

## Research Article

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# Nonlinear finite-element analysis of RC beams with various opening near supports

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**Abstract:** The structural integrity of a reinforced concrete (RC) beam could be compromised by the need for web holes for utilities like air conditioning and electricity. In places with high shear loads, these voids may appear near the columns supporting the structure. The impact of web openings close to the supports on the behavior of RC beams is inspected numerically in this article. Four-point loads were applied to the supports of seven RC beams with holes of varied sizes and locations. The crack patterns and deflections of the seven beams were analyzed in comparison to those of a solid RC beam without an aperture. The goal of the experiment was to verify that all simulation procedures were accurate and complete. The numerical analysis results showed that the experimentally tested failure load was in excellent consent with the numerical results. Therefore, the finite-element approach is a particularly reliable technique for exploring the nonlinear behavior of beams with multiple apertures, both from the perspectives of difficulty and time savings. Analytical and code equations were used to compare the measured load–deflection magnitude and shear strength of the examined RC beams to their prophesied values. The test findings demonstrated that the shear load capacity of RC beams was reduced by as much as 24.9% as compared to a solid beam, as shown by testing results. The shear load capacity for small-size openings was less than the solid beam by 12.8, 21.1, and 21.6%, while for the biggest openings by 34.6, 29.5, and 34.2% when taking the distance from the support 0, 100, and 200 mm.

**Keywords:** RC beams, opening, near supports, load–deflection, shear strength

## 1 Introduction

To allow for the routing of wires, tubes, and vents for mechanical and electrical systems, it is usual practice for structures to use reinforced concrete (RC) beams with pre-fabricated openings. Incorporating these apertures into structures helps maximize space use and prevents the loss of clear height [1]. However, stress accumulation at the corners of openings in RC beams can significantly reduce the beams' flexural and shear capacities; hence, their use should be avoided if at all possible [2]. There has been a plethora of experimental and numerical research into the behavior of RC beams with holes. Some studies looked at shallow beams, and there were studies that looked at deep beams [3].

Aykac *et al.* [4] tested nine RC beams to see how their flexural behavior changed when we introduced various web apertures. Premature failure might be avoided if diagonal reinforcement was applied around the openings, as demonstrated by the results. They performed a literature search on studies that compared the performance of RC beams with different shape apertures. Both different deeps of beams of varying aperture sizes and positions were considered in the analyses. To better understand the conduct of RC concrete beams with openings and to create sufficient analytical methods for the design of such beams, the article concluded that further research is required. It was also suggested that experimental and numerical exploration of the behavior of these rays were put through to varied loading arrangements to be pursued in the future.

Mansur *et al.* [5] conducted research on pure torsion effects on RC beams including big rectangular holes. The eccentricity of a beam appears to have only a minor impact on its torsional strength and stiffness, which are observed to decrease with increasing opening length or depth. The beams break because a technique with four hinges forms at the opening's four corners. Naik *et al.* [6] investigated the best beam opening forms where bending alone was the loading condition. Cutting openings in a beam near its neutral axis is an efficient way to lighten it for use in pure bending. It is crucial in engineering design that the

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stress concentration around these openings is kept to a minimum. It is possible to reduce the stress concentration by optimizing the opening form so that, within a given set of geometric limitations and loading conditions, the stress concentration factor is minimized. Mansur *et al.* [7] conducted a laboratory study of huge transversely opening continuous beams of RC. Considerations include the total spans, the dimensions of each opening, and their placement along each span. The openings at either end of the beam are particularly susceptible to the production of plastic hinges, which ultimately lead to the beam's failure. When the opening size of a beam is either longer or deeper, the beam's strength and rigidity are compromised. Thevendran and Shanmugam [8] looked into what happened when we cut holes in the webs of narrow beams. Beams' ultimate strength and lateral buckling capacity are both diminished by web holes. To determine the critical lateral-buckling loads of thin, doubly symmetric beams with unreinforced web holes, a computational method was devised based on the energy approach. The experimental critical loads are compared with the numerical evaluations. Both numerical and experimental values accord well, as demonstrated by this investigation.

For this study, we used the strut-and-tie model to analyze a RC beam having a transverse circular opening in the web [9]. Ultimate strength, mode of failure, and the fraction of applied shear borne by the chord members above and below the aperture all accord well with theoretical predictions and actual evidence. To reduce concrete discomfort at the throat section, the truss model demonstrates how diagonal reinforcement may carry a considerable amount of applied shear over the discontinuity. Ref. [10] conducted tests on both unreinforced and FRP-sheet-reinforced RC beams with apertures. Deflection, strain, cracking, and ultimate load were all studied to see how they changed after this strengthening method was applied. The conduct and strength of RC beams with shear holes were studied experimentally. The ultimate load-carrying capacity of a RC beam is drastically reduced if it has an unstrengthened aperture in the shear zone. Beam capacity may be reduced by as much as 75% if an opening is present whose height is only 0.6 the beam depth and is not reinforced. Beam deflection, fractures surrounding the opening, and ultimate load-carrying capability are all in a way that is likely to have a strong or far-reaching effect. Miniature when CFRP sheets are applied. For somewhat slight apertures, the full capacity of the beam may be recovered by FRP sheets used to reinforce the zone around the hole.

El-Maaddawy and El-Ariss [11] studied the consequence of externally bonded CFRP compounded sheets on the shear strength of web-open RC beams. The consignment of CFRP

sheets utilized for shear strengthening, as well as the opening's width and depth, were used as a test point of reference. According to the findings of the tests, the beam's shear capacity and stiffness were greatly diminished by the presence of web holes. It was discovered that adding CFRP sheets around the opening outstandingly increased the beam's shear resistance and stiffness from the outside. The increase in shear capacity was lessened as the opening size was made wider or deeper. The shear capacity was improved by magnifying the number of vertical CFRP sheets from one to two layers; nevertheless, this improvement was not equivalent to the increase in CFRP thickness.

