



A Material Model Approach on the Deflection and Crack Pattern in Different Panels of the RCC Flat Plate using Finite Element Analysis

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Abstract

Three reinforced cement concrete (RCC) flat plate panels, namely interior, edge, and corner panels, were considered for evaluating the deflection and crack development from the column. In this study, a numerical analysis was conducted for a steel fibre-reinforced flat plate with steel fibre volumes of 0.3% and 0.4%. The study was conducted on real- and scaled-sized flat plates. We used the ABAQUS software to model and evaluate the deflection and crack patterns. An experimental study was conducted on the scaled-sized specimens to validate the finite element analysis (FEA) results. This study presents the punching shear behaviour of various panels of a flat plate with and without steel fibres. The deflection values obtained from the FEA and experiment were compared, and we found that the interior panel exhibited better results when compared to edge and corner panels. A minimum of three sided support is preferred for the stability of a larger-sized flat plate. The interior panels provided better strength and load-bearing capacity when compared to edge and corner panels. Crack patterns for different panels of a flat plate with different steel fibre volumes were analysed by comparing the FEA and experimental results. The development of cracks moved away from the column face on addition of steel fibres and changed its brittle nature. The results indicate that the crack developed from the column face is away from the critical distance $d/2$ from the slab-column junction (specimens with fibre), further demonstrating the stability of the structure.

Keywords: RCC Flat Plate; Steel Fibers; Punching Shear; ABAQUS; Deflection; Crack Pattern.

1. Introduction

Recently, RCC flat plates have been gaining popularity in the construction of commercial structures. Several commercial buildings such as parking garages, public halls, libraries, and auditoriums prefer flat plate construction owing to its advantages over conventional slab systems. Flat plates are plates that lie on the column without providing beams. The absence of the beam reduces the floor height and provides an attractive appearance. The benefits of a flat plate include ease of construction, stiffness, simple formwork, and low cost [1]. However, there are some drawbacks to flat-plate construction, the major one being the punching shear failure. The transfer of unbalanced shear force and moments near the slab-column connection accounts for the punching shear, and its failure is unsafe owing to its brittleness. During punching shear failure, which is often unforeseen, the plate detaches from the column, further resulting in the collapse of the structure [2]. There are several methods by which we can improve the punching shear capacity of flat plates, they are: by enhancing plate thickness, placing drop panels and column heads [3]. The moments are maximum near the slab-column connected to the flat plate. Hence, the thickening of the plate near the plate-column junction by placing a drop panel and column head is one method to withstand the punching shear. Many studies have

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explained the ability of steel fibers in improving the punching shear strength, and thereby, providing a warning before failure [4]. Hence, this work aimed to study the behaviour of steel fiber-reinforced concrete flat plates against punching shear with two different volumes of steel fiber. We used hooked-end steel fibers with volumes of 0.3% and 0.4%. Different panels of the flat plate, namely interior, edge, and corner panels were considered for the study, and we observed deflection of the different panels of the flat plate. The crack patterns formed in various flat-plate panels and their distances from the measured column face are presented in this paper. We used the finite element software, ABAQUS, for the numerical study. A flat plate was modelled and analysed, and an experimental study was conducted to validate the finite-element results with the test results. This study evaluated the performance of different panels of steel fiber-reinforced concrete flat plates, and demonstrated the effectiveness of the steel fiber-reinforced concrete flat plate against punching shear failure under different support conditions.

Several researchers have concluded that steel fibers can improve the punching shear strength of flat plates and caution the collapse of the structure. Most of the experiments were conducted on flat plates with steel fibre volumes of 0.25%, 0.5%, and 1%. This study aims to analyse the deflection and crack patterns of various flat-plate panels with steel fibre volumes of 0.3% and 0.4%. Therefore, this study benefits the structural engineers and researchers by developing a better understanding of the behaviour of steel fiber-reinforced flat plates with volumes of 0.3% and 0.4%.

2. Literature Review

Several researchers have conducted studies on flat-plate designs based on various code provisions. In this study, the literature review varies with the collection of research from different areas and is listed in separate sections.

2.1. Steel Fiber Reinforced Flat plate

The available literature indicates the effectiveness of steel fiber reinforced concrete against punching shear failure. Elstner and Hognestad [5], and Moe [6] initiated studies on punching shear in slabs by conducting experiments. Different methods for improving punching shear strength of the flat plate include providing a shear band made of thin steel strips with holes, shear reinforcement, shear studs, fiber-reinforced polymers or bonded reinforced concrete overlays, improving the support conditions, and post-tensioning [7-11]. Qian and Li studied the effect of drop panels in flat slabs for strengthening the punching shear [12]. They conducted an experimental study to compare the effectiveness of drop panels. The study focused on the behaviour of drop panels, such as the load-displacement, crack pattern, and failure mechanism. The test specimens with drop panels were found to significantly increase the overall performance. The increase in the steel fiber volume significantly affected the punching shear, stiffness, and ductility [13]. The flexural strength of the specimen increased with an increase in the volume of steel fibers [14]. Barros and Figueiras (1999) [15], and Tegos and Tsonos (1996) [16] concluded that steel fibers in concrete could reduce the crack opening and improve the load-bearing capacity. The energy dissipation capacity and ductility can be increased by implementing the steel fiber-reinforced concrete (SFRC).

Nguyen-Minh et al. [17] conducted an experimental study to determine the punching shear behaviour of steel fiber-reinforced concrete with different steel fibre volume percentages. Their study demonstrated that steel fibers can achieve good results against punching shear failure. It was observed that steel fiber-reinforced concrete increased the punching shear resistance by 39%, the deflection was reduced by 36%, and the crack width was decreased by 40%. The addition of steel fibers improved the deformation capacity, modulus of rupture, splitting tensile strength, and toughness index, resulting in the failure [18-20]. Tan and Venkateshwaran [21] conducted an experimental study on the punching shear behaviour of SFRC slabs with or without traditional steel bar reinforcement. This study provides a model for predicting the punching shear capacity and mode of failure. Zamri et al. [22] conducted an experimental study on the punching shear behaviour of steel-fiber-reinforced flat slabs. The increase in the volume of steel fibers enhances the punching shear capacity, and steel fibers can bridge cracks based on the distribution and orientation of the fibers.

2.2. ABAQUS

FEA plays a vital role in predicting the behaviour of members under different loading conditions. Several authors have proposed FEA using the ABAQUS software for analyzing different types of structures. Various parameters were considered in the ABAQUS for structural modelling. The concrete damaged plasticity model was used for the numerical modelling of the specimen and for reviewing the mode of failure and crack pattern of the flat plate against punching shear [23]. The predictive model was in good agreement with the experimental results. As per the Indian standard code provision, two different methods for analyzing flat slabs are prescribed: the direct design method and the equivalent frame method. Chavan and Tande [24], and Setiawan et al. [25] conducted a comparative study on different methods, such as the direct design method, equivalent frame method, and FEA. It was concluded that the equivalent frame method provides more accurate results when compared to the direct design method; however, these were not satisfactory. Hence, the finite element method using finite element software was considered the most suitable method for analyzing flat plates. The flat plates with shear studs provided in orthogonal, radial, and critical perimeters were modelled in the

ABAQUS. A linear analysis of the shear stress distribution for a flat plate with and without a shear stud was performed [9, 10]. A study on the crack simulation of reinforced concrete beams using the ABAQUS was conducted by Wahalathantri et al. [26]. Two finite element models of the reinforced concrete beam were modelled using the ABAQUS and it was validated with experimental results. The stress-strain relationship, crack pattern, and displacements were compared, and good agreement was observed between the numerical technique and experiment. The ABAQUS was used to model and analyse the interior and edge slab column connection specimens under static and reversed cyclic and horizontal loading conditions by Genikomsou and Polak [23].

