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Performance of Reinforced Concrete Beams with Rectangular Opening in Flexural and Shear Zone

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Abstract

Transverse openings in reinforced concrete beams use to house the utility services like electricity cable, Internet cable, air-conditioning pipe, fire safety pipe line and water-drainage system. These beams opening pipe line system are usually placed underneath the soffit of the beam in term of dead space. This height of dead space that increase the overall building height. Beam opening in the reinforced concrete beams significantly decreases the ultimate load carrying capacity of beam. Transverse beam opening in the web portion of beam produces discontinuities in the usual flow of stresses and that leading stress concentration around the opening region. The importance of this study is to evaluate the performance of reinforced concrete beam with varying size rectangular opening at flexure and shear location ware investigated. A nonlinear finite element analysis was conducted to investigate the effects of different size openings, in terms of ultimate load carrying capacity, Elemental Stresses, load-deflection plot, crack pattern. The work involves investigating performance of different size of small and large rectangular opening. This paper gives new challenges for engineering practice which is in the field of strengthening of concrete structures especially in transverse RC beams with rectangular openings.

Keywords: *RC Beam with opening, Rectangular Opening, Small and large opening, Ultimate load capacity, Failure modes and Crack Pattern.*

1. Introduction

Electric Beams featuring openings are frequently employed to facilitate the passage of utilities such as electrical conduits, plumbing pipes, or ducts through structural elements. This design choice enhances space utilization and simplifies the routing of services within buildings. The incorporation of openings in beams also provides the advantage of reducing the overall dead load of the structure. This is particularly advantageous in scenarios where minimizing the self-weight of the structure is a priority, such as in high-rise buildings or structures subject to strict weight limitations. Reinforced concrete beam transverse openings exhibit a variety of sizes and shapes, including circular, square, rectangular, triangular, trapezoidal, oblong, and even irregular shapes [1]. However, the introduction of openings in beams raises complexities concerning structural safety and beam efficiency. The presence of openings can impact the flexural capacity of the beam, and with the size and location of the openings influencing the distribution of bending moments and shear force along the beam. Beams with transverse openings in reinforced concrete experience reduced stiffness and ultimate load capacity. Careful consideration of the structural implications is crucial when introducing openings. Engineers must ensure that the design maintains the required structural integrity, addresses potential issues related to stress concentrations, and complies with relevant building codes and standards. Researchers have undertaken both experimental and theoretical studies to investigate the behavior of reinforced concrete beams with various sizes of openings, aiming to determine their load-bearing capacity. Many studies involve the use of openings surrounded by fiber-reinforced plates, such as CFR plates, to strengthen the opening and mitigate potential structural issues. [2] Mansur et al. (1985) introduced a design methodology for reinforced concrete (RC) beams featuring large rectangular openings under point loads. Subsequently, Mansur et al. (1992) expanded on this approach by developing a method to compute the deflections of RC beams with large rectangular openings. Their method assumed the formation of a contra flexure point at the mid-length of each chord in a Vierendeel mechanism. [3] In a study conducted by Ramadan et al. (2009), the behavior of simply supported RC beams with a single rectangular opening subjected to a central concentrated load was investigated. In this examination, the opening, with a depth ratio (h/D= 0.5), resulted in up to a 40% reduction in beam strength. The impact of the opening presence diminished when shifted toward the tensioned side but increased when shifted toward the compressed side. [4] Aykac and Kalkan (2013) discovered that the flexural behavior of beams with rectangular openings is significantly influenced by the reinforcement ratio. They found that incorporating diagonal reinforcement at the corners of the openings effectively prevents shear failure of the posts between the openings and premature failure of the beam due to Vierendeel truss action. [5] Abdalla (2003) concluded that utilizing FRP sheets to cover beam openings enables the attainment of the beam's full capacity even with a small opening. However, shear-located openings may lead to a reduction in the maximum load capacity. [6] In a paper published by Jabbar and Al-Rifaie (2021), four beams were fabricated and tested with circular, square & rectangular openings. The results indicated that a circular opening was the optimal choice, exhibiting higher ultimate loading capacity and lower deflection compared to other opening shapes. [7] Experiments conducted by Siao and Yap (1990) demonstrated that in the absence of extra reinforcement surrounding the opening, beams with openings situated in high-shear regions break prematurely at the compression chord. [8]Ashour and Rishi (2000) concluded that the continuous deep RC beams with small or large rectangular web openings, are positioned closer to the end supports, the reduction in load capacity caused by their presence diminishes. In accordance with the aforementioned paper, the study employs nonlinear finite element analysis to examine the reinforcement of rectangular openings. This project aims to analyze the impact of rectangular beam openings, investigating their failure modes and ultimate load-carrying capacities under shear and flexure conditions, thereby addressing existing knowledge gaps. The primary focus of the investigation is to determine the maximum load that a reinforced concrete beam can bear while maintaining structural integrity in the presence of rectangular openings. The goal of this study is to determine how concrete beam behavior is affected by different size of rectangular opening without strengthening the opening region. Determining the appropriate location along the length of a beam for a rectangular transverse opening depends on various factors, and the choice often involves a balance between structural efficiency and practical considerations.