Mansur [12] presented several helpful pieces of information on the optimal size and disposition of the aperture in RC beams. Their advocacy, for instance, was that the opening depth should not be increased above 50% of the overall beam depth ( $D$ ) to put a stop to an undue loss in the beam's capacity. Further, the opening needs to be positioned at a distance of at least half a stage from the support, the concentrated load, or the openings that are near it. To avoid the critical zone, which is where the reinforcement is most likely to be crowded and where shear failure is the predominant kind of failure, this is the primary rationale for doing so. Additionally, they suggested breaking the one long aperture into numerous openings that had the same total size as the original opening. It is possible that this will assist in achieving acceptable serviceability limitations and will assure the stability of the top and bottom chord members. In addition to this, they said that the optimal position for the aperture in T-beams is just below the flange, which makes the process of construction much simpler. Alternatively, the opening point for rectangular beams is often near the section's mid-depth. This is the case in most cases. However, it is strongly advised to make a little adjustment to the opening along the beam depth in order to guarantee that there is adequate concrete cover for the reinforcement in the lower chord member. At the same time, it is essential to have a sufficient concrete portion in compression in order to prevent the upper chord member from experiencing brittle concrete failure from occurring.

Given the dearth of studies on the behavior of RC beams with web apertures that are near supports and surrounded by additional stirrups, the present work has two primary goals. First and foremost, the purpose of this study is to evaluate the impact that using a near-support web opening of varying widths has on the behavior of RC beams. The second goal is to find the best possible locations for open positions that are close to support. The importance of this research includes that it gives designers an idea about the best location for openings near the supports when designing, as well as the sizes of the openings and their effect.

Daniel's research [13] suggested that structures with floors that were supported by beams in two orthogonal orientations would become more substantial over time. While this is going on, mechanical engineers need apertures inside the beam so that they may pass through their facilities. Therefore, Daniel conducted an experiment to study the behavior of five RC beams that had elongated apertures attached to them. When the author increased the length of the aperture, they came to the conclusion that the shear and flexural modulus were both decreased. Observations were made on the Vierendeel action mechanism for beams that had significant holes. To be more specific, the collapse of the beam was caused by the formation of four plastic hinges at the opening corners. As a point of reference, some beams that had shorter opening lengths exhibited failure as a result of diagonal shear fractures.

## 2 Research significance

We set out to accomplish three goals with this work to make up for the dearth of literature on the topic of RC shallow beams with web apertures adjacent to supports and encircled by extra stirrups near supports. The primary objective is to use numerical techniques to investigate the effect of the opening with varied widths close to the support it is meant to sustain on the behavior of RC beams. The other objective is to calculate the expected impact of various separations from the support face. The third ABAQUS goal is to ensure precise simulations. Beginning with a detailed explanation of the numerical program, this article goes on to describe the specimen's construction, the relative amounts of each material used, and the four-point testing arrangement. The performance of RC beams with web holes is then compared to that of a reference without hole RC beam in the following results section. The load–deflection relationships and crack patterns for both longitudinal and transverse reinforcement are compared.

## 3 Finite-element (FE) simulation

This section presents the methods and material models of concrete and reinforcement used in the simulation of the suggested numerical model. Validation is performed using test data gathered from the published literature. Deflections, strengths, and crack patterns are compared between the computational and experimental data.

### 3.1 Model validation using historical test data

The experimental work performed is essential to the suggested numerical model [14]. There were three RC beams subjected to the usual four-point load test. A desired 40.0 MPa cube concrete compressive strength was specified. Each of the beams used in the tests had overall and pure span lengths of 2,200 and 2,000 mm respectively, and a rectangular cross-section measuring 150 by 300 mm. All beams were reinforced in the same manner over their lengths and widths. Each beam has three 16 mm water-filled longitudinal bars at its base and two 10 mm water-filled bars at its top. The whole length of the beams was lined with closed stirrups, each measuring 8 mm in diameter and spaced 200 mm apart, with an additional closed stirrup on either side of the aperture. All beams that have been put through their paces have a pure span of 2,000 mm, a shear span of 667 mm, and a shear span-to-depth ratio of 2.5. The millimeter measurements and the reinforcing pattern of the specimen are shown in Figures 1 and 2, respectively.

### 3.2 Methodology

#### 3.2.1 Simulation technique

A total of 13,561 pieces were used in the ABAQUS simulation of the beams. To prevent the shear locking effect, concrete

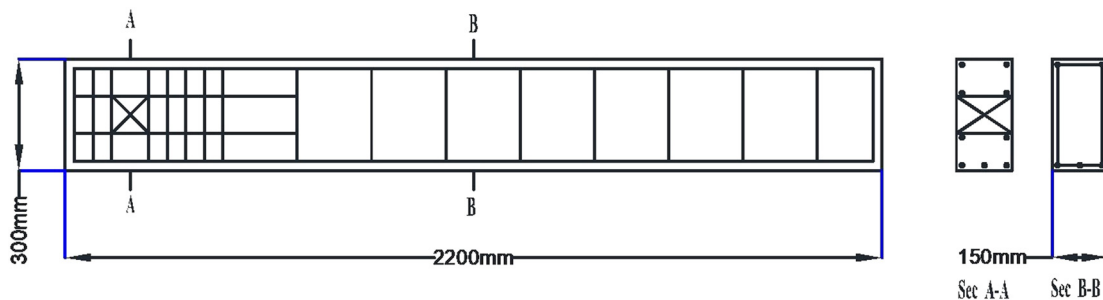


Figure 1: Specimen dimension in mm.