The damaged plasticity model was used to analyse the modes of failure and crack patterns. Experiment was conducted to validate these results. The deflection, strength, and crack patterns obtained from the experimental study were compared with the ABAQUS results. The results were in good agreement and further demonstrated the ability of FEA to deliver a consensus of punching shear failure and crack patterns. Abbas et al. [27] conducted a nonlinear analysis of flat slabs using ABAQUS. This study investigated the structural behaviour of flat slabs with Z-shape shear reinforcements. A comparative study of the ABAQUS results and experimental results was carried out, and it was concluded that the Z-shaped shear reinforcement improved the punching shear strength. Another comparative study of the experimental and finite element analyses using the ABAQUS was conducted by Khan et al. [28] for steel fiber-reinforced slabs which provided good results. The accuracy of the concrete strength for the prediction of punching shear behaviour using the ABAQUS was analysed and compared with experimental results which provided good results [29]. Most of the existing literature demonstrates that finite element analysis was conducted for steel fiber-reinforced concrete with 0.25 %, 0.5 %, 1%, and 1.5% steel fibers. Therefore, in this study, we have presented the effectiveness of finite element analysis of different flat plate panels with steel fiber-reinforced concrete with steel fiber volumes of 0.3% and 0.4%.

3. Research Significance

This study aims to analyse the deflection and crack patterns of various flat-plate panels with two different volume fractions of steel fibers. The ABAQUS model was developed, and the crack patterns were studied and compared with the experimental results with and without steel fibers for three different panels (small-scale models). This study can benefit structural engineers and researchers to gain further understanding of the punching shear behaviour of steel fiber-reinforced flat plates with steel fiber volumes of 0.3% and 0.4%, and provides evidence for the validation of existing data. Figure 1 illustrates the research methodology used in this study.

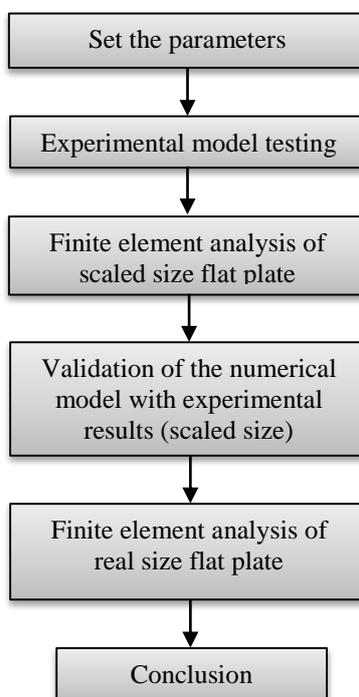


Figure 1. Research Methodology Flow Chart

4. Finite Element Modelling of Scaled-Size Flat Plate

FEM is a numerical tool used for modelling and solving complex problems with high accuracy. In this study, the ABAQUS software was used to model and analyse the flat plate. There are three types of crack model in ABAQUS: brittle crack concrete model, smeared crack concrete model and concrete damaged plasticity model [30]. The brittle

crack model is not suitable for this study as it is subjected to tensile cracking. The smeared concrete crack model is a traditional model that consists of an isotropic hardening yield surface with the associated flow that is subjected to compressive and independent cracks. In this study, we used the concrete damaged plasticity model to analyse the flat plate model as it uses the feature of isotropic damaged elasticity in an arrangement with isotropic tensile and compressive plasticity which signifies the inelastic behaviour of concrete. Another main reason for selecting the concrete damaged plasticity model is its stiffness recovery effect which is a very important factor for modelling steel fiber-reinforced concrete.

In this study, a scaled-sized model of the flat plate was modelled and analysed. An experimental study was conducted to validate the FEA results. Hence, we conducted an experimental study on scaled-sized specimens. The dimensions of the scaled model were 300 mm × 300 mm with a thickness of 50 mm. A 100 mm × 100 mm column was placed at the centre to support the flat plate. The column depth was 200 mm. The flexural reinforcement was considered as the bottom reinforcement, which was provided to the specimens in both orthogonal directions with bars of diameter 6 mm with a spacing of 50 mm. A nominal cover of 20 mm was applied to the bottom reinforcement. Reinforcement of 6 mm diameter bars with a development length of 50 mm was provided as the longitudinal reinforcement for the column, and a load was applied to the columns. The material properties were assigned to the scaled-sized model by using a property module. The material properties include the general, elastic, and plastic properties. The reinforced concrete material properties were set for the test specimens accordingly, and the values are listed in Table 1. The appropriate values for the compressive and tensile stress-strain behaviour of concrete from the ABAQUS user manual [30] were considered, and the values are listed in Tables 2 and 3.

Table 1. Material properties of concrete and steel

Properties	Concrete	Steel
Density	2400 kg/m ³	7700 kg/m ³
Young's modulus (N/mm ²)	27386.12	200000
Poisson's ratio	0.15	0.25

Table 2. Compressive behaviour of concrete material

Yield Stress (N/mm ²)	Inelastic strain
24.00	0
29.20	0.0004
31.70	0.0008
32.30	0.0012
31.76	0.0016
30.37	0.0020
28.50	0.0024
21.90	0.0036
14.89	0.0050
2.95	0.01

Table 3. Tensile behaviour of concrete material

Stress (N/mm ²)	Cracking strain
1.780	0
1.450	0.0001
1.113	0.0003
0.960	0.0004
0.800	0.0005
0.536	0.0008
0.356	0.0010
0.161	0.0020

For concrete damaged plasticity model, specific plastic properties such as dilation angle Ψ , flow potential eccentricity, initial biaxial/uniaxial ratio σ_{co}/σ_{bo} , the proportion of second stress invariant on the tensile meridian and compressive meridian Kc , viscosity parameter μ need to be defined and the values for each parameter are listed in Tables 4 and 5.

Table 4. Parameters defined in concrete damaged plasticity model without steel fiber

Plasticity parameters	Value
Dilation angle Ψ	12°
Eccentricity	0.1
Viscosity	0.05
Kc parameter	0.667
Initial biaxial/uniaxial ratio σ_{co}/σ_{bo}	1.16

Table 5. Parameters defined in concrete damaged plasticity model with steel fiber

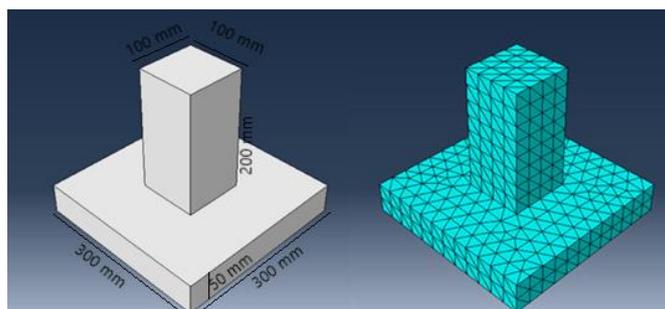
Plasticity parameters	Value
Dilation angle Ψ	36.31°
Eccentricity	0.1
Viscosity	0.05
Kc parameter	0.67
Initial biaxial/uniaxial ratio σ_{co}/σ_{bo}	1.16

These factors depend on the yield surfaces of the concrete components and are explained below [10].

- Dilation angle: The proportion of change in volume to shear strain. It controls the plastic volumetric strain imposed during plastic shearing.
- Eccentricity: A small value used for correcting the shape of the plastic potential surface. It is calculated as the proportion of the tensile strength and compressive strength.
- Initial biaxial/uniaxial ratio: The ratio of the initial biaxial compressive strength to the uniaxial compressive strength. It is denoted by σ_{co}/σ_{bo} .
- Viscosity: The viscosity parameter is considered to be 0.05 which is used for convergence difficulties.
- Kc parameter: The proportion of the second stress invariant on the tensile stress meridian and compressive stress meridian.