1.1. Scope and objective

The primary objective of this study is to comprehensively examine the influence of the presence of openings on the behavior of reinforced concrete beams. The investigation specifically focuses on meticulous modeling of reinforced concrete beams featuring rectangular transverse openings. The purpose is to accurately represent the structural elements and configurations. The research employs nonlinear finite element time step analysis conducted using the ANSYS software. A crucial aspect of the study involves comparing the results obtained from the analysis of beams with both small and large openings. The comparison is conducted at two critical sections of the beam: mid-span and quarter-span. This comparative analysis aims to discern the varying effects of opening size on the structural behavior at different locations along the beam length.

1.2. Verification of numerical RC beam

The developed numerical model underwent validation through a comparison of its results with experimental data from beams tested by Vasudevan and Kothandaraman in 2011. In this investigation, three reinforced concrete (RC) beams were chosen from the experimental study conducted by Vasudevan and Kothandaraman in 2014. The experiments included a mix of normal and high-strength concrete beams, with three beams each from both categories maintained as conventional beams for reference. These beams dimensions of 250 mm in depth, 200 mm in width, and a span of 2000 mm. Each of the RC beams was reinforced with two main bars, with diameters varying between 10 mm, 12 mm, and 16 mm. Additionally, they were equipped with shear reinforcement consisting of 8 mm diameter bars spaced at 200 mm center-to-center, along with 2-10 mm diameter compression bars. The yield strength of all reinforcements was standardized at 556 MPa and had a compressive strength of concrete 35 MPa. [9] The load-carrying capacity at the ultimate stage, as predicted by the established models, is corroborated through comparison with experimentally tested data. For instance, the experimental ultimate load value for a beam reinforced with 10mm bars(B-10) is 75.41 kN, while the ANSYS finite element (FE) model predicts a load of 77.02 kN. Similarly, the ultimate deflection observed experimentally is 18.51 mm, whereas the ANSYS FE model calculates it to be 19.08 mm. Similarly, for beam (B-12), the experimental ultimate load is 96.12 kN, with an FEA value of 101.85 kN. The corresponding experimental and FEA ultimate deflections for B-12 are 19.22 mm and 20.37 mm, respectively. These close correlations between experimental and FE model results indicate the validity of the established models. Based on the outcomes of the validation study, there is a recommendation to extend the proposed FE model for further parametric analysis. [10]

2. Problem Statement

2.1. Geometrical model

In this study, ANSYS software was employed to create a model of a simply supported reinforced concrete beam, measuring 5 meters in length with a rectangular cross-section of 300 mm in width and 600 mm in depth. The primary longitudinal reinforcement consisted of four 25mm diameter bars at the bottom and four 20mm diameter bars at the top. Additionally, stirrups were incorporated in the form of 8mm reinforcement bars spaced at 150mm center-to-center. The research considered rectangular openings sized at 250 x 300mm, 250 x 400mm, 250 x 500mm & 250mm X 600mm. The placement of these openings along the length was examined at both the middle and quarter-span sections of the beam. Due to a systematic understanding and the capabilities of computer hardware and software, the application of the nonlinear finite element method has broadened, refer Figure 1,2.