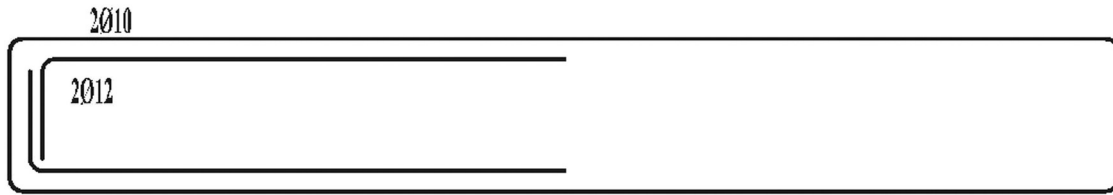


Figure 2: Specimen reinforcement arrangement.

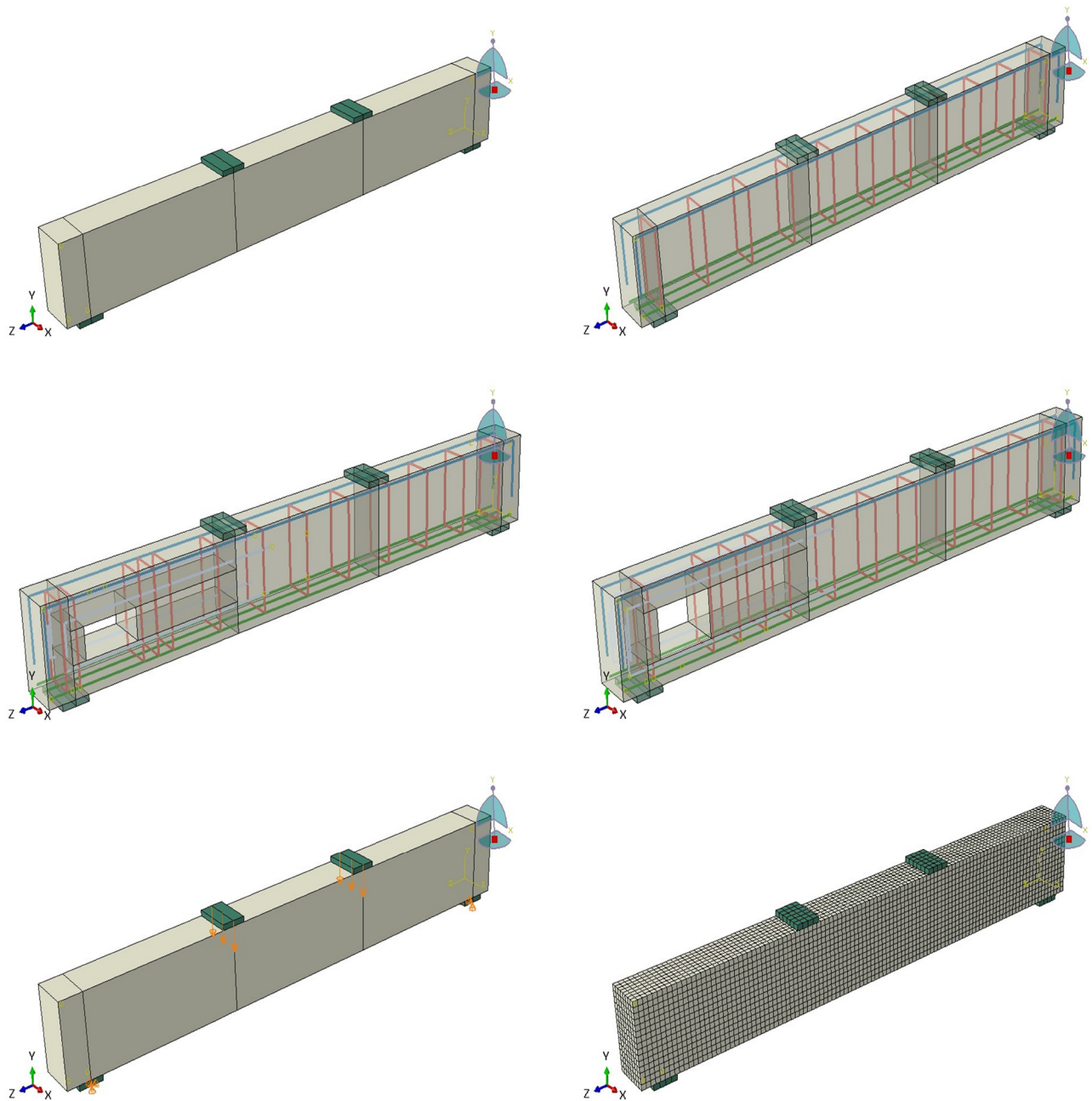


Figure 3: Simulation RC beams using ABAQUS.

with reduced integration employed hexahedral (brick) elements with eight nodes (C3D8R). Modeling reinforcements required 385 two-node linear truss elements (T3D2). Assuming a complete bond between the concrete and the reinforcement, the latter was inserted into the former [15].

Modeling information, such as geometry, boundary conditions, and meshing of specimens, employed in the simulation are shown in Figure 3. Beams in both the vertical and horizontal planes were analyzed using a mesh size of 20 mm. Therefore, six brick pieces were employed, and all concrete elements had the same size of 20 mm to span the 300 mm thickness of the beams [16]. The reference samples were analyzed using a static analysis implemented in ABAQUS/Explicit. The beams were subjected to a surface load that gradually grew from zero to the point of failure. Reactions equal to shear loads were calculated by factoring in the responses at the margins where the boundary constraints were imposed [17].