In the ABAQUS, the slab and column were modelled as three-dimensional deformable solid extrusion parts and the reinforcement as three-dimensional deformable planar wire parts. The module was used to model the structure. The slab and column were modelled separately in this module. The material properties, sections, beam section profiles, and orientation were defined by using the property module and were assigned to each part. In general properties, the density, Young's modulus, and Poisson's ratio were assigned to concrete and steel. Therefore, the concrete damaged plasticity model was used to assign the plastic properties to the concrete. In the ABAQUS, the slab and column were created separately in two parts. After placing the reinforcement in the slab and column, the two parts were merged by using the merge option in the assembly module to make them monolithic structures.

The next important step in the ABAQUS is the meshing, which plays a significant role in the FEA method and was performed using the ABAQUS mesh module. Flat plates and columns were modelled using eight-noded brick elements (C3D8R). The reinforcement of the plates and column adopted two noded linear three-dimensional (3D) truss elements, T3D3. Two noded brick elements were used for meshing the stirrups. The monolithic structure was developed by merging the plate and column and was meshed using tetrahedral element C3D4. The ABAQUS model specimen contained 2992 mesh elements and 519 nodes. The final step was to generate a job for running the analysis using the job module. The deflected shapes and results of the analysis were obtained using the visualization module. Figure 2 depicts the scaled-size finite element flat plate model with dimensions of 300×300 mm.

**Figure 2. ABAQUS model of scaled size flat plate (300×300 mm)**

4.1. Deflected Finite Element Model of Scaled-Sized Flat Plate

This study was conducted to analyse the different test specimens with two volumes of steel fibers. The percentage of steel fiber volumes considered for this study were 0.3 and 0.4%. The analysis was performed for different panels under different support conditions. The panels considered for the analysis were the interior, edge, and corner panels [31] which were categorized based on the boundary conditions. The interior panels have rigid support on four sides. The edge panels are three side-supported panels, and for corner panels, two of its sides are supported. The load was applied to the column surface, and the deflection values of all panels were analysed for different test specimens, as listed in Table 10. Figures 3 to 5 illustrate the deflected shape and distribution of the deflection values of different scaled-sized flat plate panels.

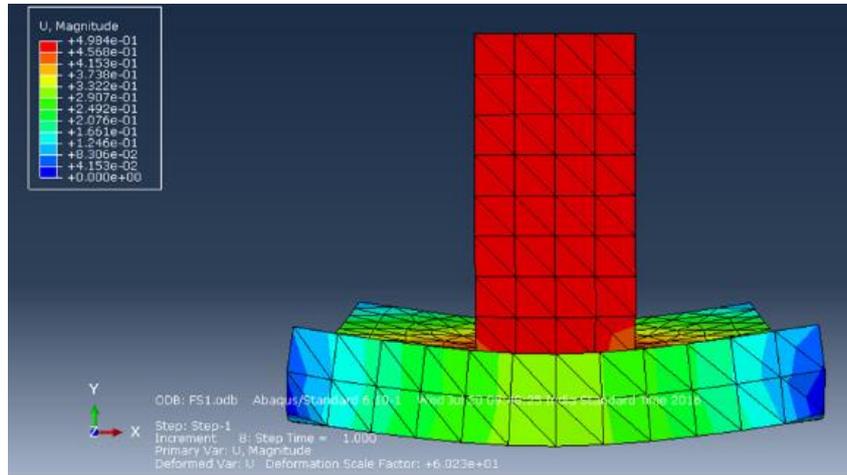


Figure 3. Deflected shape of scaled-sized flat plate (interior panel)

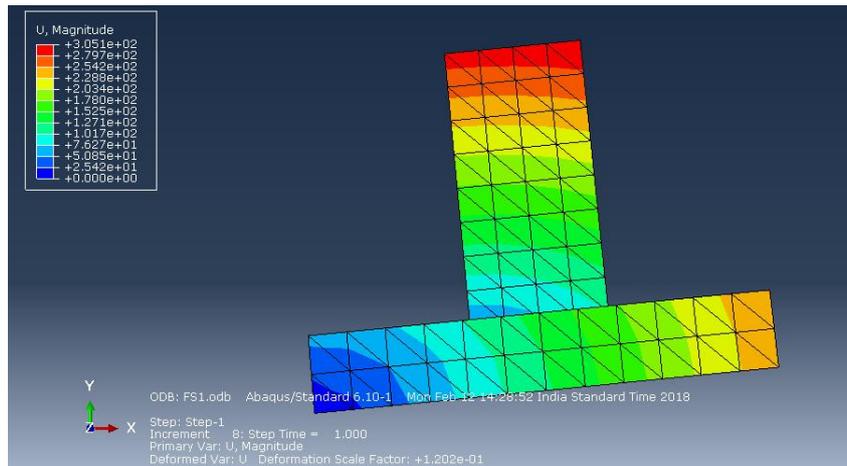


Figure 4. Deflected shape of scaled-sized flat plate (edge panel)

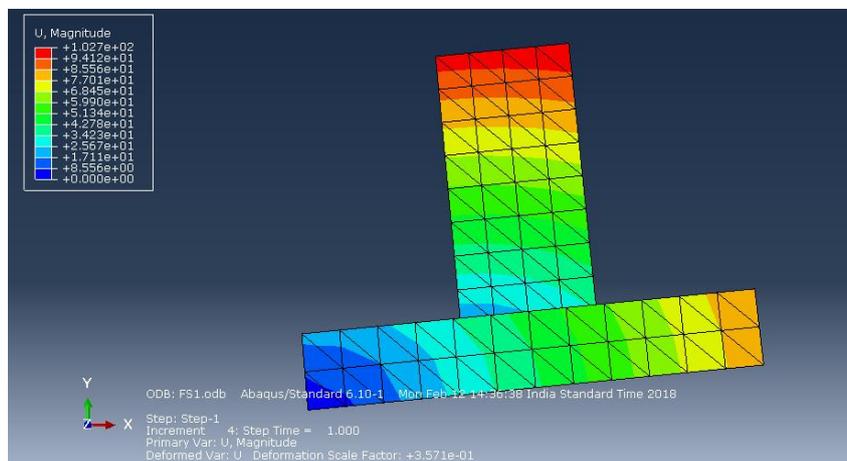


Figure 5. Deflected shape of the scaled-sized flat plate (corner panel)

5. Experimental Programme

We conducted experiments to validate the FEA results. The flat plate dimensions for the experiment were maintained similar to those of the scaled-sized flat plate modelled in ABAQUS (as described in Section 3). The dimensions of the small-scaled model were 300 mm × 300 mm, with a thickness of 50 mm. A column with dimensions of 100 mm × 100 mm and a depth of 200 mm was placed at the centre of the flat plate. The flexural reinforcement was considered as the bottom reinforcement and was provided to the specimens in both orthogonal directions with bars of diameter 6 mm and a spacing of 50 mm. A nominal cover of 20 mm was applied to the bottom reinforcement. Reinforcement of 6 mm diameter bars with a development length of 50 mm was provided as longitudinal reinforcement for the column.

5.1. Experimental Test Specimen

The test samples were cast using ordinary Portland cement, coarse aggregate, fine aggregate, and water [32]. The details of the mix proportion for 1 m³ of concrete are listed in Table 6. We used the concrete of M25 grade and a superplasticiser. The test was conducted on the plates with and without steel fibers. Here, we used Hooked-end steel fibers. The length to diameter ratio of the steel fiber was 60, with a length of 30 mm and a diameter of 0.5 mm. The test specimens used in this study were cast and cured under identical conditions. The demoulded test specimens were cured for 28 days. Figure 6 depicts the scaled test specimen of size 300×300 mm, which was prepared for the experimental study.

