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# FINITE ELEMENT ANALYSIS OF PUNCHING SHEAR IN FLAT SLABS

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***Abstract :*** Punching shear resistance of flat slabs is designed using test data from isolated slab-column connections. The compressive membrane effect of a continuous slab-column system, however, is neglected when evaluating separate slabs. As a result, punched shear strength may be lower than the actual strength of the slab structure. Testing a continuous slab system is extremely expensive and, in most situations, impossible. In this study, finite element analyses (FEA) are used to compare data from isolated specimens and continuous floor systems to explore the influence of compressive membrane action on flat concrete slabs. The FE formulation and material characteristics used have previously been calibrated on an isolated test specimen (SB1).

At First, calibrated FEA are utilised to study the boundary conditions of the slab-column connection (SB1). The boundary conditions are then changed, and the slab is assumed to have greater in-plane dimensions in order to test its continuity. The models are then evaluated for varied reinforcement ratios by giving varying diameters of flexural reinforcements using Finite element analysis. The failure displacements, failure loads, and fracture pattern of all models are investigated. A continuous floor system is also being developed to study the fracture patterns at the interior and exterior columns. The outcomes of the isolated and continuous models are compared. All of the model findings reveal that the punching shear capacity of a continuous slab is larger than that of a standard isolated slab. The predictive capacity of the FEA models may allow for more study on the effect of compressive membrane action to supplement the limited testing background in this area and give recommendations for future design provisions.

***Keywords* – Flat plates, Reinforcement ratio, Finite element analysis, Punching shear, slab-column connection, membrane action, crack pattern.**

## 1. INTRODUCTION

The two-way Reinforced Concrete (RC) flat slab supported by columns is a standard floor solution. The lack of projecting beams in flat slabs enhances the floor's clear height while decreasing construction time and effort. Punching shear failure occurs in reinforced concrete flat slabs as a result of the formation of a three-dimensional state of stresses caused by strong transverse stresses around the column and in-plane stresses. Inside the slab, inclined fractures occur, which spread and produce a massive inclined crack. When this fracture enters the compressive zone, it forms a punching shear cone around the column, resulting in punching shear failure. Punching failure is fragile and can occasionally result in a progressive collapse. Fig. 1 shows the punching shear failure at an interior column of flat slab.

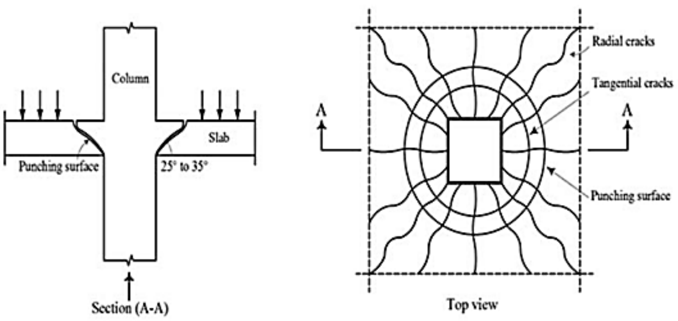



**Fig. 1:** Typical Symmetrical Punching failure around an interior column

Because of their ease of use, flawless surface smoothness, and lack of pendant joists, flat slabs are always the best structural solutions for roofs. Along with these advantages, one of the challenges that engineers have always been concerned with is the prevention of punching shear failure. Brittle failure with an abrupt decline in load bearing. Because this failure happens unexpectedly and without warning, it is seen as an undesired failure in the connection and is sought to be avoided. Punching shear is a kind of reinforcement concrete slab collapse caused by strong localised forces. This happens at the column support locations in flat slab constructions. Shear is responsible for the failure. This sort of failure is crucial since there are no obvious warning indications prior to failure. So, it is preferable to avoid slab failure by appropriately designing the slab for punching shear and studying the punching shear that occurs on the slab as a result of various loadings applied to it and under various situations.

**Compressive membrane action**

Because of the large difference between the compressive and tensile strengths of concrete, reinforced concrete slabs frequently display arching or compressive membrane action (CMA). Because to concrete cracking, the neutral axis migrates, and the slab extends in plane at the slab's borders. If the slab's natural proclivity to expand is restrained, the production of arching motion enhances its strength. The arching phenomenon in one-way spanning slabs is commonly referred to as "arching action," but the arching phenomenon in two-way spanning slabs is commonly referred to as "compressive membrane action."

Tensile stresses at the mid-depth of a slab cause the slab to expand, resulting in horizontal displacements in continuous reinforced concrete slabs. These mid-depth tensile stresses have generated as a result of nonlinearity in the concrete composition. The lateral stiffness of the columns imposes a compressive membrane force (also known as an in-plane restraint force), which inhibits this expansion (see Fig. 2). This process, also known as compressive membrane action, results in increased flexural and shear capacity of a slab.

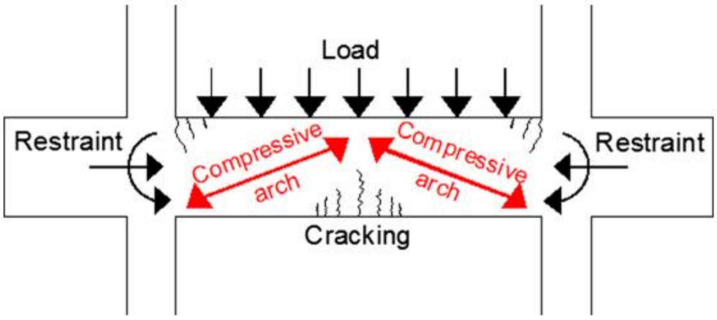



Fig.2 : Membrane action phenomenon[1]

## 2. Literature Review

Many scholars carried out experimental and computational analyses to determine the punching shear of flat slabs. Several strategies for increasing punching shear strength in flat slabs have been developed by various authors. The purpose of this study is to provide insight into the efforts undertaken to determine punching shear and enhance punching shear strengths in flat slabs.

Aikaterini S. Genikomsou and Maria Anna Polak [1] used finite element analysis (FEA) to evaluate the influence of compressive membrane action in flat concrete slabs by comparing findings from isolated specimens and continuous floor systems. Finite element analyses (FEA) are used to compare data from isolated specimens and continuous floor systems in order to examine the influence of compressive membrane action in flat concrete slabs. The study conclude that the deflections of all simulated continuous specimens are less than those of the isolated simply supported slab due to the membrane action effect.

Philipp Schmidt, Dominik Kueres, and Josef Hegger [3] studied the evolution of the concrete and steel contributions in shear-reinforced flat slabs in depth and offered a technique for computing and assessing both contributions. The evolution of concrete and steel contribution based on the quantity of shear reinforcement is examined and compared to the design provisions of Eurocode 2, Model Code 2010, and the draught (as of April 2018) of the next generation of Eurocode 2. They also proposed that by taking into account the tested range of parameters, more progressive design concepts, particularly for low and medium degrees of shear reinforcement, may be produced.

Brisid Isufi, Ildi Cismasiua, Rui Marreiros, António Pinho Ramos, Válter Lúcio [4] Horizontal cyclic loading studies on flat slab-column specimens show that inserting punched shear reinforcement significantly improves drift capacity. Seismic design codes, on the other hand, either do not suggest or do not include structures with flat slabs as part of the major lateral load resisting system. The goal of this work is to contribute to a better understanding of the advantages and disadvantages of utilizing punched shear reinforcement in seismic performance of such structure. To that goal, nonlinear static analyses and a set of fragility functions are developed for two reinforced concrete three story frame models.