### 3.2.2 Material models

The concrete model using damaged plasticity (CDP) developed in ABAQUS was selected as the constitutive model to use in this study, and a summary of this model is provided here [18]. Figure 4 depicts the stress–strain response. The CDP model uses a stress–fracture energy method to define tension in concrete. Using theories of brittle fracture, Kytinou *et al.* established the energy needed to open a crack per unit area,  $G_f$ , as a material property [19].

To include this idea in a FE model, a characteristic length connected to an integration point must be defined.

The element geometry and formulation inform this  $l_c$ , the characteristic crack length. Since the direction in which cracking may develop cannot be predicted, this method is employed. For these simulations, the critical length  $l_c$  is set to 20 mm, the same as the mesh size. Different sizes were tried the mesh size 20 mm results gave realistic and accurate results.

To describe concrete's compressive behavior, the Hognestad-type parabola is used. A bilinear strain hardening yield stress–plastic strain curve is used to simulate the uniaxial stress–strain relationship in reinforcement. Young's modulus of 200,000 MPa and Poisson's ratio of 0.3 are used to characterize the reinforcement's elastic behavior.

When the stiffness of the steel is maintained at low strain magnitudes by Young's or elastic modulus, the reinforcing bars' steel exhibits nearly linear elastic behavior. Plasticity is the nonlinear, inelastic behavior that appears at large enough strains. Steel's yield point and post-yield hardening characterize its plastic behavior [20].

At some point on the stress–strain curve, a material will go from behaving elastically to plastically. If the load is removed before the steel reaches its yield point, only elastic strains will have been created, and these will be completely recovered. However, permanent (plastic) deformation starts to occur after the tension in the steel surpasses the yield stress. As the metal continues to deform past the yield point, elastic and plastic strains build up simultaneously. Once the steel gives, its rigidity will decrease. Steel's yield stress is raised by plastic deformation so that it can withstand greater loads in the future.

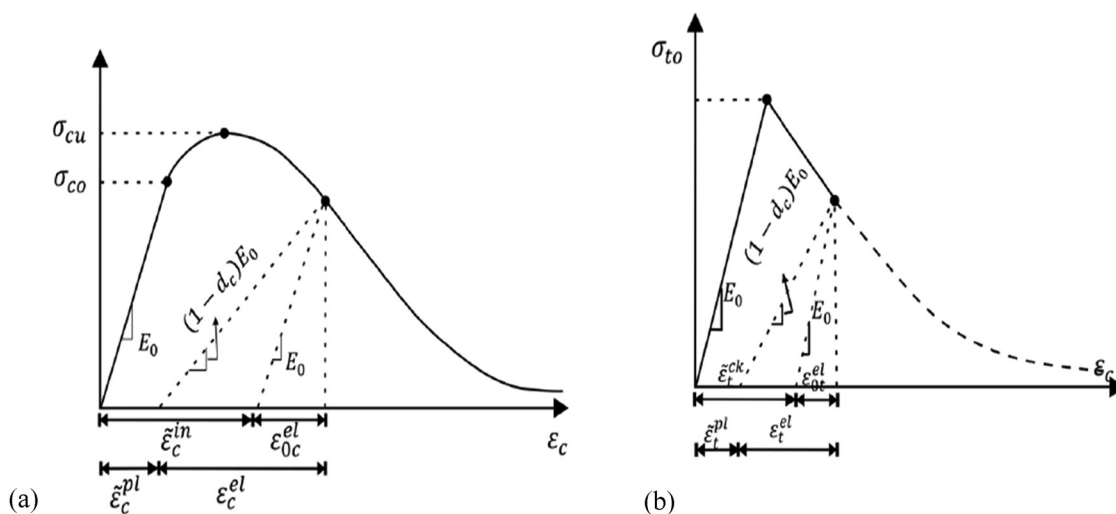


Figure 4: Modeling concrete damage plasticity (CDP): (a) models of compression and (b) models of tension.