Table 6. Proportion of concrete-mix

Materials	Quantity per m ³
Cement (53 grade OPC)	350 kg
Fine aggregate	896 kg
Coarse aggregate	1140 kg
Water	140 l
Superplasticizer	7 kg



Figure 6. Scaled-sized flat plate test specimen for experimental study (300×300 mm)

5.2. Experimental Setup

We conducted the experiment by using a universal testing machine. The columns were loaded at equal intervals. A load was applied to the column until the test specimen failed. The test was conducted for the interior, edge, and corner panels which were classified based on the support conditions. The test was carried out for test specimens with four supported sides (interior panel), three supported sides (edge panel), and two supported sides (corner panel). The deflection values for different panels were noted. A deflectometer was placed near the plate column connection to determine the deflection values. Figure 7 illustrates the experimental setup used in this study.



Figure 7. Experimental setup

5.3. Test on Specimen

Punching shear failure is the primary problem in flat-plate construction. The absence of the beam results in the failure of the structure by transferring the moment, and the local forces cause punching shear failure. Thus, the brittle failure of the structure occurs without any warning further separating the plate and column. Because it is a sudden failure, the deflectometer readings should be taken when the first crack occurs. In this study, all plates were tested under the same load with load increments. A load was applied to the test specimen until it failed with the ultimate load. The first and ultimate crack loads were observed for different panels with different support conditions. Table 7 lists the details of the first crack load and ultimate load for different panels.

Table 7. First crack load and ultimate load for different support panels

Flat Plate	Volume of Steel Fibre					
	0 %		0.3 %		0.4 %	
	First Crack Load	Ultimate Load	First Crack Load	Ultimate Load	First Crack Load	Ultimate Load
Interior	24 kN	31.4 kN	25 kN	33 kN	31 kN	45 kN
Edge	25 kN	31 kN	23 kN	25 kN	25 kN	36 kN
Corner	8 kN	13.3 kN	18 kN	28 kN	30 kN	44 kN

6. Results and Discussion

The FEA and experimental research have indicated that steel fibers enhance the properties of test specimens. Crack patterns for the finite-element scaled-sized model with different support conditions were obtained from the plastic strain model results in the visualization module. These results provided crack patterns around the plate column connections for various panels. The crack patterns and the distance between the cracks from the column face in a scaled-sized flat plate were compared with the cracks in the experimental study to validate the finite element results, as depicted in Figures 8 to 16.

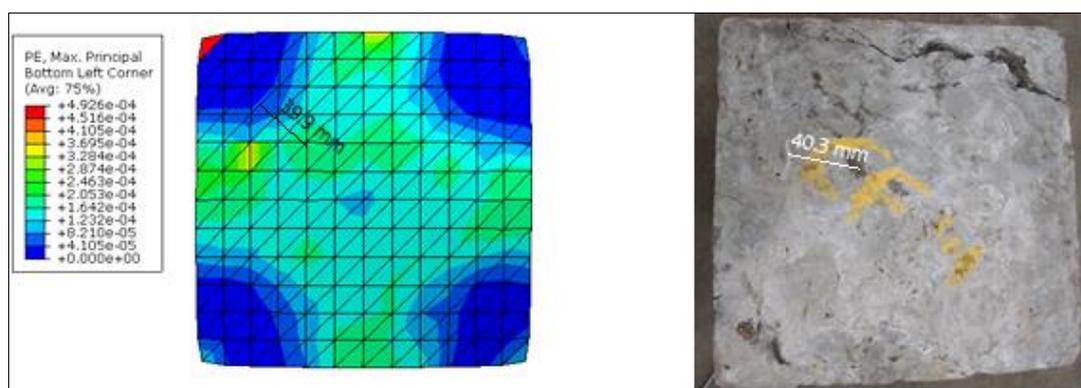


Figure 8. Finite element and experiment crack pattern for scaled-sized plate interior panel (without steel fiber)

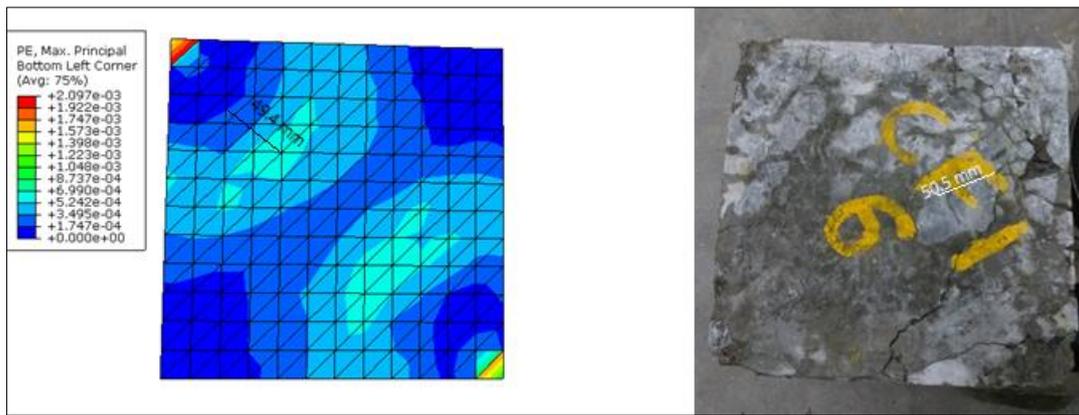


Figure 9. Finite element and experiment crack pattern for scaled-sized plate edge panel (without steel fiber)

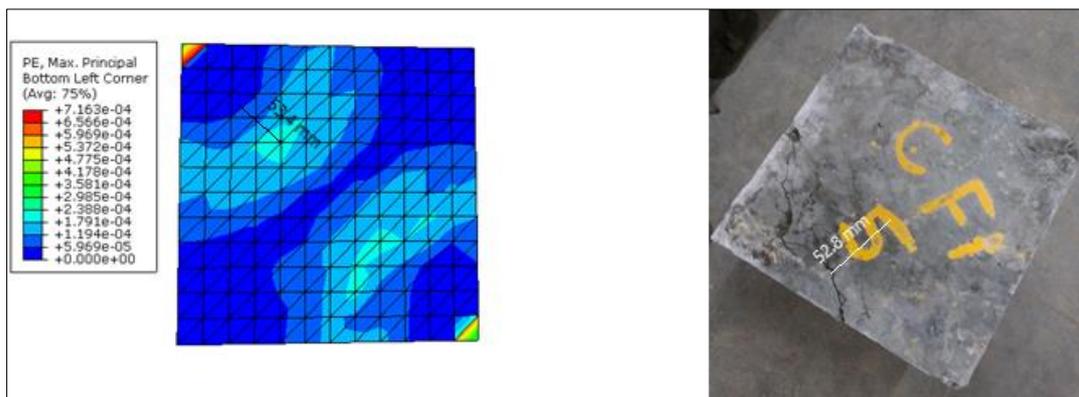


Figure 10. Finite element and experiment crack pattern for scaled-sized plate corner panel (without steel fiber)

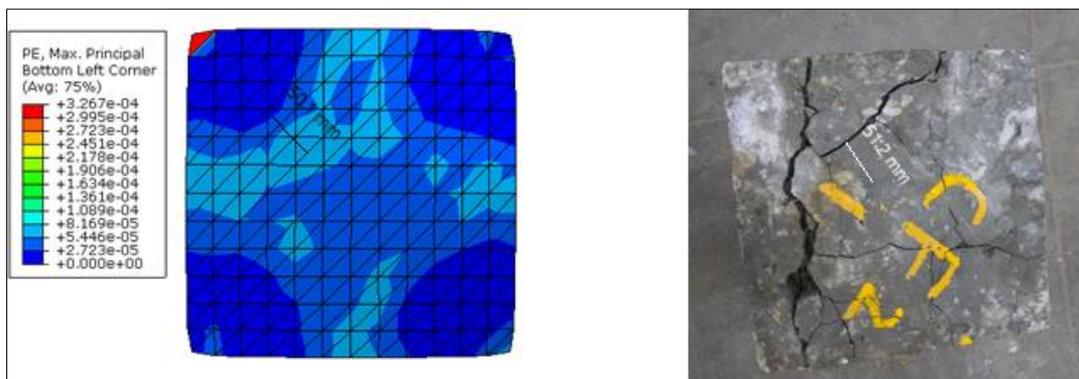


Figure 11. Finite element and experiment crack pattern for scaled-sized plate interior panel (with 0.3% steel fiber)