Brisid Isufi, Mariana Rossi, and Antonio'Pinho Ramos [7] investigate how flexural reinforcement affects the seismic performance of such connections. Three specimens were examined and studied alongside two previously published specimens tested under comparable conditions, under continuous vertical loading and cyclic horizontal displacements, for a total of five specimens. The top flexural reinforcement in these specimens ranged from 0.64% to 1.34%, and the estimated value of applied gravity shear ratio (GSR, equal to the ratio of applied gravity load to punched shear resistance) was about 55%. Two of the specimens (low and median reinforcement ratio) were also reinforced with headed studs against punching shear to investigate the slab-column connections' imbalanced moment transmission capability. The specimens are described and studied in depth. The results reveal that the degree of flexural reinforcement affects performance during cyclic loading, even while GSR was about the same for all specimens.

A. Pinho Ramos , Válter J.G. A. Pinho Ramos , Válter J.G. Lúcio , Duarte M.V. Faria [9] showed the experimental results of pounding flat slab specimens with tendons. Unbonded prestress with high strength steel tendons was used to test nine slabs. The effects of slanted tendons near the column and their distance from the column on the punching capacity of the vertical component of prestress forces are investigated. To examine simply the deviation force impact, the in-plane compression force owing to prestress was not applied to the slabs. This work attempts to better knowledge of the behaviour of prestressed flat slabs under punching load so that the punching resistance of these structures may be correctly evaluated. The experimental punching loads are compared to the EC2, ACI 318-11, and MC2010 requirements.

P. Olmati, J. Sagaseta, D. Cormie, and A.E.K. Jones [11] presented a framework for a simplified reliability analysis and the development of safety factors for calculating the probability of punching in flat slab concrete buildings subjected to accidental loads such as column removal, slab falling from above, or blast load. The key benefit of the proposed method is that it considers the uncertainty in the gravity load imposed in the slab prior to the unintentional occurrence, which impacts the inertial effects and demand/capacity ratio in the slab-column connections in a straightforward manner. Using computer-based time history finite element simulations, Eurocode 2 and the Critical Shear Crack Theory for punching are employed and expanded to dynamic applications for assessing the demand/capacity ratio. The suggested dependability approach is used to a case study of an existing structure, demonstrating that column removal is not necessarily necessary, although slab collapsing from above is far more damaging.

## 3. Numerical Study

### 3.1 Finite element modelling:

Finite Element models are established with Abaqus to simulate the behaviour of flat slabs under punching shear loading. The Failure load, displacement, and cracking pattern of the Flat slabs are researched by finite element analysis. A comprehensive parametric study is carried out to investigate the influence of parameters including column dimensions, slab thickness on the behaviour.

For the purpose of validation the Specimen SB1 is taken from Aikaterini S. Genikomsou, Maria Anna Polak [1]. The finite element model was created in 5 parts using three dimensional 8-Noded hexahedral element (C3D8R) for concrete and three dimensional 2-noded linear truss (T3D2) elements were used for flexural reinforcement. in Abaqus as shown in Fig. 3.

The analysis was performed in step 1 (Dynamic, Explicit), a step after the initial step. Automatic increment and one second total ''Time period'' were chosen. The total displacement of the reference point at the end of the analysis was 10 mm as shown in fig. 4.

It was found that the results from the from Aikaterini S. Genikomsou, Maria Anna Polak [1] and validation modelling is matching near about 80%.

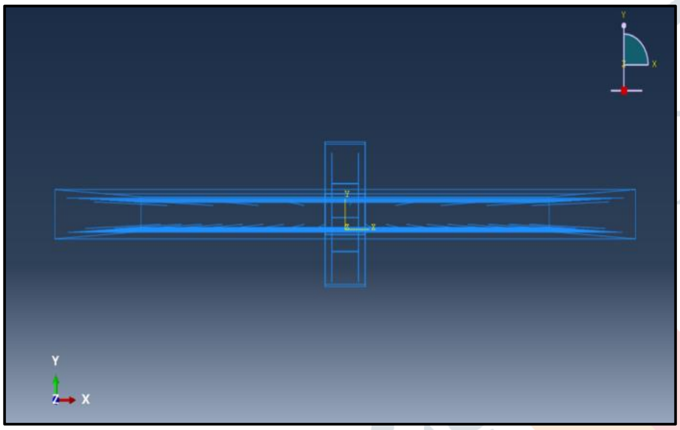


**Fig. 3:**FE model showing slab with reinforcements

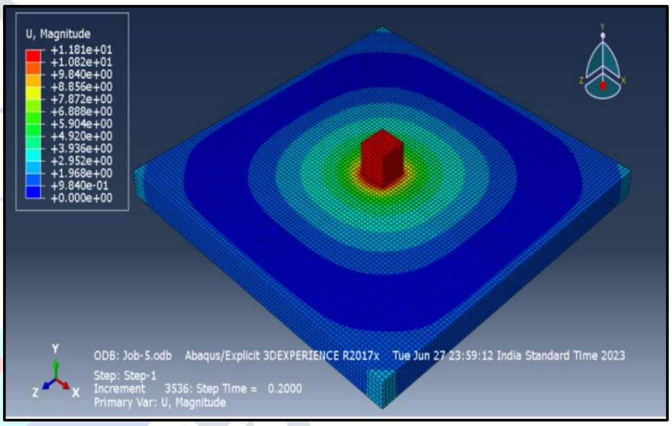



**Fig. 4:**Total displacement of Specimen SB1

The following fig.5 compares the result of SB1 in validation and is given in Aikaterini S. Genikomsou, Maria Anna Polak's[1] (2017) research.

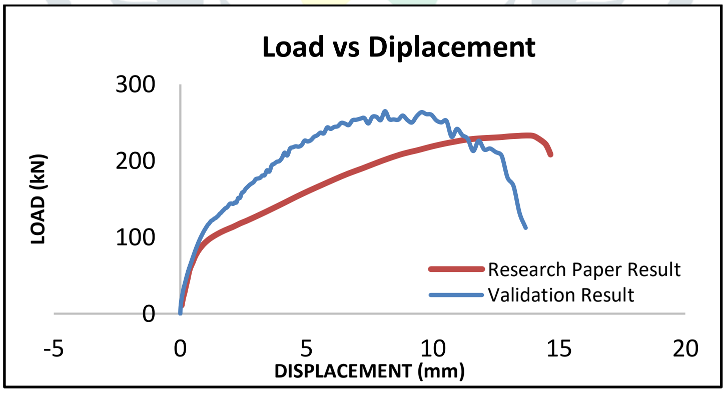



**Fig. 5:** Comparison of Load- displacement curves of validation results and Research paper results.

### 3.2 Details of specimens

The flat slab models are modelled in Abaqus/CAE 2017 . The isolated model SB1 is created and continuous models were created by applying different boundary conditions to isolated model. The parameters of the samples are listed in Table 1. All the models have a column size of 230mm x 230mm and a slab thickness of 150mm. In all the models, tensile flexural reinforcement consisted of 10M bar (i.e., As= 100sq.mm), 10mm bars and 8mm bars at 90mm and 100mm c/c (spacing) in orthogonal directions and Compressive flexural reinforcement consisted of 10M bars (i.e., As= 100sq.mm), 10mm bars and 8mm bars at 200mm c/c (spacing)in both directions for different models. The various diameter bars are provided to get different reinforcement ratios.