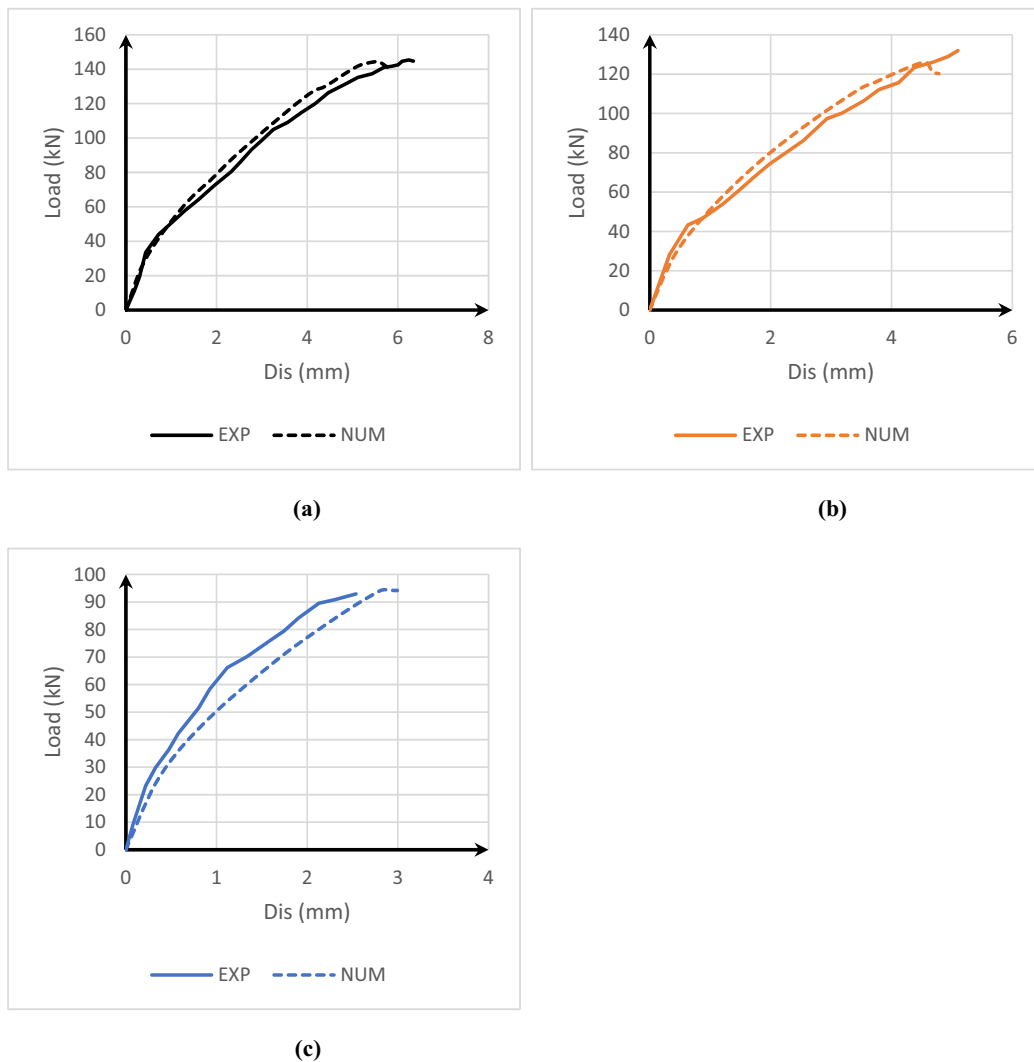
## 4 Results and discussion

### 4.1 Model validation

Figure 5 displays the results of a comparison between computational and experimental load–deflection curves for a control RC beam with no apertures and an RC beam with openings near the support. For all beams, the results of the FE analysis and the experimental data correspond quite well. The correlation coefficient typically ranges within reasonable thresholds of (0.003–0.045). Because the FE analysis assumes a perfect connection between the concrete and the steel reinforcement, the beam is usually seen as stronger and somewhat stiffer than it is. Additionally, the results demonstrate that a cohesive zone material

constitutive model yields high agreement when compared to experimental data. The comparison's goal is to verify the accuracy and sufficiency of all simulation procedures, such as element type, material properties, and convergence criteria.

ABAQUS may produce results that are roughly in agreement with those from actual experiments, while there are also discrepancies between the analyzed values and those obtained experimentally. It is illustrated with pictures. However, the actual concrete's constitution is quite complex, containing cement, sand, gravel, and so on, and these assumptions are not met in FE simulations. Their complex interaction is not simply duplicated by a single form. While the embedded technology used in FE analysis' processing of the connection between concrete and steel greatly simplifies modeling, this impact is not



**Figure 5:** Load–deflection curves: an experimental *versus* numerical comparison of validation study beams: (a) load *versus* deflection of B0, (b) load *versus* deflection of B1, and (c) load *versus* deflection of B2.

replicated with an increase in the load of RC or a shift in the nature of the friction moment, especially in the context of reinforced slip simulation. This has the potential to produce skewed findings. Convergence of the FE analysis, appropriateness of simulation parameter values, shape and number of FE division, casting quality, and loading

circumstances of the beam in the test all play a role in influencing the final conclusions of the analysis.

In conclusion, the FE method for nonlinear analysis of beam tests is practical, and the simulation test of RC using FEs is quite close to the real thing. It is a no-brainer crack development simulated using FEs (Figure 6) (Table 1).