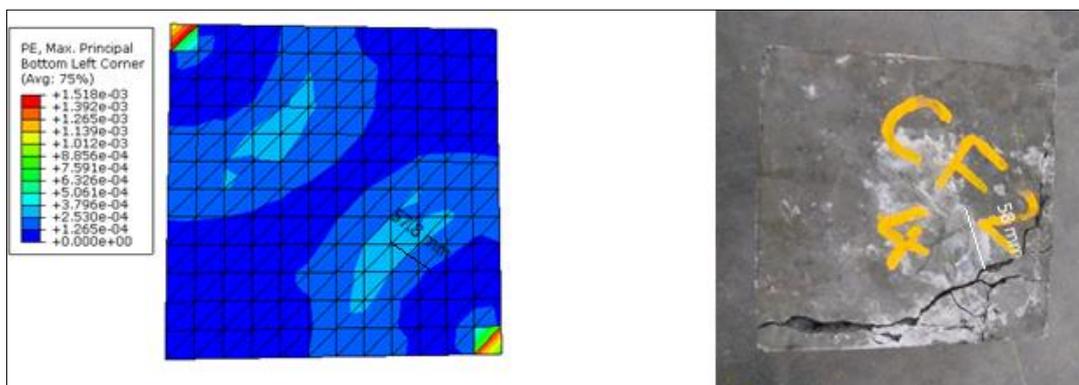


Figure 12. Finite element and experiment crack pattern for scaled-sized plate edge panel (with 0.3% steel fiber)

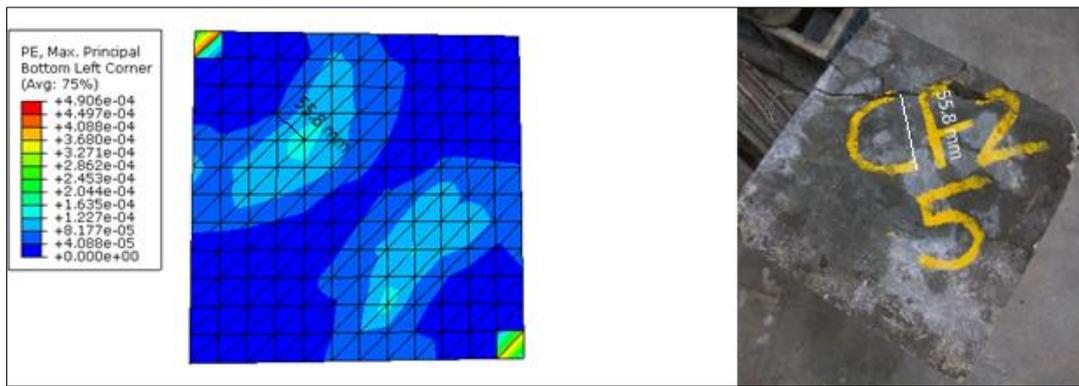


Figure 13. Finite element and experiment crack pattern for scaled-sized plate corner panel (with 0.3% steel fiber)

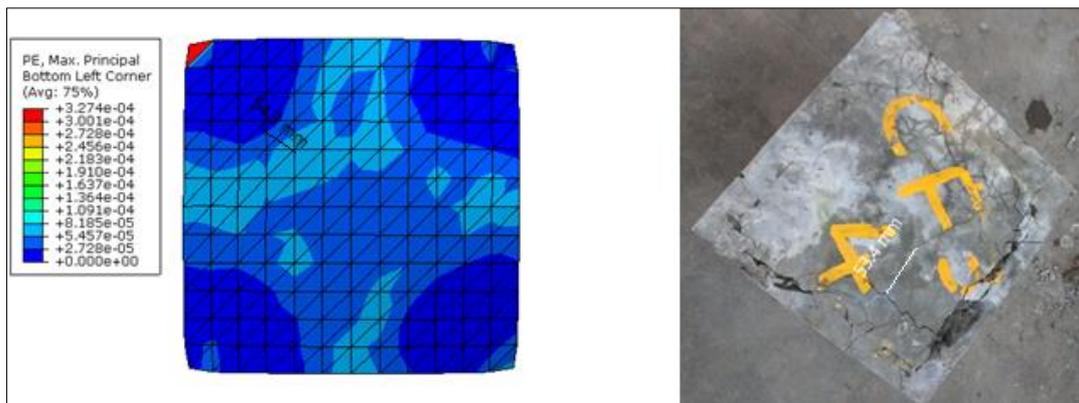


Figure 14. Finite element and experiment crack pattern for scaled-sized plate interior panel (with 0.4% steel fiber)

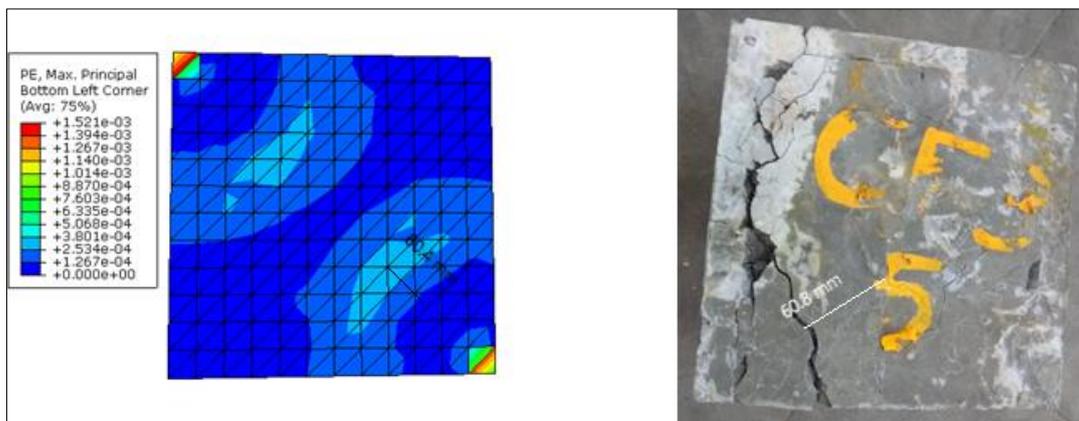


Figure 15. Finite element and experiment crack pattern for scaled-sized plate edge panel (with 0.4% steel fiber)

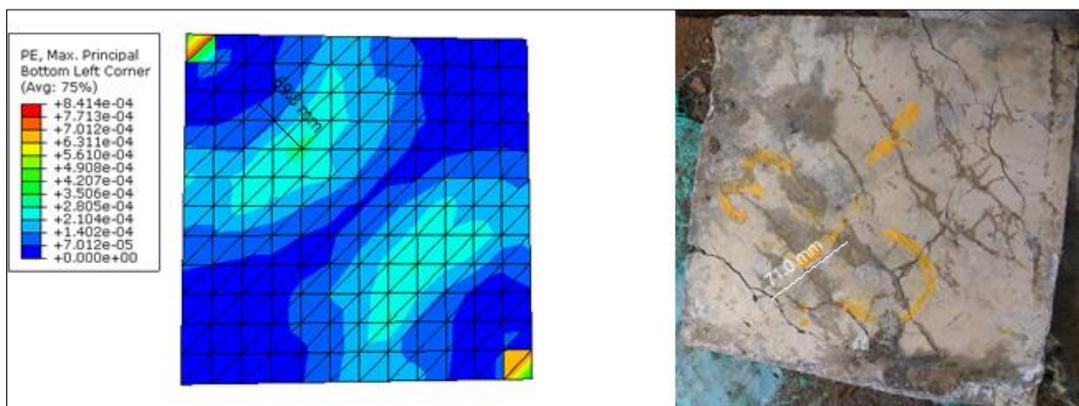


Figure 16. Finite element and experiment crack pattern for scaled-sized plate corner panel (with 0.4% steel fiber)

A comparative study revealed that cracks were developed far from the column with increasing steel fibre content. By incorporating steel fibers, we observed that the bridging property of steel fibers helps the specimen to withstand more load and provides a warning before the structure collapses. The shear stress values were obtained from the ABAQUS results for a scaled-sized flat plate. The ABAQUS evaluated the shear and normal stresses for different panels, and the values were obtained from the ABAQUS results of a scaled-size flat plate. Table 8 lists the shear stress values for the three panels with 0.3% and 0.4% steel fiber volumes.