**Table 1:** Details of Specimens.

| Sr. No. | Specimen | Slab Dimensions | | | Reinforcement Ratio (%) |
|---|---|---|---|---|---|
| | | Length(mm) | Width(mm) | thickness (mm) | |
| 1 | Continuous Model 1 A | 3750 | 3750 | 150 | 2 |
| 2 | Continuous Model 1 B | 3750 | 3750 | 150 | 1.6 |
| 3 | Continuous Model 1 C | 3750 | 3750 | 150 | 1.0 |
| 4 | Continuous Model 2 A | 6000 | 6000 | 150 | 2 |
| 5 | Continuous Model 2 B | 6000 | 6000 | 150 | 1.6 |
| 6 | Continuous Model 2 C | 6000 | 6000 | 150 | 1.0 |
| 7 | Continuous floor system A | 7845 | 7845 | 150 | 2 |
| 8 | Continuous floor system B | 7845 | 7845 | 150 | 1.6 |
| 9 | Continuous floor system C | 7845 | 7845 | 150 | 1.0 |

**3.3 Model Overview**

**3.3.1 Part and element of FE model**

The finite element models were created in five parts including Column, Column rebars, Column stirrups, slab and slab rebars as shown in fig. 6, fig. 7 and fig. 8 three dimensional 8-noded hexahedral elements with reduced integration (C3D8R) were used for modelling the concrete. For modelling the flexural reinforcement, three dimensional 2-noded linear truss (T3D2) elements were used.

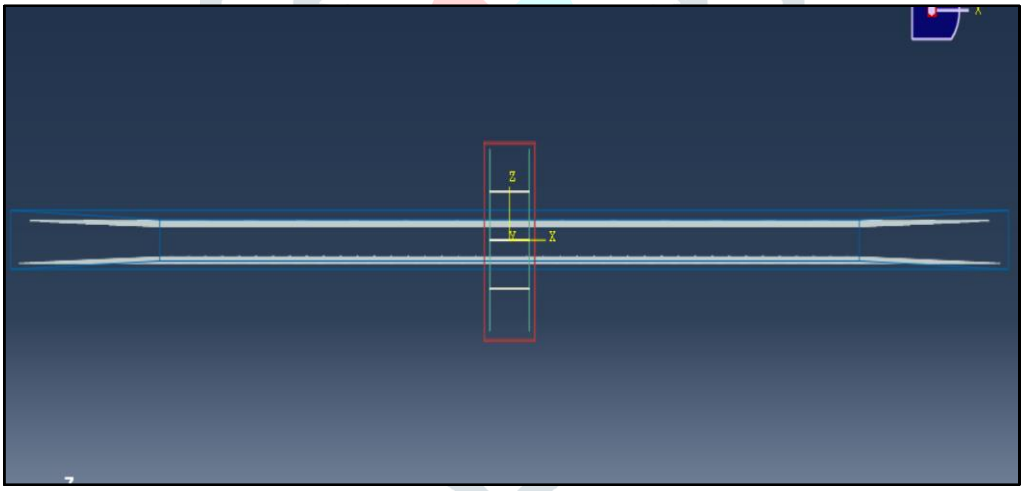


**Fig. 6:** Details of Continuous model 2

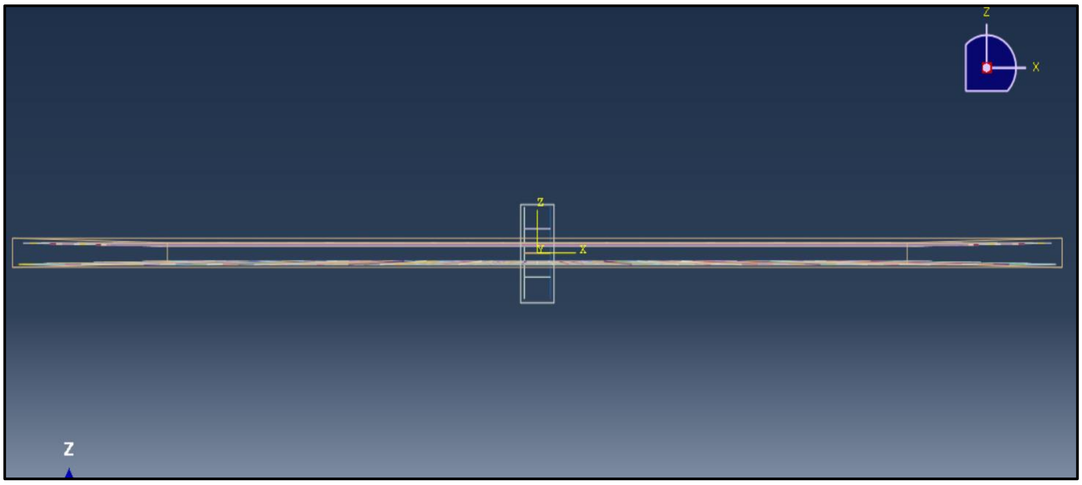



**Fig. 7:** Details of Continuous model 2

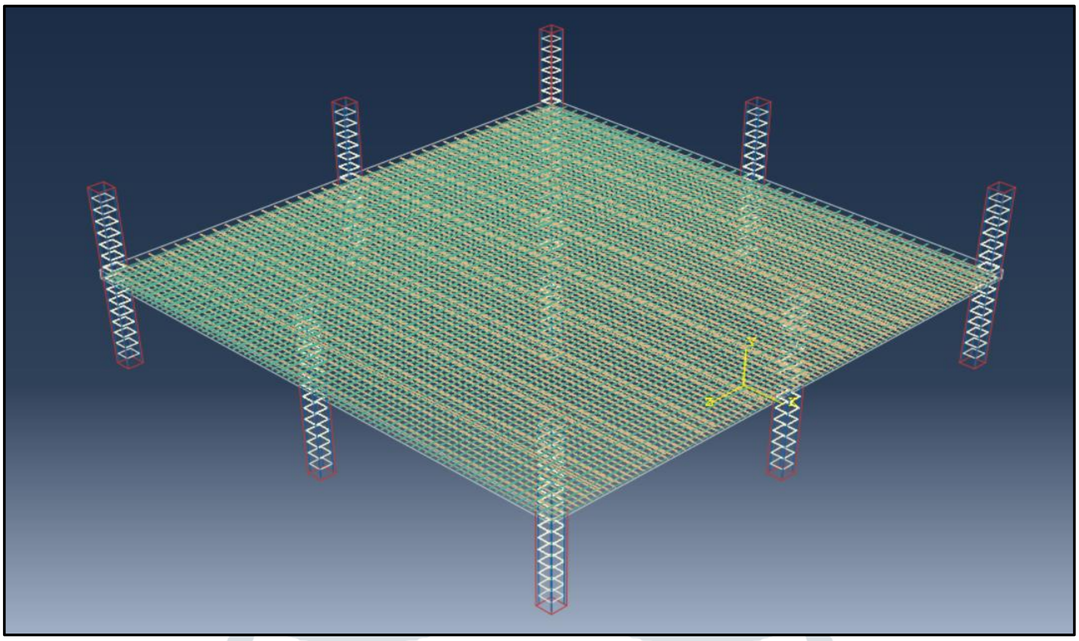


**Fig. 8**: Details of Continuous floor system

**3.3.2. Assembling of parts and contact properties**

Position constraints were utilized to assemble the whole model. For the simulation of the interface between steel reinforcement and concrete , the option of having For the reinforcement which is embedded in concrete "embedded region" constrain was used. Tie constraint was used for the contact between Slab and column faces. The default value of tie constraint was considered. In MPC constraint, each node on the slave surface is constrained to have the same motion as the point on the master surface at top of the Column.

