Numerical Analysis on Structural Behaviour of Biaxial Voided Slab

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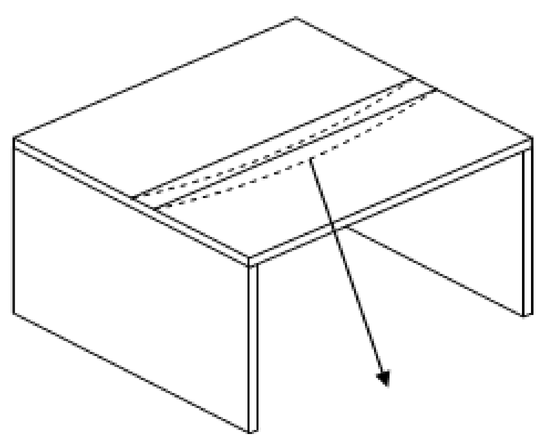
Abstract*- The biaxial voided slab is a cutting-edge structural system that has gained attention due to its ability to significantly reduce the self-weight of reinforced concrete (RC) slabs while maintaining their flexural capacity. By incorporating voids within the slab, up to 50% weight reduction can be achieved compared to solid slabs. However, the presence of voids introduces certain challenges that need to be addressed. One major challenge is the reduction in the effective concrete area due to the presence of voids. This reduction leads to a decrease in flexural stiffness, which affects the overall performance of the slab under load. Additionally, the shear capacity of the slab is also impacted by the presence of voids. Another important consideration is the alteration of the location of the critical failure section for punching shear. The voids within the slab can affect the distribution of forces, potentially shifting the point of failure and necessitating careful analysis and design considerations. To enable the wider implementation of biaxial voided slabs in the construction industry, this study focuses on developing comprehensive design guidelines specifically tailored for their behaviour under flexure and concentrated load conditions. The investigation takes into account various factors, including the influence of tensile membrane action and the orientation of reinforcement, on the ultimate flexural capacity of RC solid slabs. Furthermore, the study aims to explore whether the beneficial effects observed in enhancing the capacity of RC solid slabs can also be achieved in RC voided slabs. This analysis will provide valuable insights into the ultimate capacity of biaxial voided slabs with a reasonable level of accuracy. To accomplish these objectives, the study relies on experimental results obtained from the current research and data collected from the existing literature. By combining these findings, analytical formulations are developed to guide the design process and assess the structural behaviour of biaxial voided slabs. This study contributes to the understanding of the biaxial voided slab system, offering valuable guidelines and insights for its practical application. By leveraging the knowledge gained, engineers and designers can confidently incorporate biaxial voided slabs in their projects, taking advantage of their lightweight nature without compromising structural integrity.

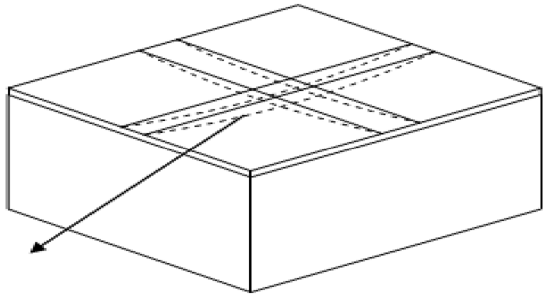
Key Words: ABAQUS, Voided slab

I. INTRODUCTION

Slabs are two-dimensional flat horizontal structural members, being used to transfermainly gravitational loads such as dead loads and imposed loads. In addition, slab systems are acting as a horizontal diaphragm for a structural building, which helps to transfer the lateral loads (usually developed by wind loads and earthquakes) effectively to vertical members suchas columns, structural walls, etc. The slab systems are mainly classified as one- and two-way slabs based on its structural behaviour. If the slab predominantly bends (deflects) in one direction, then it is known as a one-way slab (Figure 1.1a). Similarly, if the slab bends in two directions (longitudinal and transverse), then it is known as a two-way slab (Figure 1b). The various types of conventional slab systems are wall-supported, beam-supported, grid beam- supported, ribbed, flat plate, and flat slab.