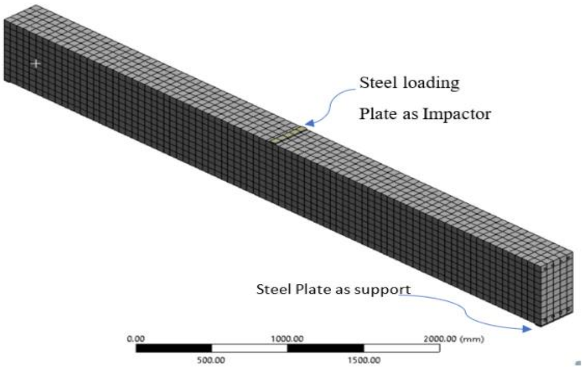

Figure 1 **Solid Beam with Meshing**

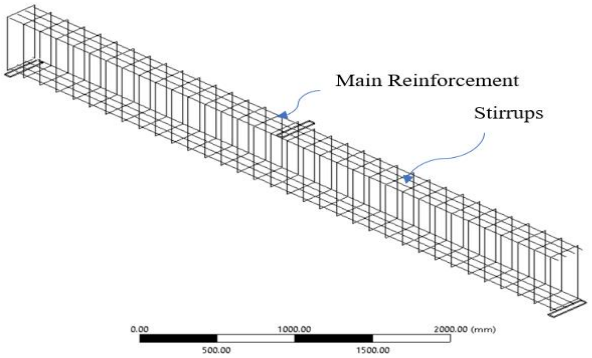

Figure 2 **Reinforcements Details**

2.2. Material Characteristics

Modeling the actual behavior of a reinforced concrete beam element presents a formidable challenge due to the intricate nature of concrete and steel, both of which exhibit complex and nonlinear characteristics. To capture these complexities, the concrete beam model employs the Nonlinear-Multilinear Property to represent the concrete material, while the steel bar in the reinforced concrete (RC) beam is modeled using Bilinear Isotropic Hardening. In this finite element model, a distinct composite approach is employed to represent reinforcement and concrete, utilizing SOLID45, SOLID65, LINK80, and SOLID185 elements for simulating concrete material, reinforcement, and casing, respectively. The SOLID65 element is chosen for its capabilities in modeling concrete, incorporating characteristics of cracking and crushing. This element, widely used for concrete simulation, requires careful parameterization during the simulation process. For the support zones, thick steel plates are simulated, assuming isotropic and linearly elastic behavior. To model these plates, the SOLIED45 element is adopted. This comprehensive material and element selection provides a robust foundation for simulating the complex behavior of the reinforced concrete beam in the study. The modulus of elasticity for concrete is calculated according to IS 456:2000 standards, resulting in a value of 27386 MPa. The Poisson's ratio is specified as 0.2. For open and closed cracks, the shear transfer coefficients are set at 0.3 and 1, respectively. The uniaxial tensile cracking stress is determined following IS 456:2000 guidelines, resulting in a value of 3.834 MPa. The multi-linear isotropic material employs the Von-Mises failure criterion to define concrete failure within the simulation. The steel reinforcement is modeled as an elastic-perfectly plastic material, demonstrating identical behaviors in both tension and compression. The elastic modulus for steel is specified as 210,000 MPa, with a Poisson's ratio of 0.3. To represent the beam reinforcement, a three-dimensional spar element with plasticity, LINK180, is employed. The yield strength of the steel used for stirrups is set at 240 MPa, while that of longitudinal reinforcement is 415 MPa. The entire load is distributed across multiple load phases within the finite element model. The ANSYS software is equipped with an automatic time-stepping feature, facilitating the estimation of failure. Time adjustments are made based on the response frequency during this process. The resolution of nonlinear problems is accomplished through the Newton-Raphson equilibrium iteration method.