Table 8. Maximum shear stress values (in MPa) from FEA for scaled-size flat plate

Flat Plate	Steel Fibre Volume		
	0 %	0.3 %	0.4 %
Interior	6.70	5.38	5.38
Edge	9.13	8.81	8.81
Corner	9.82	8.88	8.24

A comparative study of the deflection values for scaled-sized plates was conducted using FEA and experimental results, as indicated in Figure 17. The deflection values of the scaled-sized flat plate from the FEA agreed well with the experimental findings. The interior panel exhibited better strength than the edge and corner panels. The distance of the crack from the column face for the FEA and experimental studies was measured to analyze the structural stability. Tables 9 and 10 compare the crack distances and deflections obtained from FEA and experimental research.

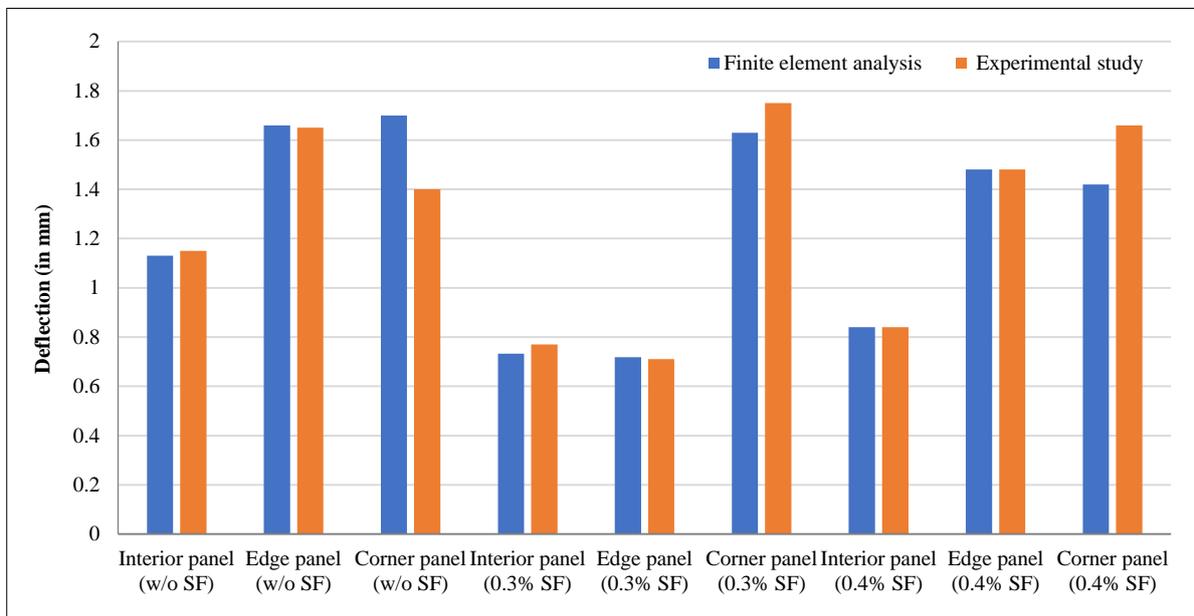


Figure 17. Deflection values of the scaled-size flat plate with different panel

Table 9. Distance between crack and column face obtained from FEA and experiment for scaled-size flat plate

Flat Plate	Distance between crack and column face of scaled-sized specimen (in mm)					
	FEM			Experiment		
	0 %	0.3 %	0.4 %	0 %	0.3 %	0.4 %
Interior	39.9	50.1	54.3	40.3	51.2	53.4
Edge	49.4	57.8	60.4	50.5	58.0	60.8
Corner	53.4	55.8	69.8	52.8	55.8	71.0

Table 10. Deflection values from FEA and experiment for scaled-size flat plate

Flat Plate	Deflection of scaled-sized plate (in mm)								
	0 %			0.3 %			0.4 %		
	FEM	Experiment	Percentage error (%)	FEM	Experiment	Percentage error (%)	FEM	Experiment	Percentage error (%)
Interior	1.13	1.15	1.7	0.732	0.77	4.9	0.84	0.84	0.0
Edge	1.66	1.65	0.6	0.719	0.71	1.3	1.48	1.48	0.0
Corner	1.7	1.4	17.6	1.63	1.75	6.9	1.42	1.66	14.5

7. Finite Element Modelling of Real Size Flat Plate

For the scaled-size flat plate, the finite element model and experimental study provided good results. Therefore, after conducting a scaled-size flat plate study, we conducted a study to observe the deflection and crack patterns of different panels of the actual or real-sized flat plate in the ABAQUS. For this study, a flat plate with dimensions of 6 m × 6 m [33] and a thickness of 220 mm was designed. The flat plate was supported by a column at the centre. The cross section of the column was 500 mm × 500 mm, with a depth of 400 mm. The reinforcement was 10 mm in diameter with 100 mm spacing. We used a clear cover of 20 mm, and the real-sized flat plate was modelled in seven different parts. In the flat-plate system modelling, the column and plate were modelled separately in the part module. After placing the reinforcement at the appropriate location, the plate and column were merged to form a single part. The interaction between steel and concrete was connected by generating embedded constraints. Figure 18 depicts the real size flat plate of 6 m × 6 m modelled in the ABAQUS.

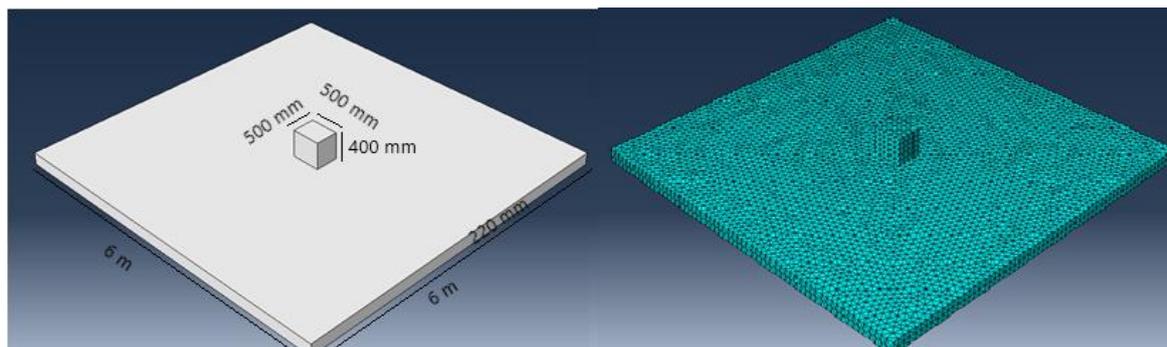


Figure 18. The ABAQUS model of real size flat plate (6 m × 6 m)

For analysing the real-sized flat plate, two panels were considered. In the ABAQUS, a minimum of three-sided support is required for plates with a larger dimension. Therefore, the interior and edge panels were considered for analysing a real-sized flat plate. Hence, a large span should provide peripheral support to reduce the deflection. We found that the interior panel experienced less deflection than the edge panel for a real-sized flat plate, as listed in Table 11 and Figure 19. Figures 20 to 22 illustrate the deflected shapes and crack patterns of different real-sized flat-plate panels.