(a)One-way Slab



(b)Two-way Slab

Fig 1: Wall-supported Slab Systems

II. VOIDED SLAB

enerally, the self-weight of the conventional slab systems explained in Section 1.1 are much higher than that of the imposed loads acting on it. In order to overcome this one-way voided slab (2) were introduced by Hatt in 1907 at Purdue University, In ABAQUS, by means ofhollow tiles (Mota, 2013).

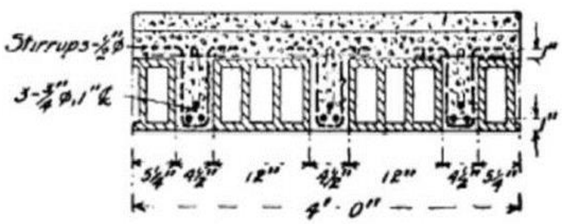


Fig 2: Cross Section of One-way Voided Slab with Hollow Tiles (Source: Mota, 2013)

In 1914, hollow cores (void formers) made of metal and tar paper were used to create voids inthe slabs (Figure 3). Studies showed that the structural behaviour of one-way hollow core slabs in orthogonal directions was observed to varying significantly. In 1997, Cobiax, Germanydeveloped a lightweight, environmentally effective two-way hollow slab by using plastic voidformers, as shown in Figure 1.4. In the two-way hollow core slabs (biaxial voided slab), the void former units usually placed with equal spacing in both lateral and longitudinal directions.The void formers used to be placed between the top and bottom reinforcement gauge. Typicalcross-section of the biaxial voided slab with its components is shown in Figure 1.5. The voids usually placed where the stress in concrete is minimum, generally on the tension side. Typical conceptual strain and stress variation in a section of the slab are shown in Figure 6.

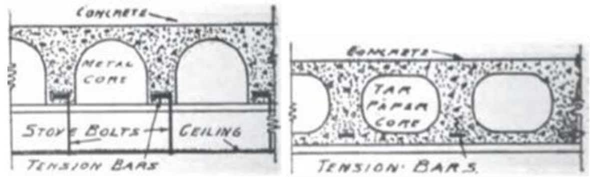


Fig 3: Cross Section of One-way Voided Slab with Hollow Core (Source: Mota, 2013)

Fig 4: Two-way Voided Slab with Plastic Void Formers (Source: www.cobiax.com)

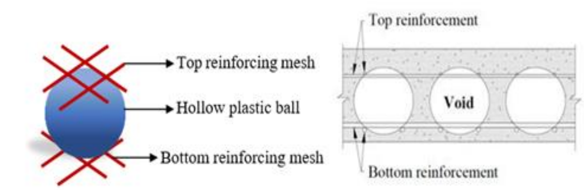


Fig 5: Components of Two-way Voided Slab and Typical Cross-section

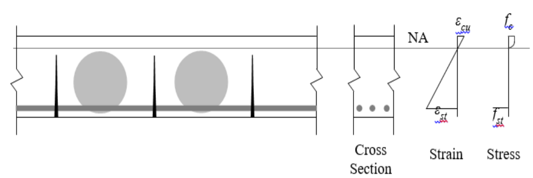


Fig 6: Concept of Voided Slab

The voids lead to a reduction in self-weight up to 50% in comparison with conventional reinforced concrete solid slab without any significant change in its structural performance under flexure (Björnson, 2003 and Harding, 2004). The voided slab reduces the size and reinforcement requirement about 15% of other structural elements such as beam, column and footing. The overall result is the voided slab renders a significant cost saving of about 10% oftotal construction cost. The voided slab system is one of the Green Design techniques as 1 kg of recycled plastic replaces 100 kg of concrete and it reduces carbon emission from transportation and equipment. Further, the voided slab system is leads to energy efficiency buildings by means of thermal performance.