3. Results and Discussion

The analysis covered various aspects, including displacements, stress, strain, ultimate load, cracking patterns, and modes of failure, providing a comprehensive understanding of the behavior of RC beams with rectangular opening. The maximum ultimate loading capacity of the solid beam was recorded at 333.54 kN, with a corresponding maximum deformation of 38.90 mm. Conducting nonlinear finite element analysis, rectangular openings sized 250 x 300mm, 250 x 400mm, 250 x 500mm, and 250 x 600mm were utilized in both flexure and shear zones. Results indicated that introducing rectangular opening in flexure zone of 250mm X 300mm led to an average reduction in ultimate load of (13%), while a size of 250mm X 600 mm caused reduction of (31%). When the opening was positioned at the shear zone, a sudden decrease in the ultimate load of (65%) was observed, whereas the flexure zone exhibited the lesser effect, with reduction of (31%).

Table 1 Rectangular Opening at Mid-Span Section

Sr. No	Beam Specifications	Ultimate load (kN)	Percentage Reduction of Ultimate load Compare to Solid Beam	Directional Deformation in mms	Failure Location	Type of Crack
1	Solid Beam	333.54	-	38.90	Top of beam	Flexural
2	250 mm X 300mm	289.64	13.16	31.32	Top of beam	Flexural
3	250 mm X 400mm	281.25	15.68	29.29	Top of beam	Flexural
4	250 mm X 500mm	265.87	20.29	26.13	Top of beam	Flexural
5	250 mm X 600mm	229.93	31.06	23.92	Opening region	Flexural

Table 2 **Rectangular Opening at Quarter Span Section**

Sr. No	Beam Specifications	Ultimate load (kN)	Percentage Reduction of Ultimate load Compare to Solid Beam	Directional Deformation in mms	Failure Location	Type of Crack
1	Solid Beam	333.54	-	38.90	Top of beam	Flexural
2	250 mm X 300mm	287.22	13.89	30.80	Top of beam	Flexural
3	250 mm X 400mm	203.75	38.91	22.41	Opening region	Shear
4	250 mm X 500mm	140.93	57.75	16.58	Opening region	Shear
5	250 mm X 600mm	114.78	65.59	13.05	Opening region	Shear

The table presents a comprehensive summary of the performance of reinforced concrete beams with varying rectangular openings. As the size of the openings increased, there was a proportional reduction in the ultimate load capacity of the beams, with directional deformation predominantly observed in the opening region.

3.1. Load -Vs Deflection

The graph illustrates plastic deformation in the form of ductile failure experienced by the RC beam. The presence of the opening led to a reduction in the moment of inertia, resulting in decreased beam stiffness and an associated increase in deflection, Refer Figure 3,4.

