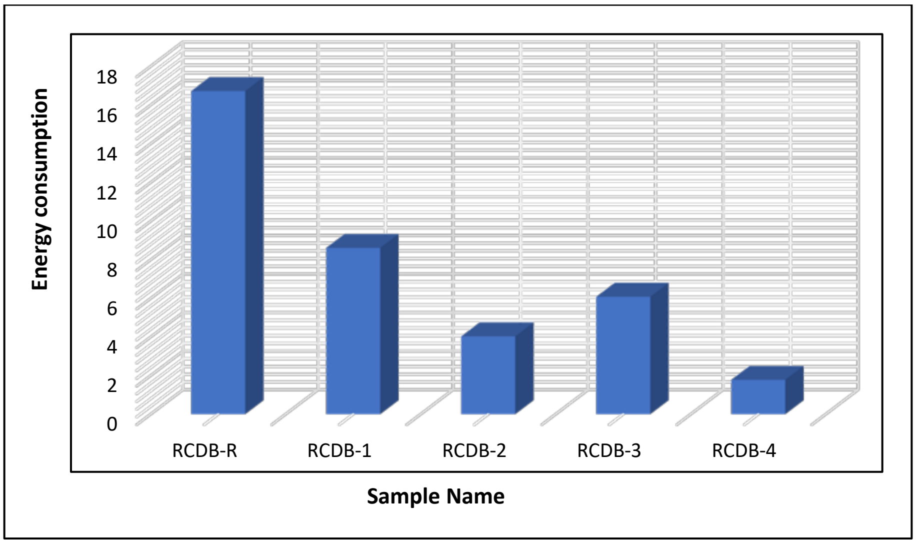
Figure 14. Definition of curvature for the finite element model

Accordingly, the moment - curvature relationship obtained as a result of finite element analysis of deep beams with and without regular openings is shown in Figure 15a. The area under the moment - curvature graph gives the energy consumption capacity of reinforced concrete elements during earthquakes. In this context, it is known that reinforced concrete structural elements with high energy consumption capacity will exhibit more ductile behavior.

According to Figure 15b, the energy consumption capacity of reinforced concrete deep beams without regular openings is higher than the deep beams with regular openings. The reduction in energy consumption capacity of RCDB-1 and RCDB-2 specimens with regular openings in circle geometry was determined as 48% and 75%, respectively. In RCDB-3 and RCDB-4 specimens with rectangular geometry of regular openings, the reduction in energy consumption capacity was determined as 63% and 89%, respectively. In the specimens where the regular openings are in circular and rectangular geometry, it is seen that the position of the openings prevents the formation of diagonal compression supports less, the energy consumption capacities are much lower in RCDB-2 and RCDB-4 specimens and these specimens are far from ductile behavior.



(a)



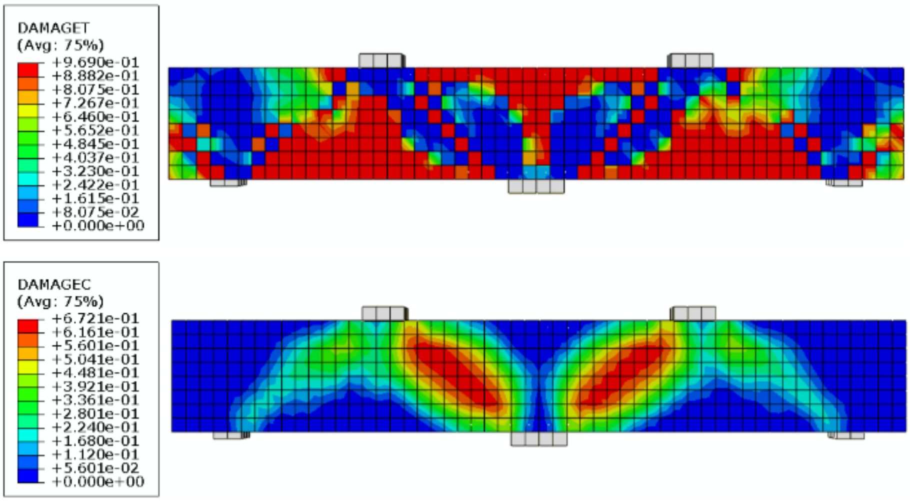
(b)

Figure 15. a) Moment-curvature relationship determined by finite element analysis b) Comparison of energy consumption capacities of deep beam specimen models