ABAQUS

ABAQUS is part of SIMULIA family of codes which is a Multiphysics modelling and simulation software. ABAQUS is a commercial software package for finite element analysis. The ABAQUS product suite consists of three core products: ABAQUS/Standard, ABAQUS/Explicit and ABAQUS/CAE. ABAQUS/Standard is a general-purpose solver using a traditional implicit integration scheme to solve finite element analysis. ABAQUS/Explicit uses an explicit integration scheme to solve highly nonlinear transient dynamic and quasi-static analyses. ABAQUS/CAE provides an integrated modelling (pre-processing) and visualization (post processing) environment for the analysis products.

III. NEED FOR THE PRESENT INVESTIGATION

The present investigation on a biaxial voided slab is motivated by the need to enhance structural efficiency, optimize costs, explore innovative construction techniques, gain a better understanding of structural behavior, evaluate performance under different loading conditions, and promote sustainability in the construction industry.

IV. OBJECTIVES OF THE RESEARCH

The objective of the research on biaxial voided slabs is to advance the understanding, design, and application of this innovative structural system. By conducting a comprehensive investigation, the research aims to contribute to the field of structural engineering in several ways. It aims to enhance the understanding of biaxial voided slabs, optimize their design, validate numerical models, and provide guidance for their practical application in terms of structural performance, cost-effectiveness, and sustainability.

V. NUMERICAL INVESTIGATION OF BIAXIAL VOIDED SLAB

Biaxial voided slabs exhibit unique behaviour due to the presence of voids, which affect their structural response. To study the behaviour of biaxial voided slabs, nonlinear analysis using finite element methods can be conducted, including the use of software like ABAQUS.

NONLINEAR ANALYSIS OF VOIDED SLAB USING FINITE ELEMENT ANALYSIS

A proper material model in finite element modelling should inevitably be capable of representing both elastic and plastic behaviour of concrete in compression and tension. The complete compressive behaviour should include both elastic and inelastic behaviour of concrete including strain hardening/softening regimes. Simulation of proper behaviour under tension should include tension softening, tension stiffening and local bond effects with reinforcements in reinforced concrete elements. ABAQUS (2020) is a general purpose simulation tool based on the finite element method that can be used to analyse variety of civil engineering structures.

Finite Element Modelling of Voided Slab

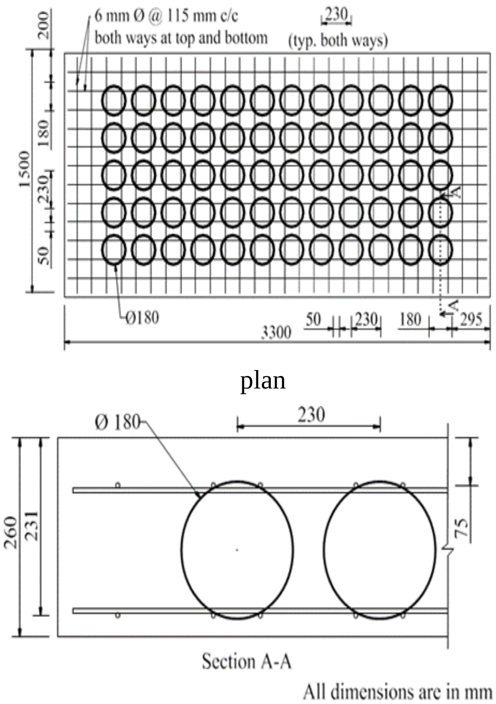
To perform finite element modelling of a biaxial voided slab with the given dimensions and materials in ABAQUS, you can follow these steps:

Geometry Creation: Create a 3D model of the biaxial voided slab with the dimensions provided (3300x1500x260mm). This can be done using ABAQUS/CAE, the graphical interface of ABAQUS. Define the slab as a solid object with the appropriate dimensions.