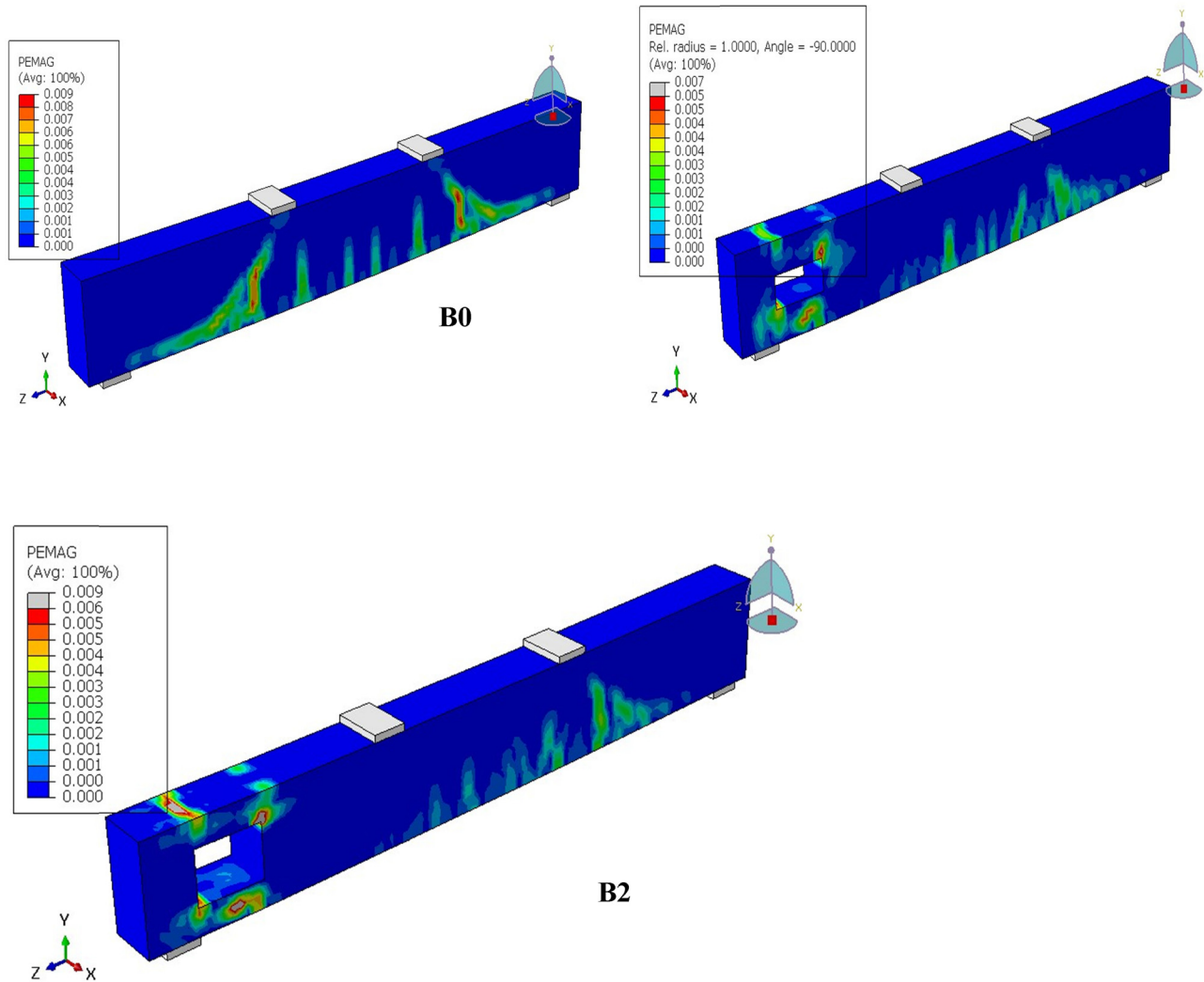


Figure 6: FE validation models crack propagation.

Table 1: Comparison load and deflection of the failure

| Beam | Opening size | Distance from support in mm | Experimental ultimate load kN ( $P_{ex}$ ) | Numerical ultimate load kN ( $P_{num}$ ) | Experimental deflection ( $Def_{ex}$ ) | Numerical deflection ( $Def_{num}$ ) | $P_{num}/P_{ex}$ | $Def_{num}/Def_{ex}$ |
|------|--------------|-----------------------------|--------------------------------------------|------------------------------------------|----------------------------------------|--------------------------------------|------------------|----------------------|
| B0   | —            | —                           | 144                                        | 144.469                                  | 6.341                                  | 5.540                                | 1.003            | 0.873                |
| B1   | 200 × 100    | 0                           | 132                                        | 125.952                                  | 5.100                                  | 4.561                                | 0.954            | 0.894                |
| B2   | 200 × 150    | 0                           | 93                                         | 94.508                                   | 2.539                                  | 2.874                                | 1.016            | 1.132                |

## 4.2 Effect of the distance of openings from supports

As was noted, the experimental sample from a prior work has been successfully simulated within the FE model. However, more research into the effect of varying opening distances from the support is warranted. This is achieved in practice by varying the distance from the support, as illustrated in Table 2. The effect of two different aperture widths and two different distances from support on the structural behavior of the considered RC beam is investigated. The models have also been compared to the first numerical model. Figure 7 compares the proposed numerical four models' mid-span deflection to that of the original model.

The fracture geometry of the failed beams tested is depicted in the elevation view in Figure 8. Spacious cracks at the openings zone and tiny flexural cracks at the mid-span are visible in beams B1 and B2. There was no discernible difference in the mode of failure between a solid beam and one with an aperture. These beams, as well as the standard beam B0, failed in a shear failure due to diagonal tension in the shear span zone. However, diagonal cracking occurred quickly once the openings were introduced, and the load at the first crack decreased as opening dimensions grew larger. Since there was no additional reinforcing at the opening's corners, the fissures there were likewise much larger. The hole also diminished the beams' maximum load-bearing capacity. As the applied stresses were increased, fractures in the shear direction of tension appeared in the shear span surrounding the hole. These fissures extended throughout the shear span, creating a connection between a combination of a loading point and a support. Beams B3, B4, B5, and B6 also broke under shear due to diagonal stress in the shear span zone. The shear fractures propagated along the shear span that was closed off, precisely as they did in the reference beam B0.

The tested beams' load-to-midspan deflection relationship up to failure is depicted in Figure 7. All load–deflection curves have a roughly bilinear form, revealing that concrete behavior precracks and steel behavior post cracks. For the

tested beams one slope transitions into another may be observed to be smooth due to the nonlinearity of the curves. When compared with the reference beam, we notice a decrease in the load by 12.8% when the opening size ( $200 \times 100$ ), and the decrease in bearing the applied loads increase by 21.1% when the opening is 100 mm away from the bracket and by 21.6% when the opening is 200 mm away. As for the opening measuring  $150 \times 200$ , the loads decreased by 34.6% when the opening was adjacent to the support, while it was 29.5% when it was 100 mm away and 34.2% when the opening was 200 mm away. We conclude from this that the change in force decreases with increasing distance from the support.