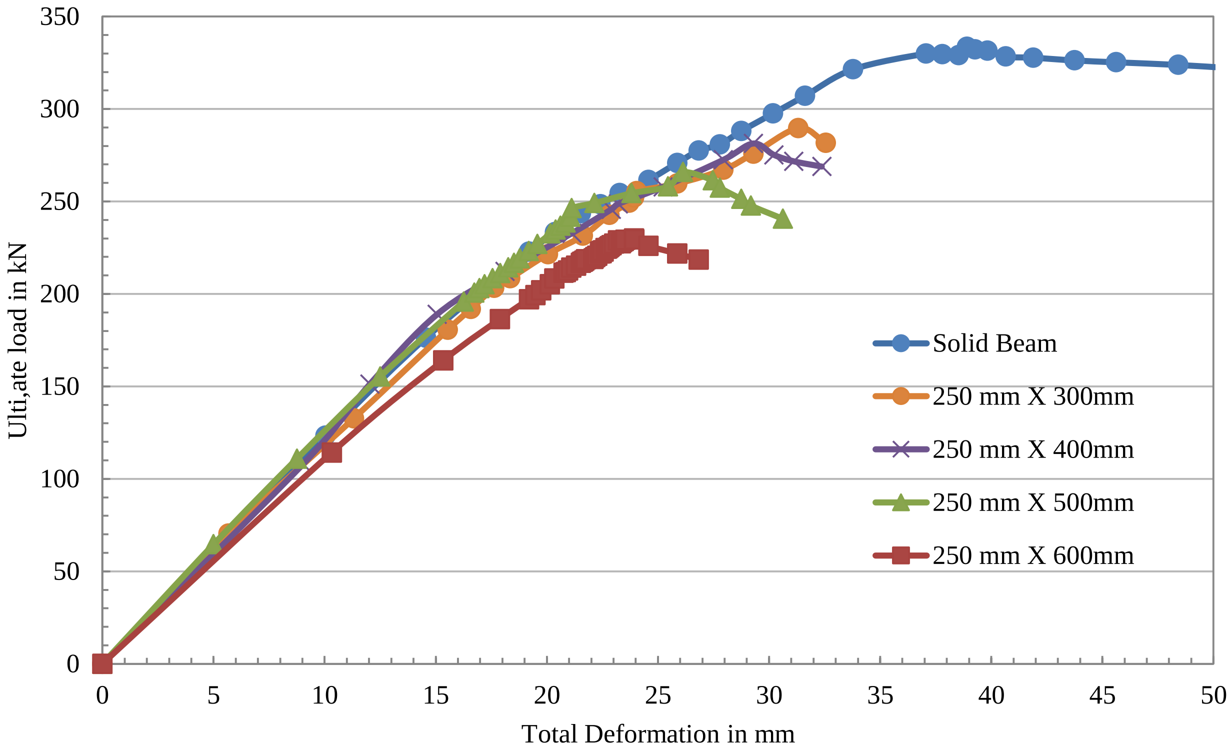

Figure 3 **Ultimate Load Vs Total Deformation of RC Beam with Rectangular Opening Mid-Span Section**

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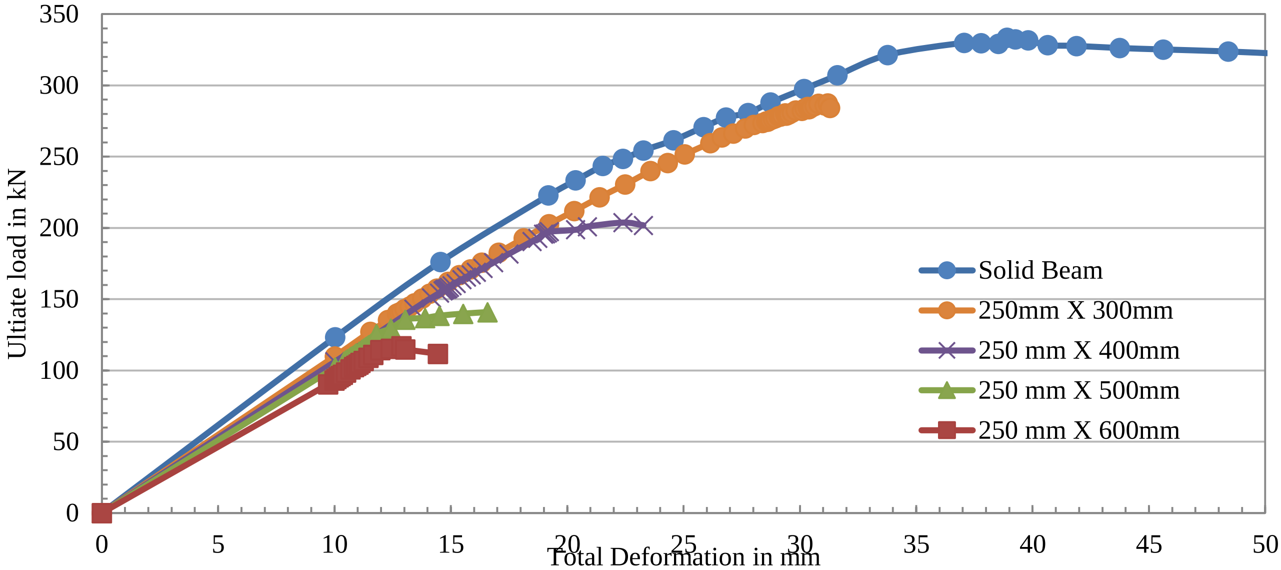

Figure 4 Ultimate Load Vs Deformation of RC Beam with Rectangular Opening at Quarter Span Section