Material Properties: Define the material properties for the concrete, steel reinforcement, and hollow plastic balls. For the concrete, you can specify the compressive strength, elastic modulus, and Poisson's ratio. For the steel reinforcement, specify the material properties for the 6mm diameter bars of FE415 steel. The hollow plastic balls can be defined with appropriate properties, such as the elastic modulus and Poisson's ratio.

Length	3000mm
Width	1560mm
Thickness	200mm
Ball wall thickness & diameter	3mm &180mm

Table 1 – Dimensions of voided slab



Cross section of voided slab

Fig 7: Detailing of Voided slab

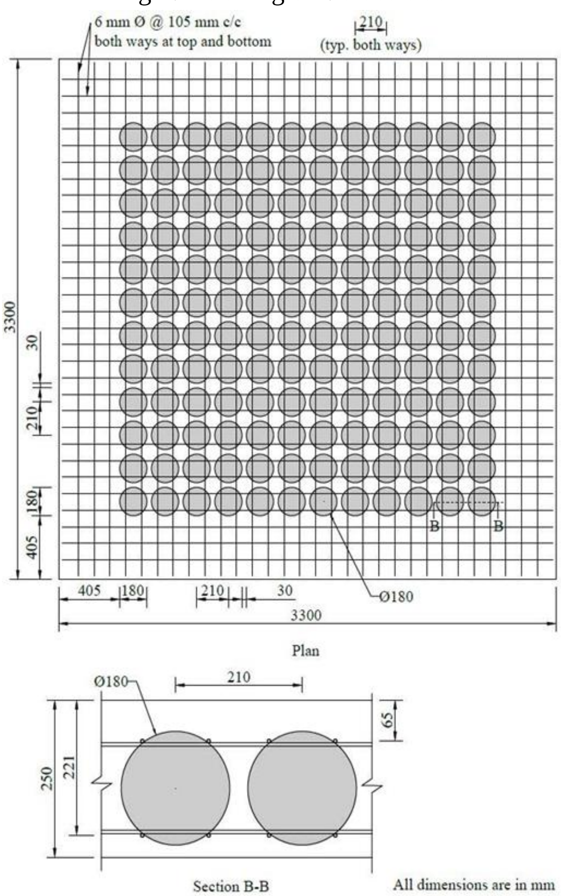


Fig 8: Detailing of Voided slab

VI. PARTS

Concrete Modelling

The concrete portion is modelled in ABAQUS with settings of three-dimensional, deformable body, solid base features and extrusion type.

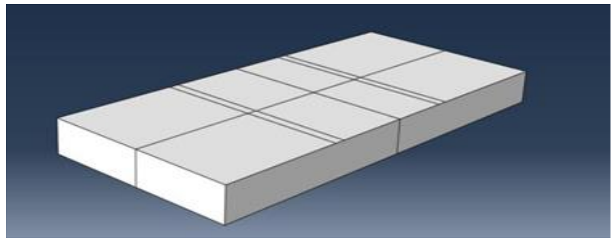


Fig 9: Concrete slab

Steel Portion

The steel portion is modelled in ABAQUS with settings of three-dimensional, deformable body, wire base features and planar type.

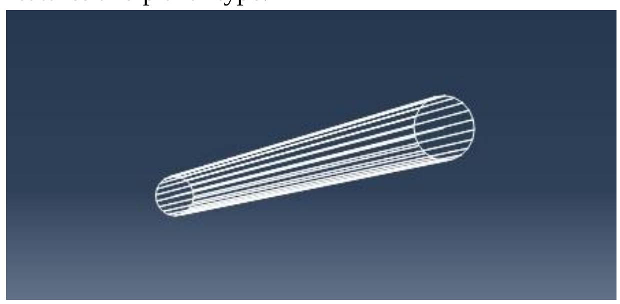


Fig 10: Steel bar

Spheroid

The ball portion is modelled in ABAQUS with settings of three-dimensional, deformable body, Shell features and revolution type.