**3.3.3 Boundary conditions**

The boundary condition of each model is different. The supports are applied at different locations.

**For Continuous Model 1**

Restrained supports with both horizontal and vertical restraints (pinned supports) at the locations of the lines of the contraflexure in order to provide lateral restraints and simulate the continuous scenario (Fig. 9a). The lateral restraints are applied not only at the bottom of the slab but also at the whole height of the slab.

**For Continuous Model 2**

Simple supports are introduced at distance 0.4L = 1500 mm and at 1.5L = 5625 mm (Fig. 9 b), where L denotes the center-to-center span of the slabs (L = 3750 mm).

**For Continuous floor system**

Due to symmetry, one quarter of the floor flat system is considered . The columns are restrained at the bottom. The adapted boundary condition are presented in Fig.10. z-x Symmetry and z-y symmetry is also applied.

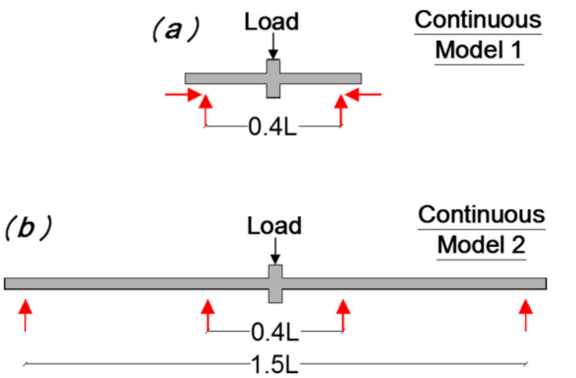



**Fig. 9:** Boundary conditions of Adopted continuous models for the slab SB1

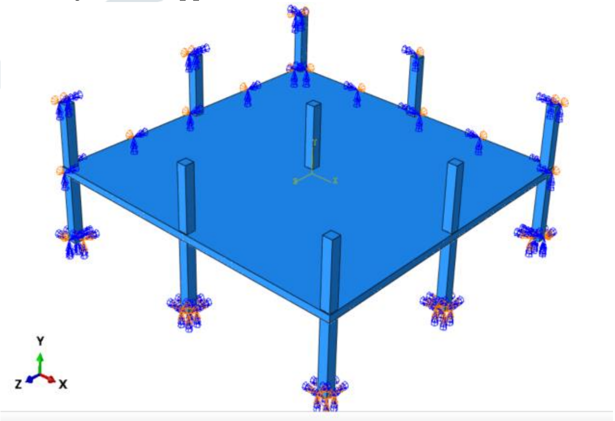



**Fig. 10:** Boundary conditions of continuous floor system.

**3.3.4 Meshing**

Three dimensional 8-noded hexahedral elements with reduced integration (C3D8R) were used for modelling the concrete. For modelling the flexural reinforcement, three dimensional 2-noded linear truss (T3D2) elements were used. For all models default mesh seeding is used as presented in fig. 11.

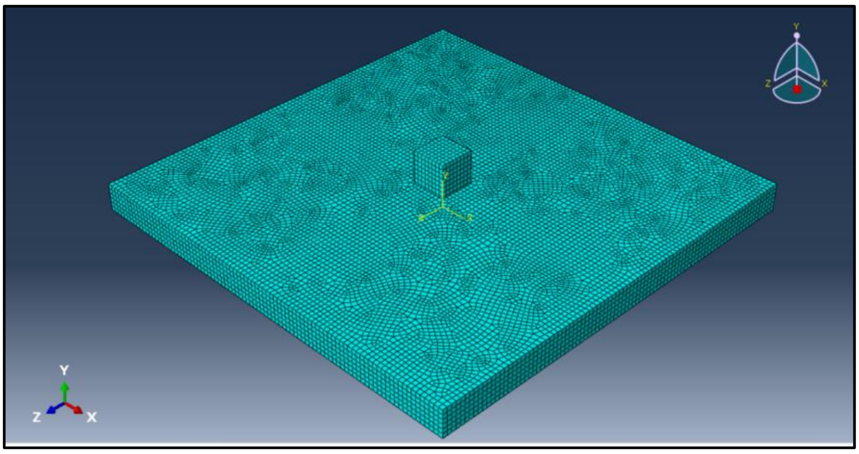


**Fig. 11:** The meshing of specimen.

### 3.3.5 Loading

The Velocity loads are applied through the column stub till Failure in all models (except in floor system). The velocity load are applied using the boundary conditions. The reference point was created through which the load is applied. The RP position is located at the top of the specimen as shown in fig. 12. The prescribed loading was achieved by using the amplitude function. For the continuous floor system, a high uniformly distributed factored load of 18.5 kPa is applied to the floor system as shown in Fig. 13.

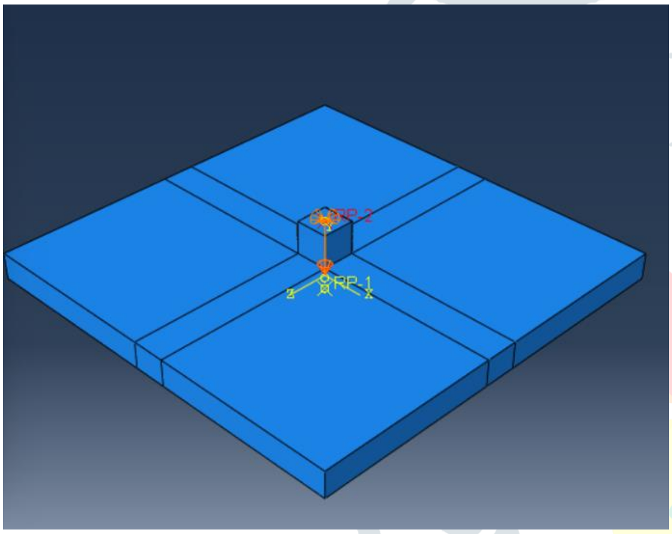



**Fig.12:** Loading of specimens (Continuous models 1&2)

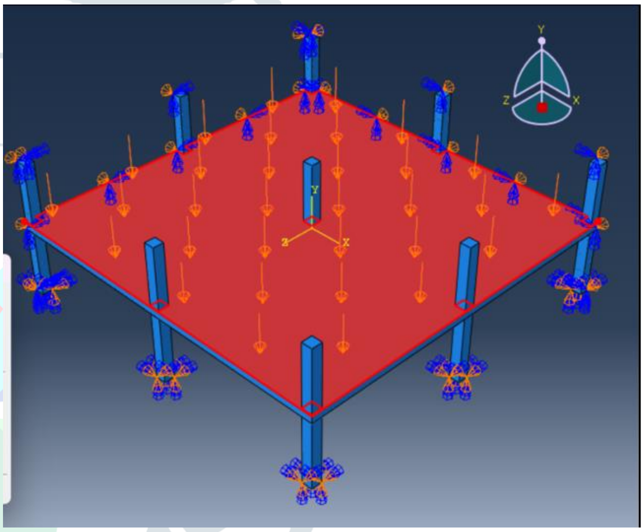


**Fig.13**: Loading of Floor system.

### 3.3.6 Material

The flat slab models is consisting of two materials i.e., Concrete and Flexural reinforcement. The concrete damaged plasticity properties are mentioned in table 2. The properties of flexural steel is density = 7850 Kg/m$^3$ , modulus of elasticity is $2X10^5$ and yield strength is 455 MPa.