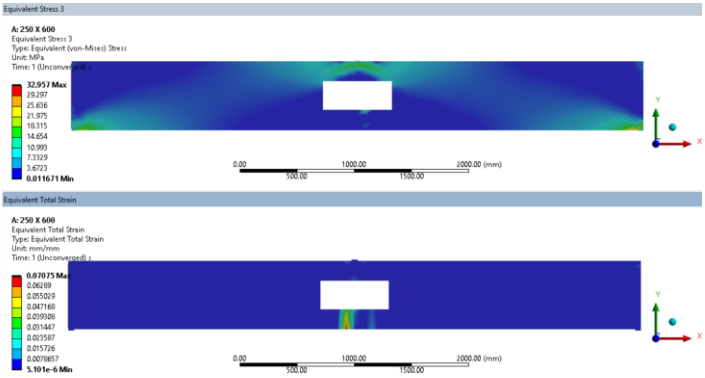

Figure 5 Equivalent Stress and Equivalent Total Strain in Beam with Rectangular Opening of 230mm X 600 Mm at Mid Span Section

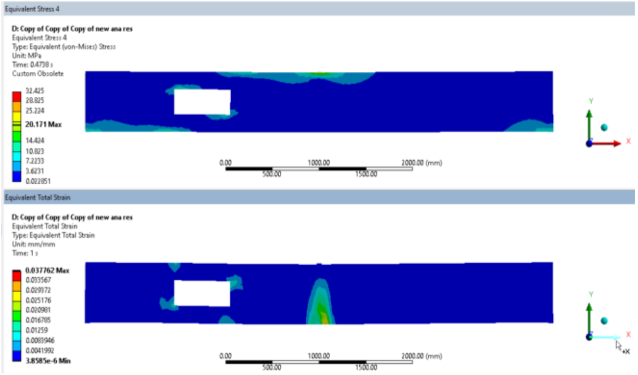

Figure 6 Equivalent Stress and Equivalent Total Strain in Beam with Rectangular Opening of 230mm X 600 Mm at Quarter Span Section

3.2. Crack patterns and failure modes

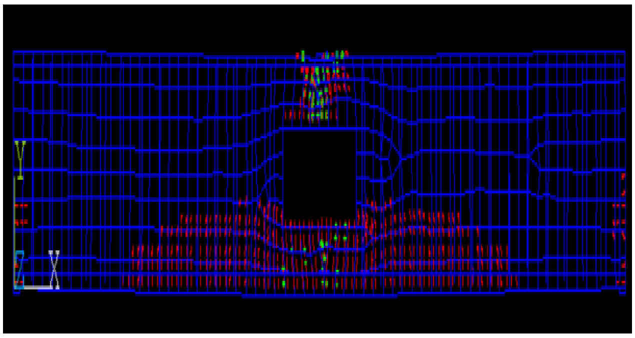

Figure 7 Crack Pattern of Beam with Rectangular Opening of 230mm X 600 Mm at Center Span Section

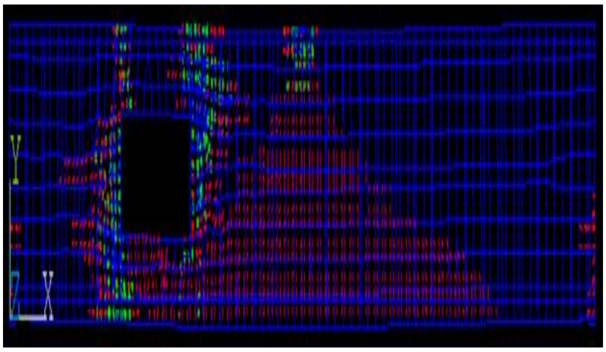

Figure 8 Crack Pattern of Beam with Rectangular Opening of 230mm X 600 Mm at Quarter Span Section

Figure 7 & 8 shown that inclined and vertical cracks develop frequently at the corners of the opening at the service load stage. Such cracks reduce the load carrying capacity of the beam. Early indications of cracks emerged in the beam soffit between the two longitudinal members at mid-span. Cracks were identified in the soffit of the beam at the region of the rectangular opening, extending towards the left side of the opening in the lower chord. The significant central opening in the flexure zone resulted in the beam being effectively divided into upper and lower horizontal beams. This led to acceptable deflection and induced a point of contra-flexure at the center of the beam, exhibiting Vierendeel action. At the quarter span, the rectangular opening failed in shear in the upper chord. Diagonal cracks initiated near the loading point and propagated towards the lower chord. A diagonal crack penetrated the opening corner due to concentrated load, indicating the failure of the top chord due to localized shear failure. Cracks initially appeared at the bottom corner near the closest support, followed by the upper right corner on the opposite side. The subsequent stages involved diagonal shear fractures and vertical cracking under the lower inner corner. In the fourth stage, vertical cracks emerged over the top exterior corner of the beam, closest to the support.