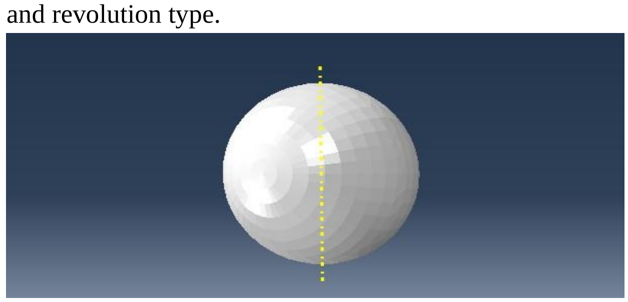


Fig 11: Void former

MATERIAL PROPERTY

CONCRETE

A. Density
B. Elasticity

Density

The Density of Concrete = 2.40X10^{-9} $\frac{tonnes}{mm^3}$

Table 2: Concrete density

Data

	Mass Density
1	2.4E-09

Elasticity

The young's modulus of the Concrete is found out by plotting Stress- Strain curve.

Tab 3: Concrete elasticity

Data

	Young's Modulus	Poisson's Ratio
1	22360	0.15

STEEL

A. Density
B. Elasticity
C. Plasticity

Density

The Density of steel = 7.85X10^{-9} $\frac{tonnes}{mm^3}$

Tab 4: Steel density

Data

	Mass Density
1	7.85E-09

Elasticity

The young's modulus of the steel is found out by plotting Stress- Strain curve.

Table 5: Steel elasticity

Data

	Young's Modulus	Poisson's Ratio
1	200000	0.3

BALL

A. Density
B. Elasticity

Density

The Density of steel = 0.91X10^{-9} $\frac{tonnes}{mm^3}$

Table 6: Ball density

Data

	Mass Density
1	9.1E-10

Elasticity

The young's modulus of the ball is obtained from Poly Metal India Material Data sheets.

Table 7: Ball elasticity

Data

	Young's Modulus	Poisson's Ratio
1	1200	0.35

ASSEMBLY

- The Assembly module is used to combine multiple parts and create a complete assembly model. The Assembly module allows you to position, connect, and define interactions between different parts of a structure.

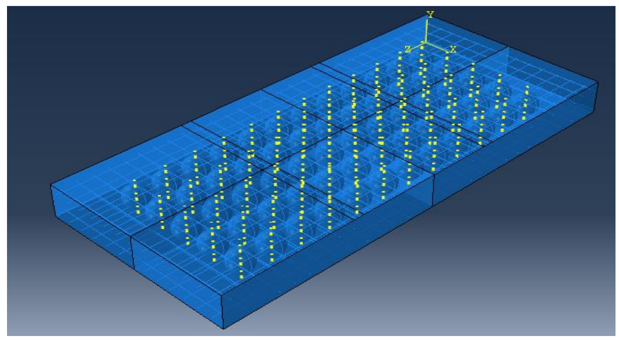


Fig 12: Assembled Biaxial voided slab

STEP

- The Initial step is used to define the initial conditions of the model before applying any loads or boundary conditions.
- It allows you to specify the initial state of the model, such as initial displacements, velocities, or temperatures.
- A general, static analysis step, in which you will apply a pressure load on the top face of the slab.
- A general, static analysis step, in which you will apply a Displacement Controlled Point Load on the side face of the top slab.

Table 8: Step Manager

Step Manager

Name	Procedure	Nlgeom	Time
Initial	(Initial)	N/A	N/A
Step-1	Static, General	ON	1

Create... Edit... Replace... Rename... Delete... Nlgeom... Dismiss

INTERACTION

The interaction is used to make Concrete and Rebar portion as a Whole part. The Embedded region is used to combine Concrete and Rebar.