**Table 2:** Material properties and plasticity parameters of concrete used in the analysis

| | |
|---|---|
| $f'_c$ [MPa] | 44 |
| $f'_t$ [MPa] | $0.33\sqrt{f'_c} = 2.2$ |
| $G_f$ [N/mm] | $G_{fo}(f_{cm}/f_{cmo})^{0.7} = 0.082$ |
| $E_c$ [MPa] | $5500\sqrt{f'_c} = 36,483$ |
| $\upsilon$ | 0.0 |
| Dilation angle $\psi$ [degrees] | 40 |
| $\varepsilon$ | 0.1 |
| $\sigma_{bo}/\sigma_{co}$ | 1.16 |
| $K_c$ | 0.667 |
| $\mu$ | 0 |

## 4. ANALYSIS RESULTS

We are finding Failure load and displacement at failure of our continuous models in the analysis including the crack pattern of each and every specimen. The continuous models 1, continuous models 2 and the continuous floor system with varying reinforcement ratios are tested.

### 4.1 For Continuous Model 1 And Continuous Model 2

The continuous model-1 and continuous model-2 are observed for failure load, failure displacement and crack width (crack pattern). Both the models are observed for different reinforcement ratios. The results are presented in table 3.

a) 2% reinforcement ratio
b) 1.6% reinforcement ratio
c) 1% reinforcement ratio

**Table 3:** Results for Continuous model 1 and Continuous model 2 for varying reinforcement ratios

| Results for Continuous model 1 and Continuous model 2 | | | | |
|---|---|---|---|---|
| Reinforcement Ratio (%) | Model | Failure load (kN) | Failure displacement (mm) | Crack width (mm) |
| 2 | Continuous model-1A | 874.282 | 4.033 | 500 |
| | Continuous model-2A | 1193.61 | 4.93 | 460 |
| 1.6 | Continuous model-1B | 859.258 | 4.135 | 520 |
| | Continuous model-2B | 1100.21 | 4.81 | 470 |
| 1 | Continuous model-1C | 857.27 | 4.469 | 535 |
| | Continuous model-2C | 1013.18 | 4.4638 | 510 |

#### 4.1.1 For Models with reinforcement ratio 2%

Based on the statistics presented above, we can conclude that with a 2% reinforcement ratio, the failure load in continuous model-2 is 36.52% more than that in continuous model-1, and the failure displacement in continuous model-2 is 22.33% greater than that in continuous model-1. However, the continuous model-2 crack width is 8.7% smaller than the continuous model-1 crack width.

The load vs displacement curves for the models are presented in fig. 14, and the crack pattern (crack width) is displayed in fig.15.

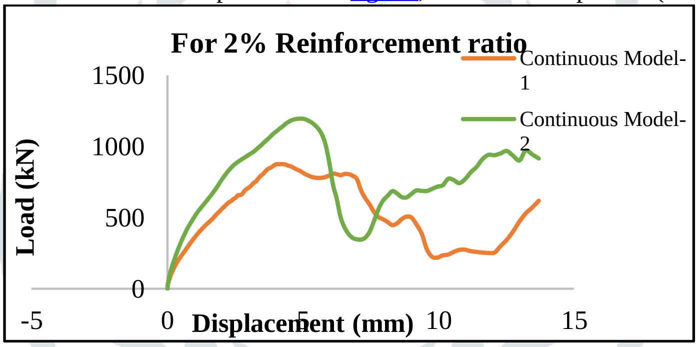
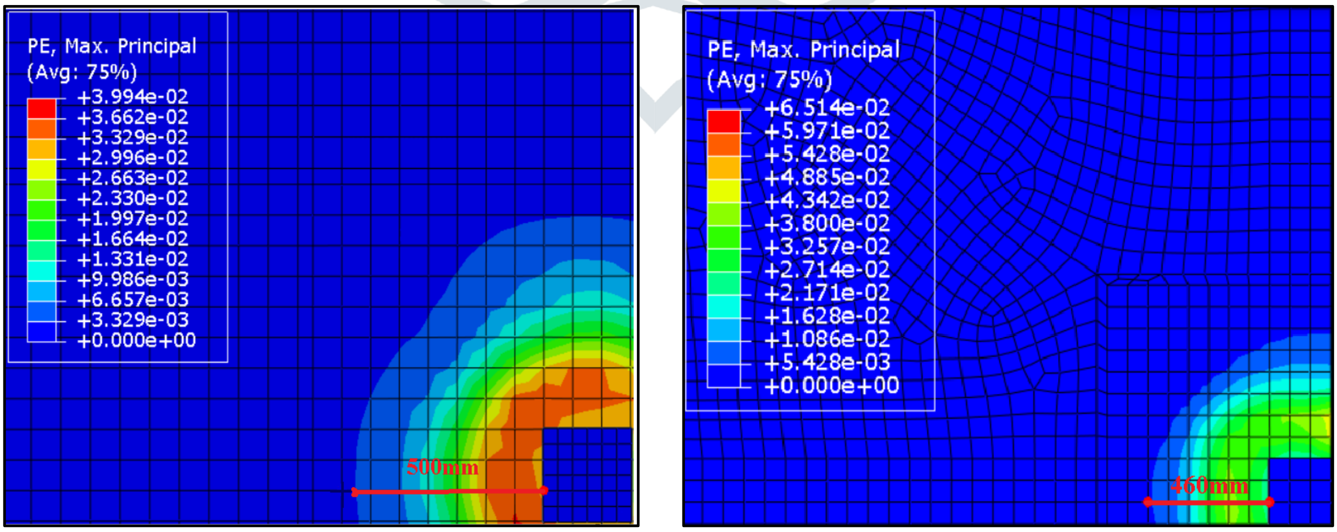



**Fig.14:** Load vs Displacement curves for models with 2% reinforcement ratio.




(a) (b)

**Fig. 15:** Crack Pattern for continuous models with reinforcement ratio 2% : a) Continuous model-1, b) Continuous model-2.

#### 4.1.2 For Models with reinforcement ratio 1.6%

According to the aforementioned statistics as in table 3 , with a 1.6% reinforcement ratio, the failure load in continuous model-2 is 28.05% greater than that of continuous model-1, and the failure displacement in continuous model-2 is 16.34% greater than that of continuous model-1. However, the crack width of continuous model-2 is 9.6% smaller than that of continuous model-1.Fig. 16 shows the load versus displacement curves for the models, and Fig. 17 shows the crack pattern (crack width).