3.3. Flexural Effect:

It was found that small opening at mid-span section, reduction of 13 to 15 % loss in capacity and large openings at beam mid-span, suffered about 31 % loss in capacity. The concrete was crushing at midspan section due to flexural opening and the flexural cracks appeared in the tension zone. Excessive flexural fractures have been found at the tension zone surrounding large openings in reinforced concrete beams located in the flexure zone. Flexure was the mode of failure. RC beams with large openings had a maximum reduction in ultimate load of 31%.

3.4. Shear Effect:

In the case of Beam with openings at quarter span section, where shear is dominant, after plastic hinge formation, the diagonal cracks started viewing up around the rectangular openings, that accelerate the loss of strength in beam. In RC beams with opening at shear zone, the failure mode was in shear, reduction ultimate load caring capacity was about 65 %. And total Deformation is decreased by 66% more than the Solid Beam. In all instances of beams with openings, the initial crack consistently manifested at the external lowest corner, particularly when positioned closer to the support. The appearance of the first crack occurred more rapidly in beams with openings located at or near the support, as the relative impact of bending moment compared to shearing force increased. Conversely, beams with openings shifted away from the support experienced a delayed initiation of the first crack, requiring larger applied loads. For shear located large openings, an average reduction of 60% and 65% was observed in the cracking and failure loads of the beams. This underscores the substantial influence of opening location on the structural behavior, with openings near the support significantly affecting the beam's response in terms of cracking and ultimate failure loads. Figure 5 Equivalent Stress and Equivalent Total Strain in Beam with Rectangular Opening of 230mm X 600 Mm at Mid Span Section. Figure 6 shows the Equivalent Stress and Equivalent Total Strain in Beam with Rectangular Opening of 230mm X 600 Mm at Quarter Span Section

Conclusions

- The choice of opening shapes and sizes plays a critical role, with sharp-edged and cornered openings causing stress concentrations and disrupting load patterns, underscoring the importance of optimal design.
- The efficiency of the beam is markedly compromised when the height of openings reaches at least half of the overall beam depth. This results in a substantial reduction in beam strength. Openings with lengths approximately in the range of 30–40% of the effective span are not recommended unless the upper and lower chords are appropriately designed.
- In scenarios where, reinforced concrete RC beams openings solely within the pure flexure zone, their ultimate capacity remains unaffected if the depth of the top chord equals

or exceeds the depth of the concrete stress block at the ultimate state. in cases where the depth of the top chord is less than the depth of the concrete stress block, the top and bottom chord should design separately and strengthen accordingly.

- With the increase in the size of the openings, particularly in the shear located regions, a notable decrease in the ultimate load capacity of the beams was observed. For instance, in cases where openings measured 250mm x 400mm, 500mm, and 600mm, significant reductions in the ultimate load were noted. Specifically, when the opening was situated at the shear zone, there was a drastic decrease in the ultimate load capacity, amounting to approximately 65%. Conversely, the flexure zone experienced a relatively lesser effect, with a reduction of approximately 31%.
- Large rectangular openings at mid-span and quarter span section pose a substantial risk, leading to a significant reduction in ultimate load-carrying capacity, requiring careful attention to prevent structural failure. This will demand specialized reinforcement strategies around the opening. This reinforcement may take the form of additional stirrups positioned both above and below the opening, supplementary stirrups on either side of the opening, and longitudinal reinforcement incorporated into the top and bottom chords.
- Proper location planning for openings, reinforcement detailing, and strategic placement in the middle third of the beam span are crucial considerations to maintain structural integrity, minimize deformation, and enhance overall beam performance. [11]
- It is crucial to avoid placing the opening in critical zones such as areas with high shear or bending moments. Placing the opening away from regions experiencing maximum stresses helps preserve the beam's overall performance.

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