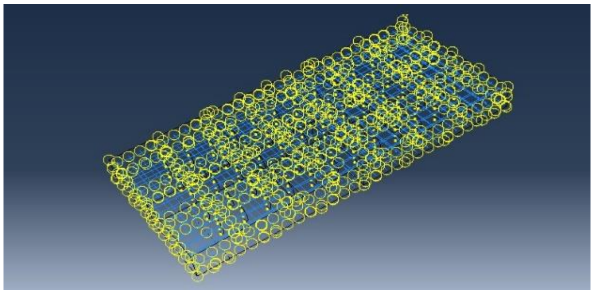


Fig 13: Embedded Region

LOADS

- In load module, Choose the appropriate boundary condition type based on your requirements.
- Apply a displacement constraint, select "Displacement/Rotation".
- In the "Create BC" dialog box, enter the desired values for the selected boundary condition.
- For a displacement constraint, enter the prescribed displacements or rotations.
- For a force load, enter the magnitude and direction of the force.

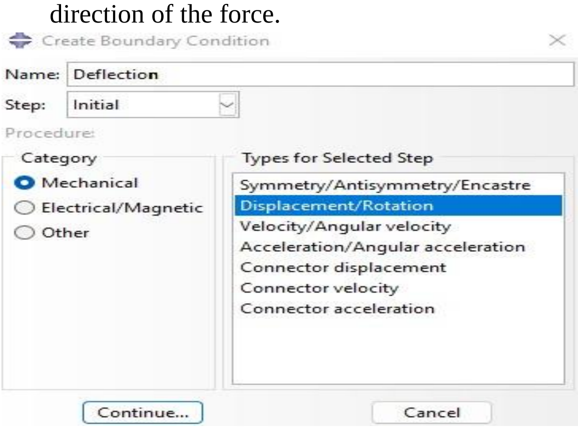


Table 9: Boundary Condition Manager

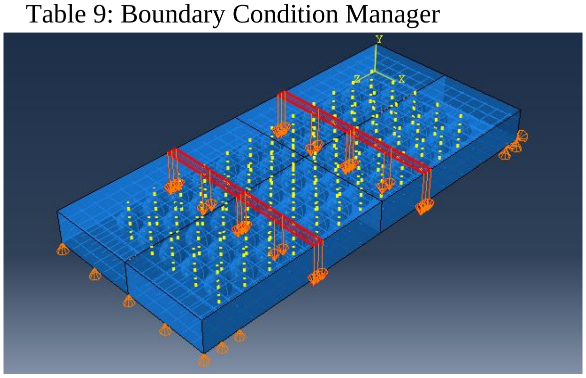


Fig 14: Applying Deflection

MESH

- Meshing is the process of dividing a geometric model into a collection of smaller, interconnected elements or cells.
- In computational modelling and simulation, a mesh is essential for discretizing the geometry and representing it in a format suitable for numerical analysis.
- Meshing is required to convert a continuous geometry into a discrete representation composed of finite elements.

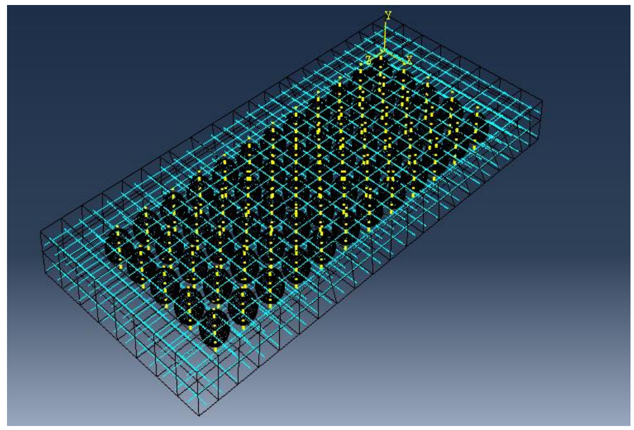


Fig 15: Finite Element Model with Mesh (One way slab)