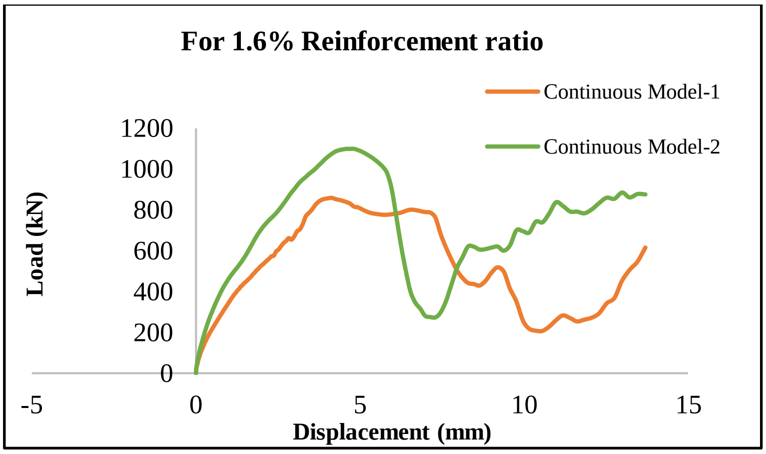
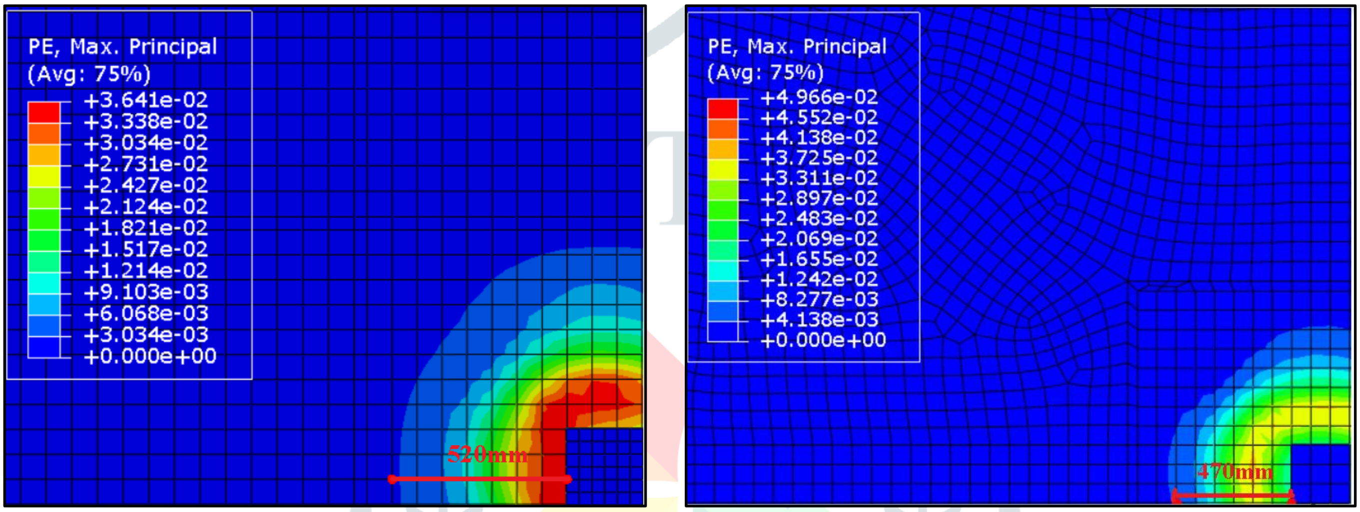



**Fig. 16:** Load vs Displacement curves for models with 1.6% reinforcement ratio.




(a) (b)

**Fig. 17:** Crack Pattern for continuous models with reinforcement ratio 1.6% : a) Continuous model-1, b) Continuous model-2.

### 4.1.3 For Models with reinforcement ratio 1%

According to the preceding statistics (table 3), the failure load in Continuous model-2 is 18.18% more than that in Continuous model-1 for 1% reinforcement ratio. The failure displacement of continuous models 1 and 2 is found to be almost identical. However, the continuous model-2 crack width is 4.67% smaller than the continuous model-1 crack width. The load vs displacement curve for the models are as shown in fig. 18 and the crack pattern (crack width) is shown in fig. 19.

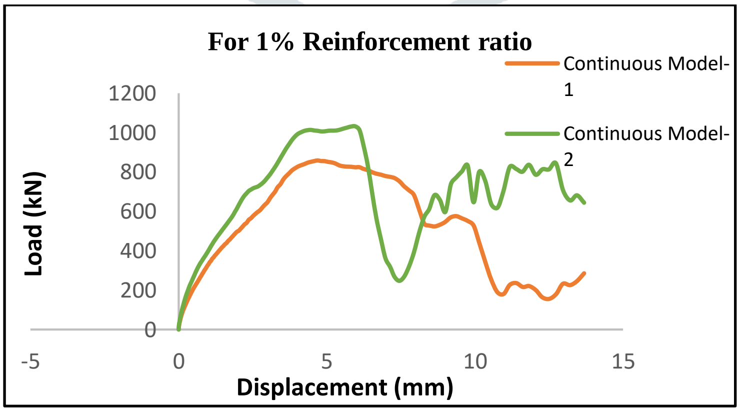
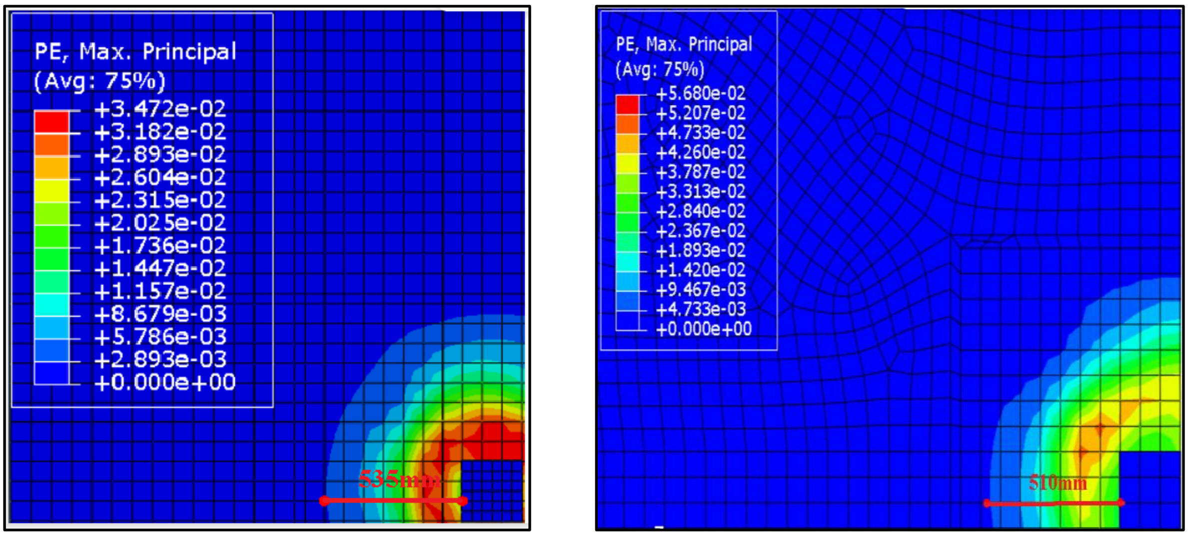



**Fig. 18:** Load vs Displacement curves for models with 1% reinforcement ratio.




(a) (b)

**Fig. 19:** Crack Pattern for continuous models with reinforcement ratio 1% : a) Continuous model-1, b) Continuous model-2.