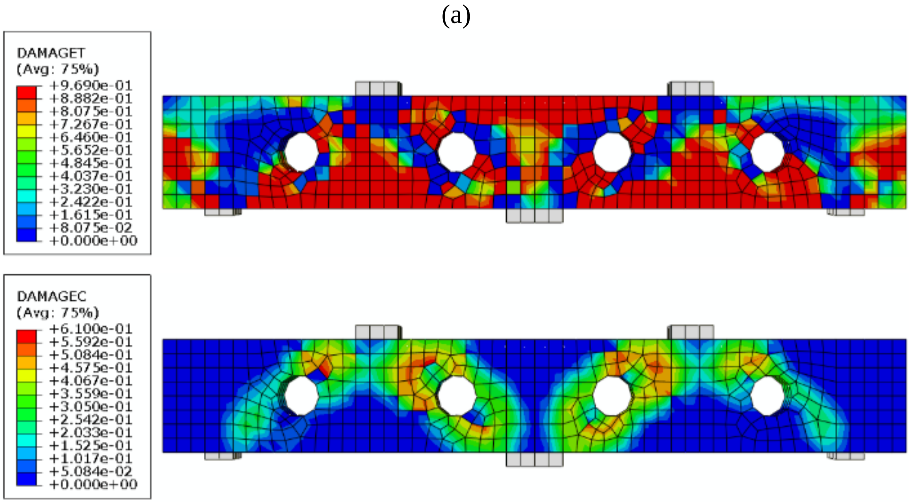
3.4 Damage Mechanisms Obtained from Finite Element Analysis

Figures 16(a) - 16(e) show the damage conditions of the five deep beams analyses by finite element analysis at the time of collapse caused by compressive (damagec) and tensile (damaget) effects on a 0-1 scale. Here '0' means no damage and '1' means total damage.

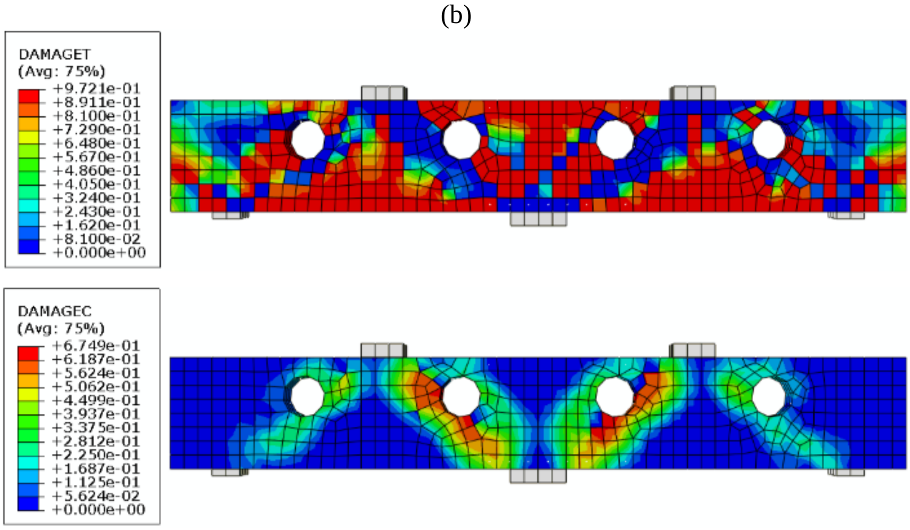
As a result of the numerical analysis, it is seen that flexural cracks start first in the spans of the RCDB-R control deep beam without regular openings, and then diagonal shear cracks develop in the regions where the diagonal compression supports of the deep beam are located. These diagonal shear cracks propagated until the concrete fractured near the bearing plates as shown in Figure 15a. In specimens RCDB-1 and RCDB-3, where regular circular and rectangular openings were in the middle of the beam shear spans on the deep beam, diagonal shear cracks started from the corner region of the rectangular and circular openings and expanded in the diagonal direction until the concrete fractured near the bearing plates. In RCDB-2 and RCDB-4 specimens, it was determined that diagonal shear cracks, which cause an increase in brittle fracture behavior due to the fact that the openings are closer to the top surface of the deep beam, were formed in more intense and irregular forms throughout the beam.



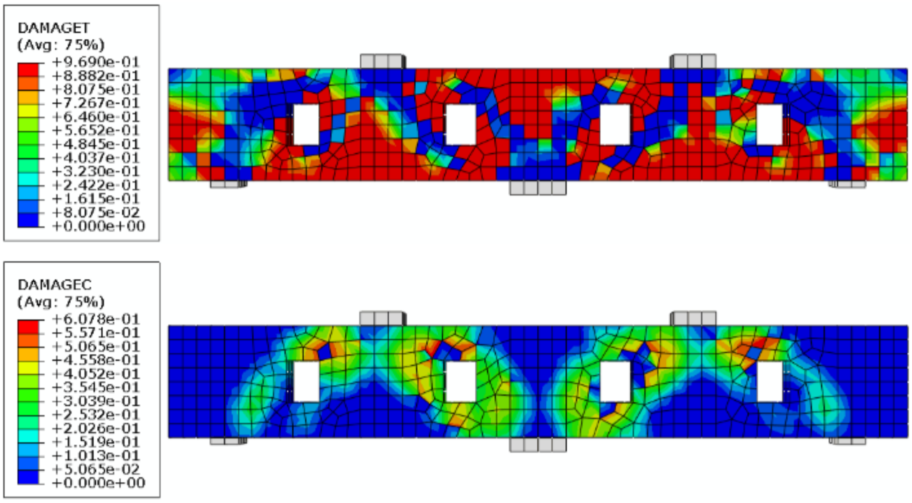
(a)