Table 11. Comparison of deflection and distance between crack and column face obtained in the interior and edge panel of real-sized flat plate

Flat Plate	Deflection of real size plate in mm (FEM)			Distance between crack and column face of real size plate in mm (FEM)		
	0 %	0.3 %	0.4 %	0 %	0.3 %	0.4 %
Interior	2.43	2.68	2.14	1133	1165	1248
Edge	5.66	5.05	5.07	432	500	617

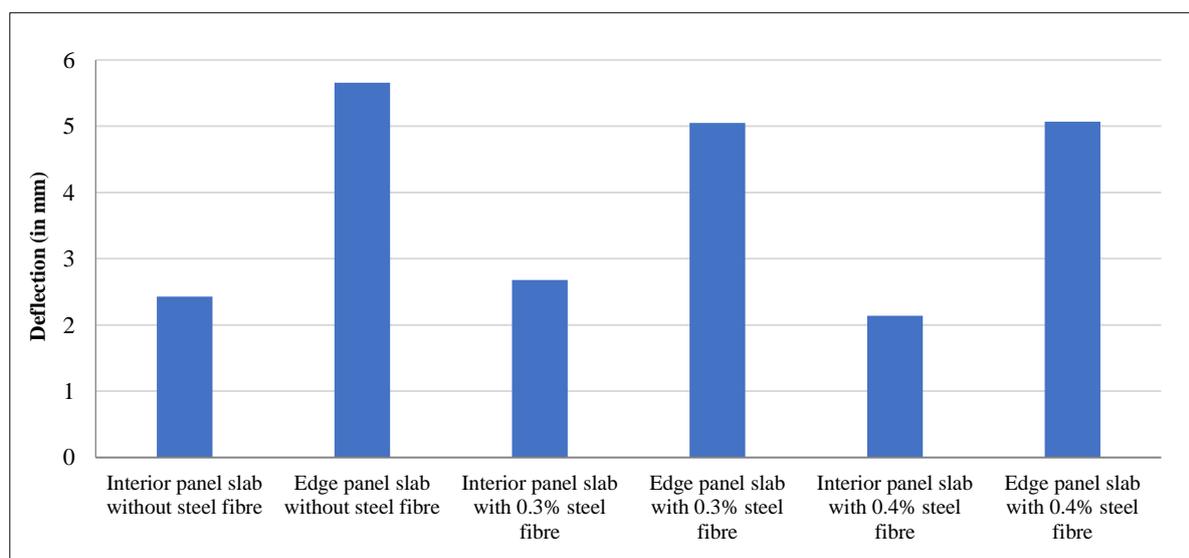


Figure 19. Deflection values of the real-sized flat plate with different support conditions

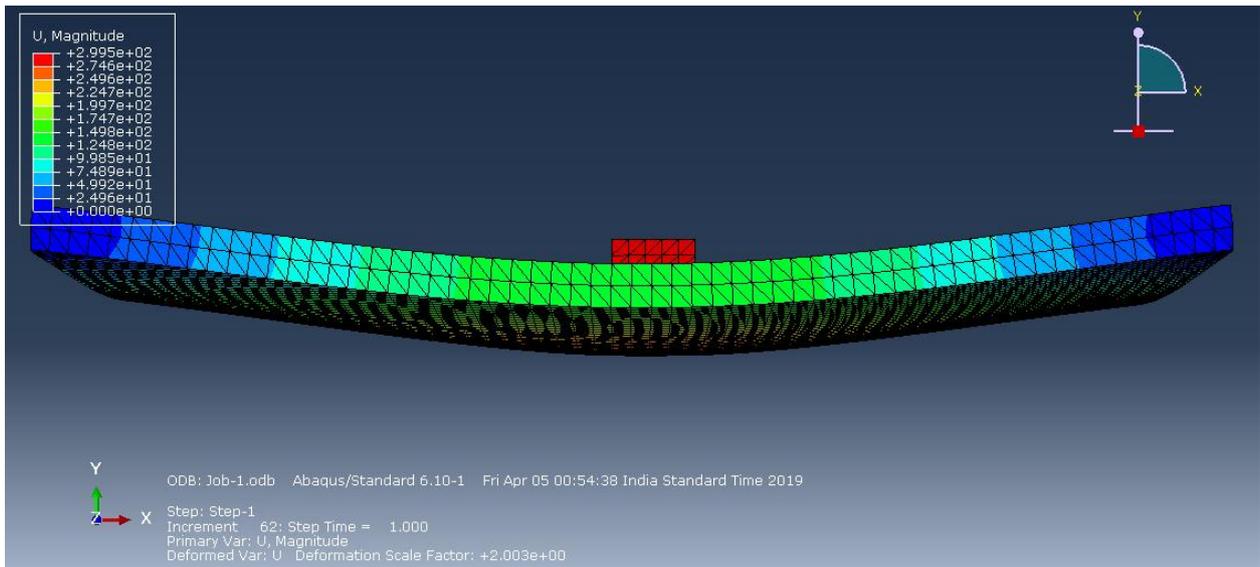


Figure 20. Deflected shape of real-sized flat plate (interior panel)

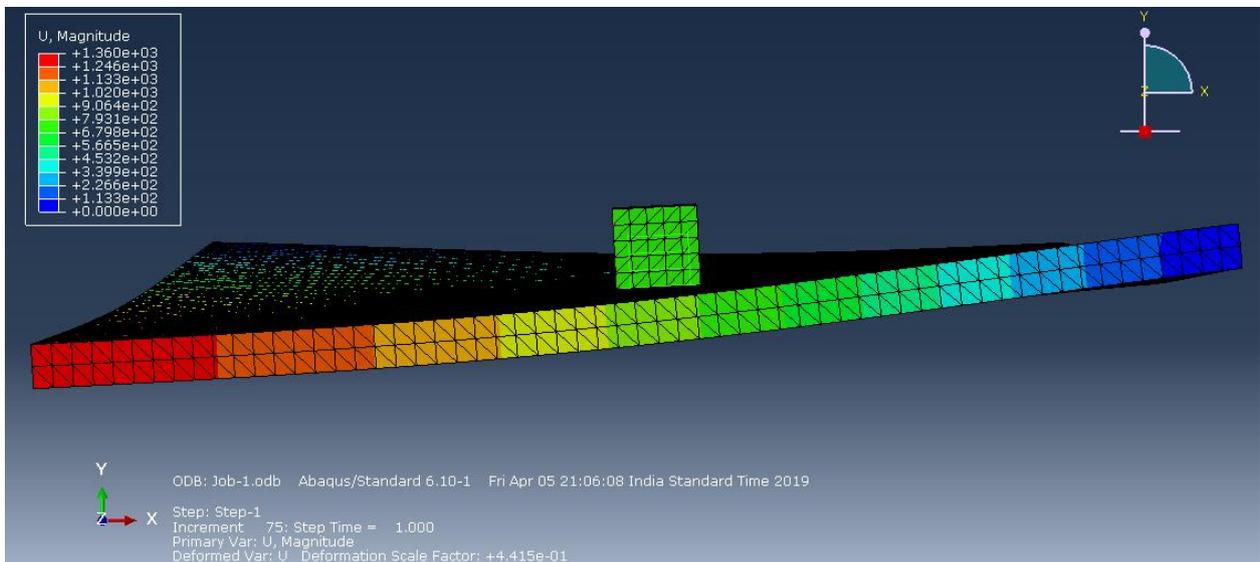
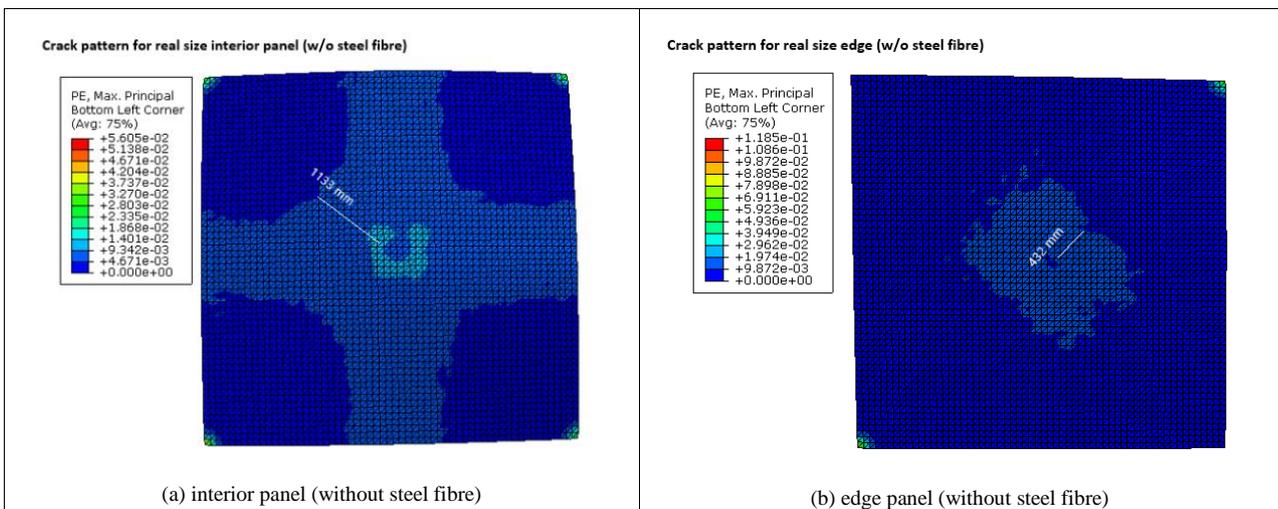