### 4.2 For Continuous Floor System

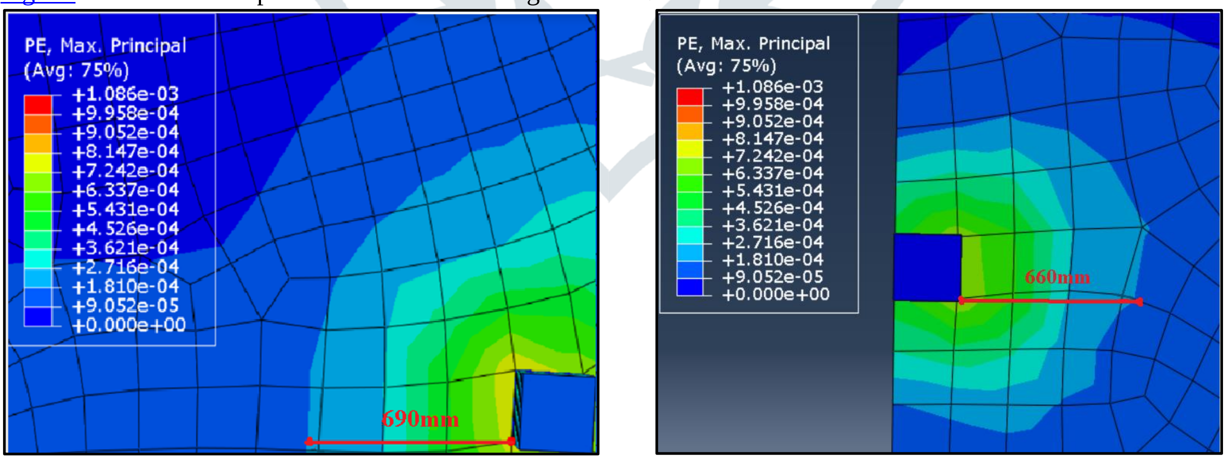
The continuous floor system is also tested with varying reinforcement ratios to check the crack pattern for interior and edge columns. The results for different reinforcement ratios are summarized in Table 4.

**Table 4:** Crack patterns for Continuous floor system with different reinforcement ratios

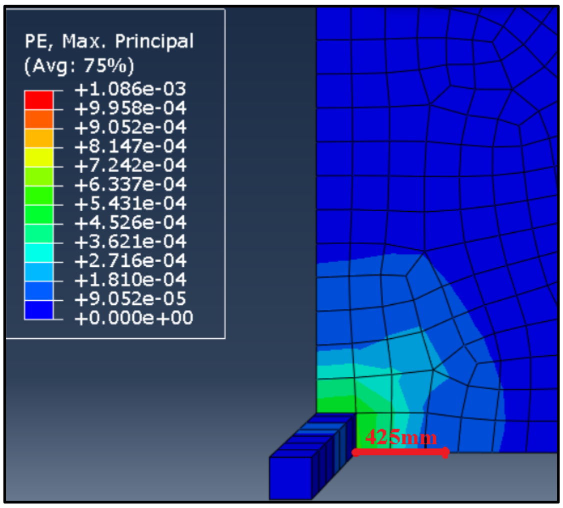
| Reinforcement Ratio (%) | Crack pattern for Continuous Floor system at different column position (crack width from the column face) (in mm) | | |
|---|---|---|---|
| | Interior column | Edge Middle Column | Edge Corner column |
| 2 | 690 | 660 | 425 |
| 1.6 | 660 | 610 | 410 |
| 1 | 670 | 590 | 395 |

#### 4.2.1 For Floor System with reinforcement ratio 2%.

From the above results we can conclude that the crack width is maximum at interior centre column and minimum at edge corner column. The crack width of edge middle column is 4.35% less and crack width of edge corner column is 38% less than that of interior column. Fig. 20 shows the crack pattern for interior and edge columns.




(a) (b)

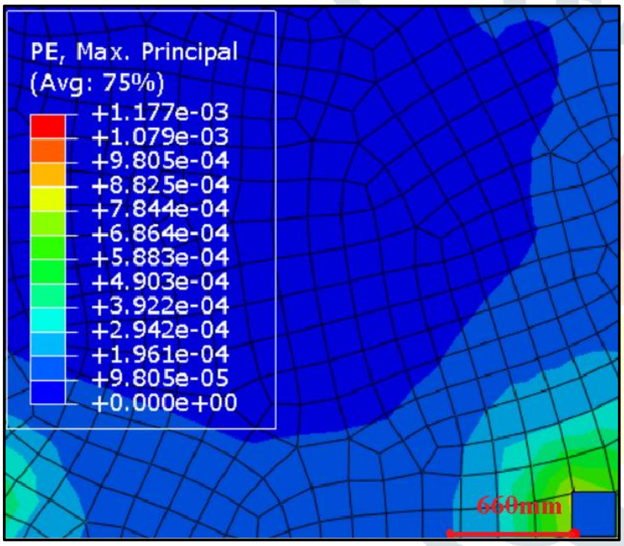



(c)

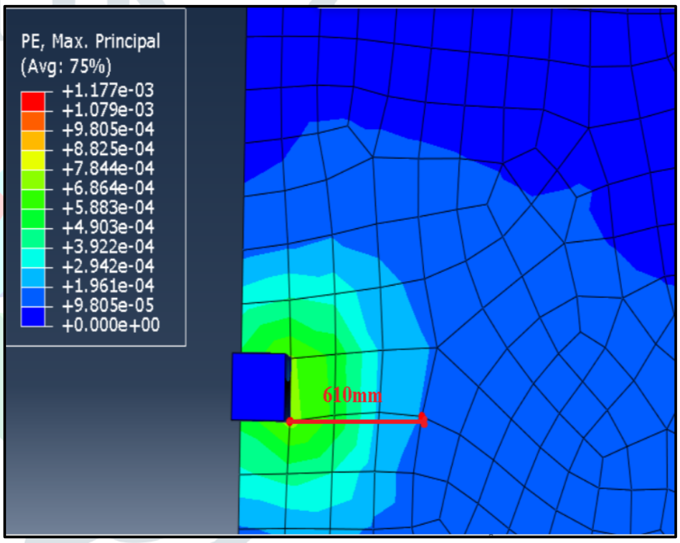
**Fig. 20:** Crack pattern of floor system with 2% reinforcement ratio: a) at interior column, b) at edge middle column, c) edge corner column.

### 4.2.2 For Floor System with reinforcement ratio 1.6%.

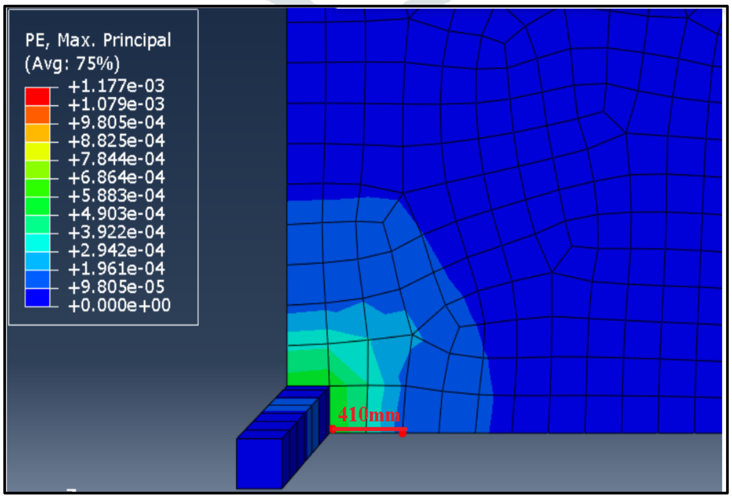
From the above results from table 4, we can conclude that the crack width is maximum at interior centre column and minimum at edge corner column. The crack width of edge middle column is 7.57 % less and crack width of edge corner column is 37.88% less than that of interior column. Fig. 21 Shows the crack pattern for interior and edge columns.