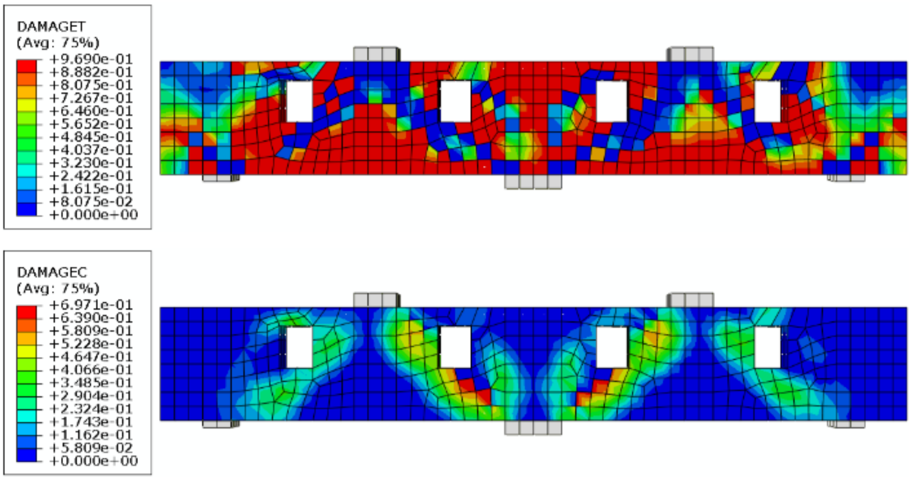
(b)



(c)



(d)



(e)

Figure 16. Damage mechanisms determined by finite element analysis: (a) RCDB-R; (b) RCDB-1; (c) RCDB-2; (d) RCDB-3; (e) RCDB-4

IV. CONCLUSIONS

Four deep beams with opening geometries of circles and rectangles and a deep beam without openings are the subject of this research paper. In the study, a nonlinear static analysis was performed using finite element modeling technique. For the deep beams with openings, the height and cross-sectional areas of the circular and rectangular openings are taken as equal. The results obtained from the nonlinear numerical analysis are summarized below.

Leaving openings on the deep beam reduced the load level required for the onset of shear cracks expected to occur due to shear stresses. This reduction in load level was realized between 35% and 44% compared to the control deep beam without openings.

For deep beams with openings at the same location and equal cross-sectional area but different geometry (RCDB-1 - RCDB-3 and RCDB-2 - RCDB-4), there is a difference of 6% and 8% in the reduction of the failure load, respectively. Positioning the openings closer to the top surface of the deep beam reduces the fracture load and causes the behavior to change from ductile to brittle. The decrease in the fracture load is also due to the decrease in energy consumption capacity.

It is important that the openings are located closer to the top surface of the deep beam in order to utilize the ceiling height more. The fracture load level in deep beams RCDB-2 and RCDB-4 is higher than in deep beams RCDB-1 and RCDB-3 where the openings are located at mid-depth. However, in deep beams RCDB-2 and RCDB-4 where the openings are located closer to the top surface of the deep beam, the reduction in energy consumption capacity increases up to 75% and 80%. Since this situation will change the ductile behavior of the deep beams towards brittle, it is thought that it would be more appropriate to leave the openings in the middle depth of the beam.

Regular geometric openings in deep beams partially or indirectly prevent the formation of diagonal compression supports, which are assumed to form under load effect. This situation reduces the shear load capacity of deep beams with regular openings. However, the regularity of the openings allows the shear behavior of the deep beam to vary more consistently along the beam compared to beams with irregular openings. This improves the shear behavior. However, keeping the regular openings close to the top surface of the beam adversely affects ductile behavior.

In many engineering structures manufactured for different purposes in our country and around the world, it is very common to manually open random openings on traditional reinforced concrete beams or reinforced concrete deep beam elements in order to pass various installation pipes later. The current study focuses on the seismic behavior disorder created by this situation on the structures and tries to reach the reader in this respect.

The results obtained above are within the limitations of a study involving the consideration of regular openings in the critical shear zone at a depth less than the mid-depth and mid-depth of the beam. Therefore, the study can be further extended by considering different opening shapes and locations or changes in the reinforcement arrangement. In addition, the results of the present study are limited to deep beams with a compressive strength of 30 MPa, and further research is needed for deep beams with higher concrete strength classes.

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