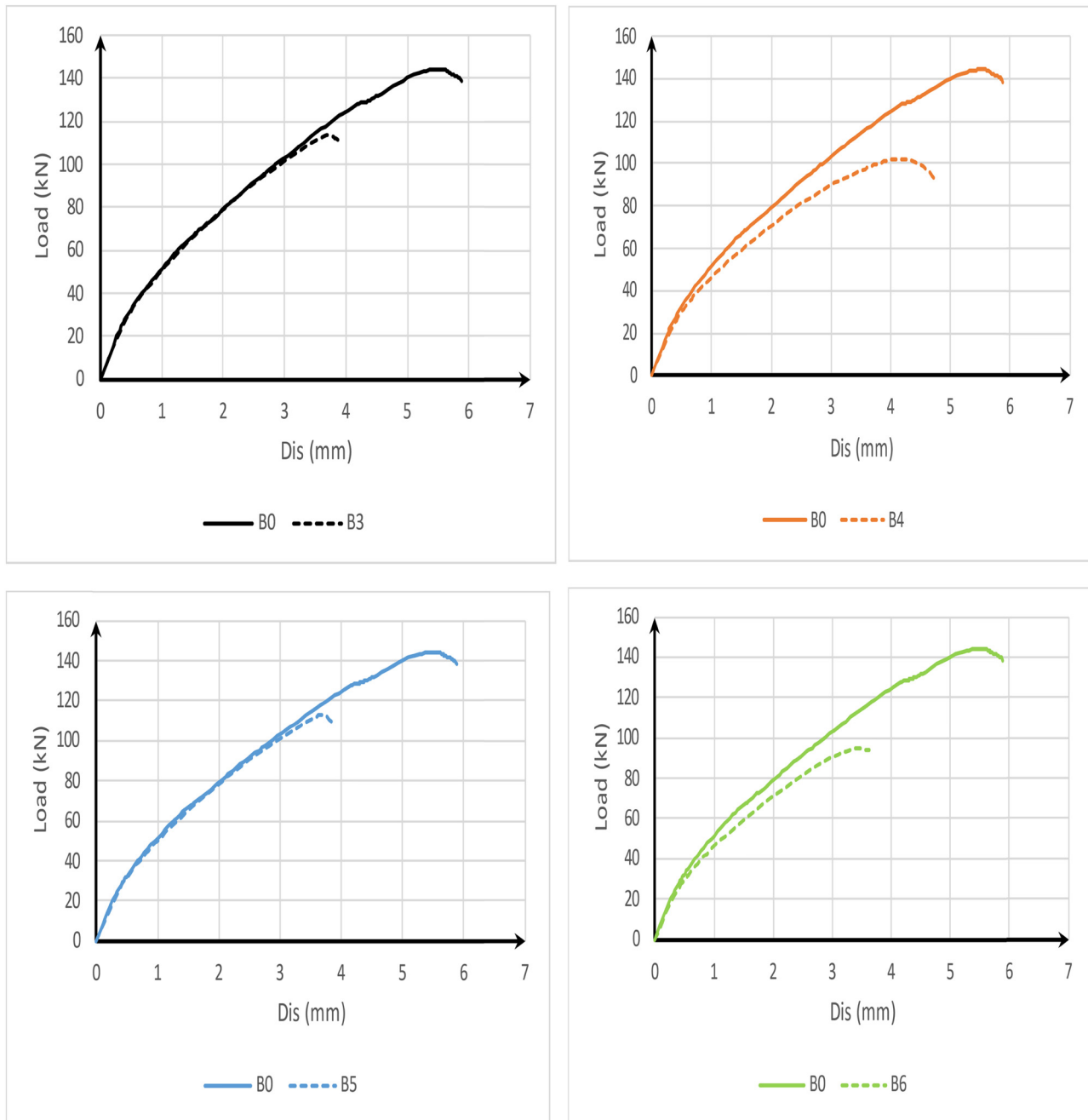
Beams having holes in them had failure deflections between 2.8 and 4.5 mm. Compared to the other beams with apertures, the reference beam failed at a heavier load; therefore, it had a little larger mid-span deflection of 5.5 mm. When contrasting how different beams behave, the influence of the opening size becomes apparent. B1, B2, B3, B4, B5, and B6 with the reference beam B0. Beams B2, B4, and B6 have a similar depth of opening as beams B1, B3, and B5 with a wider width. When compared with the reference sample, we notice a decrease in deflection by 17.7% when the opening is farther from the support for the opening ( $200 \times 100$ ), and the decrease in deflection increases by 32.7% when the opening is 100 mm away from the support and by 32.9% when the opening is 200 mm away as for the opening measuring ( $150 \times 200$ ), the deflection decreased by 48.1% when the opening was adjacent to the support, while it was 22.3 when it was 100 mm away and 34.2% when the opening was 200 mm away.

Figure 7 demonstrates that the load–deflection relationships of beams B1, B2, B3, B4, B5, and B6 were all quite comparable, indicating that the opening width did not have as much of an influence on load–deflection conduct as the opening depth. However, there is no discernible bilinear behavior. The magnitude of the deflection at the opening position to the mid-span deflection remains relatively constant at roughly 0.28 for both the B0 beam and whole beams that have openings.