(a)




(b)

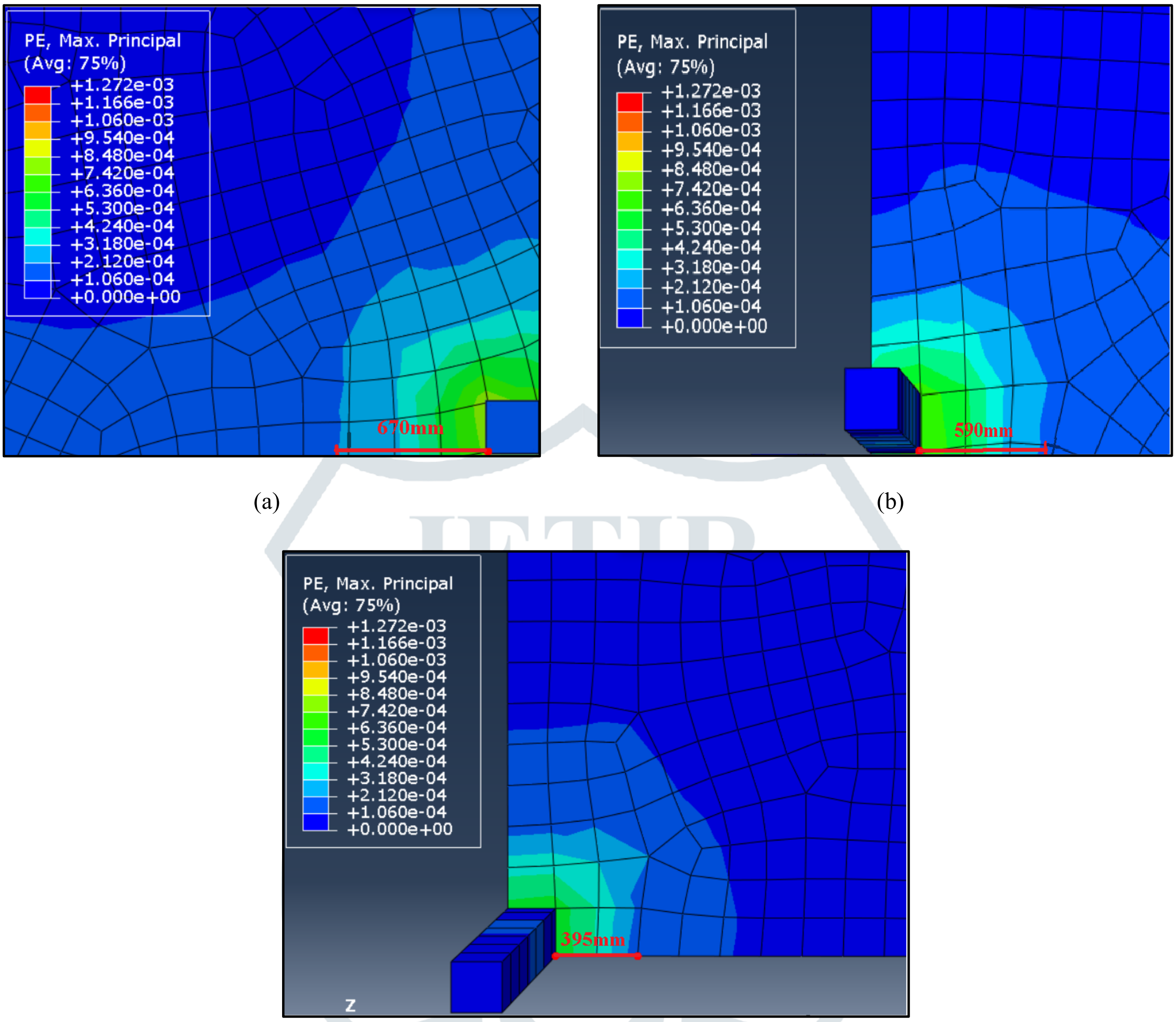



(c)

**Fig. 21:** Crack pattern of floor system with 1.6% reinforcement ratio: a) at interior column, b) at edge middle column, c) edge corner column.

**4.2.3 For Floor System with reinforcement ratio 1%.**

From the above results from table 4, we can conclude that the crack width is maximum at interior centre column and minimum at edge corner column. The crack width of edge middle column is 11.94% less and crack width of edge corner column is 41.04% less than that of interior column. Fig. 22 shows the crack pattern for interior and edge columns.




(c)

**Fig. 22:** Crack pattern of floor system with 1% reinforcement ratio: a) at interior column, b) at edge middle column, c) edge corner column.

## 5. Conclusion

After modelling the flat slabs of continuous model 1 and continuous model 2 and floor systems different reinforcement ratios. The following conclusions were made.

### 5.1 For Continuous Models 1 And 2

#### 5.1.1 Failure Load

1) For all reinforcement ratios, the continuous model-2 having simple supports shows higher punching strength as compared to continuous model -1 which is having simple supports with lateral restrains. The continuous model-2 has about 25% more punching shear strength than continuous model-1.
2) The failure load in Continuous Model-1 does not increase significantly when the reinforcement ratio increases. However, the failure load of continuous model-2 increases by around 10%.

#### 5.2.2 Failure Displacement

1) Because of the compressive membrane action effect, the failure displacement of continuous model-1 is less than that of continuous model-2. The displacement of continuous model-1 is around 13% smaller than that of continuous model-2.
2) The failure displacement decreases with increasing reinforcement ratio in both continuous models-1 and continuous model -2, however the decrease in continuous model-1 is relatively small.

### 5.2.3 Crack pattern

1) For each reinforcement ratio it is observed that the Continuous model-1 have larger crack width as compared to the Continuous model-2. This is because of the continuity and compressive membrane action. The cracks of continuous model-2 are about 10% smaller as compared to continuous model-1.
2) With increase in reinforcement ratio, the crack width of both continuous model-1 and continuous model-2 is decreasing. There is 2-3% decrease in crack widths.

### 5.3 For Continuous Floor System

1) In floor system, it is seen that larger cracks are developed at the interior column as compared to the edge columns. In edge columns , the cracks are more at the middle column with respect to the corner columns,
2) For all reinforcement ratio, crack width of edge corner column is found out to be nearly 40% less than that of interior column and the crack width of edge middle column is 7-8% lesser than interior column.

### 5.4 Effect Of Reinforcement Ratio

1) By studying all the models and parameters, it is concluded that

The failure load increases with increase in reinforcement ratio. This means the punching shear capacity can be increase with increase in reinforcement ratio.

2) The displacement at failure decreases with increase in reinforcement ratio. The decrease is not much.
3) The increase in reinforcement ratio helps in reducing the cracks in all the models. Increase in reinforcement shows significant reduction in cracks.

### 5.5 FUTURE SCOPE OF STUDY

1) Understanding of membrane action effect is also needed for slab with high strength concrete and slab with openings.
2) Reinforced concrete slabs with punching shear reinforcement should be also considered in the future studies.

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