Figure 21. Deflected shape of real-sized flat plate (edge panel)



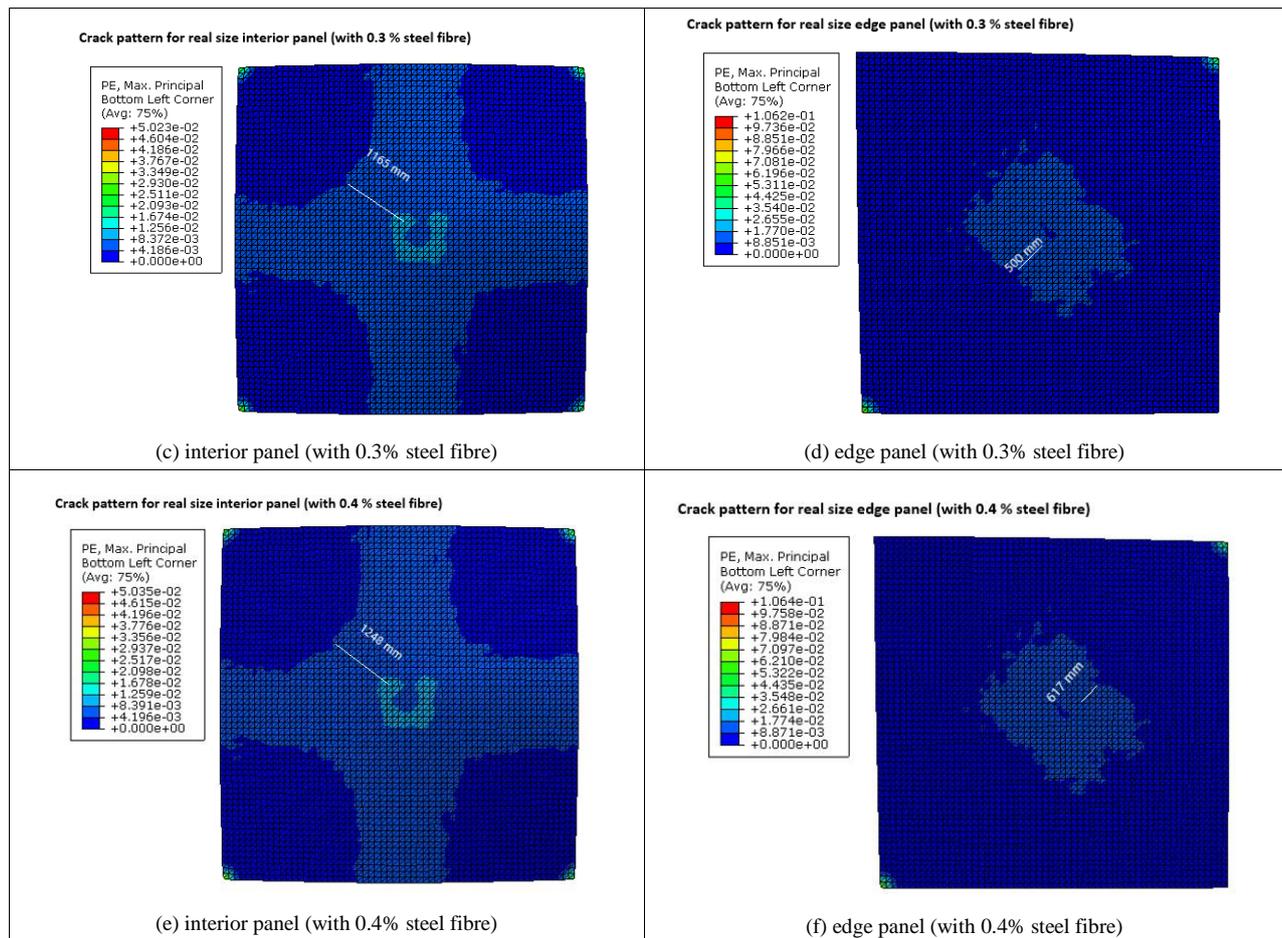


Figure 22. Finite element crack pattern of a real-sized plate

8. Conclusions

In this study, the FEA of a flat plate for different support conditions was conducted using the ABAQUS software to predict the behaviour of the flat plate against punching shear. Experimental research on scaled-sized flat plates was conducted to validate the results of FEA. Based on the results, the following conclusions were drawn:

- From the study, it was observed that the punching shear resistance and stiffness of the flat slab improved with the four-sided support and could withstand more loads.
- The crack observed in the ABAQUS model and the experimental study exhibited a comparable pattern for different flat plate panels. The distance between the crack and column face for scaled-sized test specimens and finite element models indicated good results with a difference of 2%.
- From the observations, it was noticed that the crack developed far from the column face by increasing the volume of the steel fiber. The crack developed from the column face in the finite element model and experimental results was at a distance greater than the critical distance $d/2$ which was away from the plate column junction. Thus, brittle punching shear failure could be avoided which in turn prevents the complete collapse of the structure. Thus, the stability of the structure can be improved.
- With the addition of steel fibers, the cracks moved away from the column surface. Punching shear failure is a dangerous failure that is often unforeseen and is the main drawback of flat plates. With the help of the bridge cracking property of steel fibers, it was observed that the mode of failure changed from a brittle nature and cautioned before failure.
- In the presence of steel fibers, the shear stress decreased from the column surface. The deflection and crack pattern from the FEA for the scaled-sized plate were validated with the experimental outcome for accuracy, and it demonstrated good agreement.
- We found a percentage error of 0–17% in deflection values between the experimental and analytical studies. This is because of the random distribution of steel fibers in the experimental test specimen because of the mixing, which was performed manually.
- It was observed that a minimum of three-sided support is required for the stability of a flat plate with a larger dimension.

9. Declarations

9.1. Author Contributions

Conceptualization, P.M.P. and S.A.S.; methodology, P.M.P. and S.A.S; software, P.M.P.; validation, P.M.P. and S.A.S; formal analysis, P.M.P.; investigation, P.M.P.; writing—original draft preparation, P.M.P.; writing—review and editing, S.A.S.; supervision, S.A.S. All authors have read and agreed to the published version of the manuscript.

9.2. Data Availability Statement

The data presented in this study are available in article.

9.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

9.4. Conflicts of Interest

The authors declare no conflict of interest.

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