**Table 2:** FE analysis results and experimental results are compared

| Name | Size             | Distance from support (mm) | Ultimate load (kN) | Decrease of load (%) |
|------|------------------|----------------------------|--------------------|----------------------|
| B1   | $200 \times 100$ | 0                          | 125.952            | —                    |
| B2   | $200 \times 150$ | 0                          | 94.508             | 24.965               |
| B3   | $200 \times 100$ | 100                        | 113.957            | 9.523                |
| B4   | $200 \times 150$ | 100                        | 101.890            | 19.104               |
| B5   | $200 \times 100$ | 200                        | 113.177            | 10.142               |
| B6   | $200 \times 150$ | 200                        | 95.032             | 24.549               |



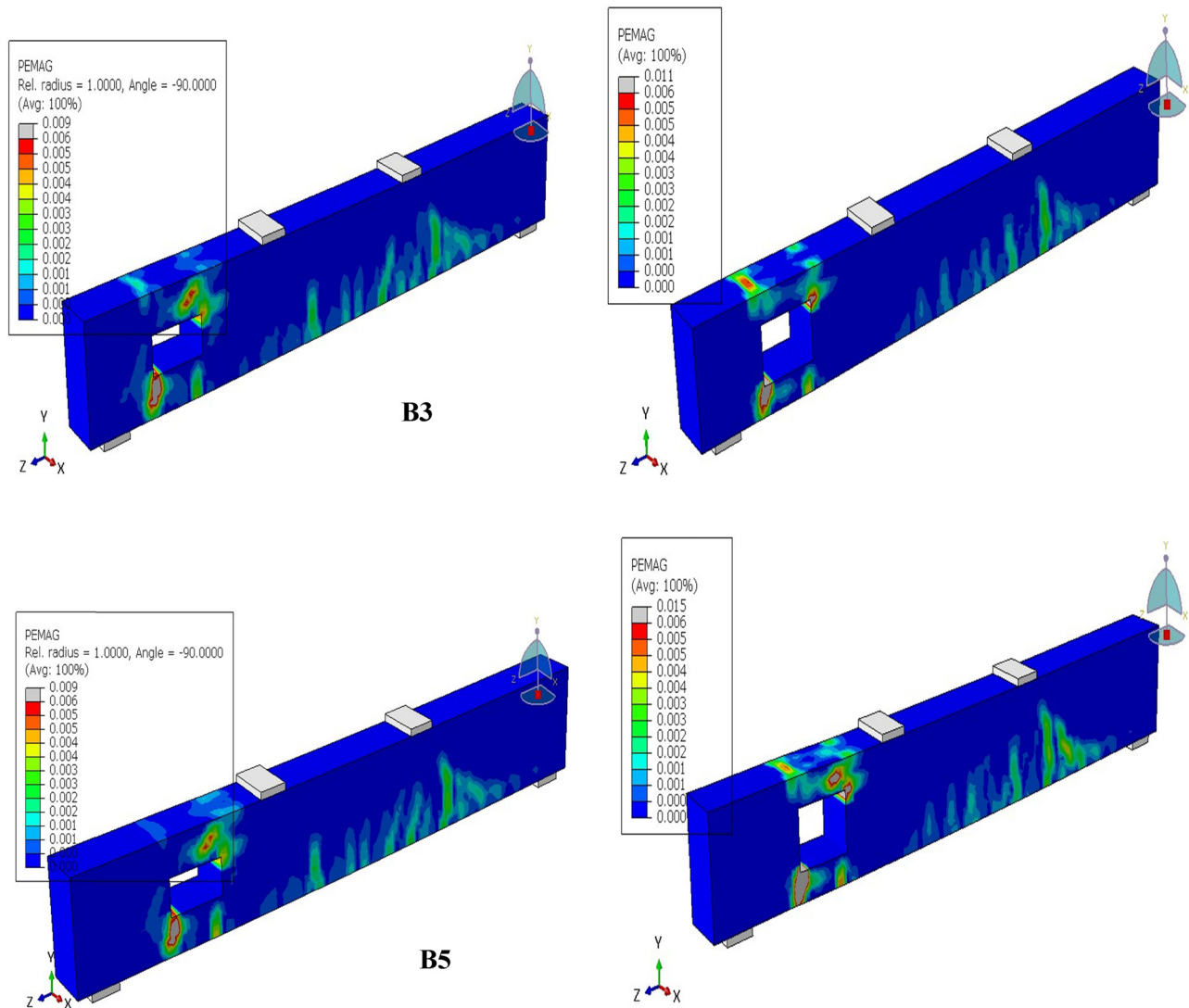


**Figure 7:** Load–deflection curves: an experimental *versus* numerical comparison of parametric study beams.

## 5 Conclusions

There appears to be a pattern in the reactions of the few beams that have been examined; without additional numerical analysis, this may not be enough to demonstrate the repeatability of this study. To simulate the shear behavior of the specimens of RC beams, FE analysis was performed using the ABAQUS program, and the most important findings are shown here.

1. When compared to experimental data for the same geometrical parameters of RC beams, such as dimensions, boundary conditions: loading and supporting conditions, and mechanical features of materials, the results of the FE analysis demonstrated an acceptable level of agreement in general behavior, failure technique, load–deformation, and load capacity. On average, the ultimate load capacity measured in experiments was 0.8% less than what the ABAQUS computer program had



**Figure 8:** FE model crack propagation.

estimated it would be. Although the experimental and numerical results differed in terms of deflection at ultimate loads by an average of 3.3%, the difference was not statistically significant.

2. Every single one of the tested beams failed due to shear, exhibiting a distinct and large crack close to one of the supports as well as tiny flexure cracks close to the midspan.
3. A decrease in shear capacity of up to 24.9% was incurred as a consequence of the insertion of apertures with bigger diameters.
4. As a result of the pre-cracking tendency of concrete being so prominent, and steel behavior after cracking, all RC beams exhibited almost similar load–deflection characteristics. These relationships were observed for all beams.

5. The beams that had apertures in them had failure deflections that varied from 2.8 to 4.5 mm, which were lower than the failure deflections of solid beams.

6. Beams with tiny aperture sizes exhibited load–deflection behavior that was comparable to that of the solid beam that served as the reference.

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**Conflict of interest:** The author states no conflict of interest.

**Data availability statement:** Data sharing does not apply to this article as no datasets were generated or analyzed during the current study.

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