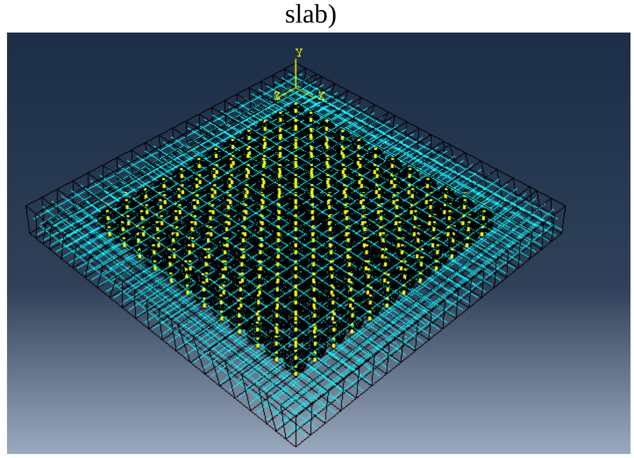


Fig 16: Finite Element Model with Mesh (Two-way slab)

VII. RESULTS

Once the analysis is complete, post-process the results to visualize and analyze the structural behavior of the biaxial voided slab. ABAQUS provides various tools to generate contour plots, stress distributions, displacements, and any other desired output.

DEFORMED SHAPE OF ONE-WAY SLAB

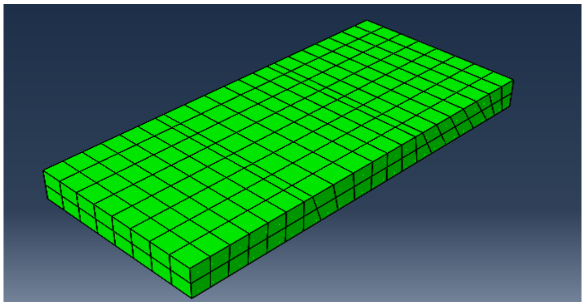


Fig 17: Undeformed shape

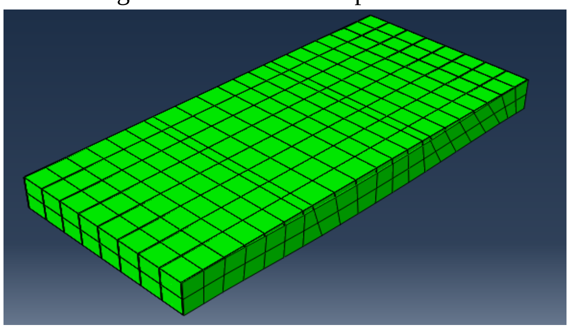


Fig 18: Deformed shape

DEFORMED SHAPE OF TWO-WAY SLAB

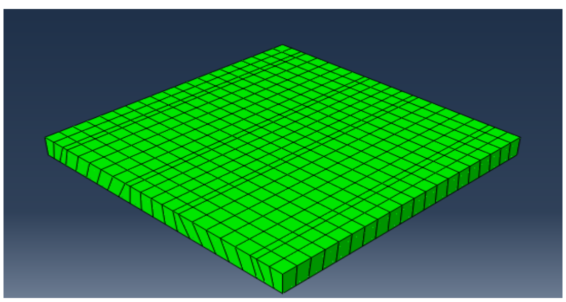


Fig 19: Undeformed shape

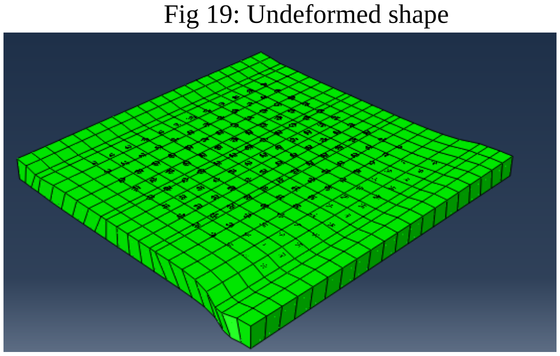


Fig 20: Deformed shape

CONTOURS ON DISPLACEMENT

The displacement of the voided slab has the magnitude of about 1.703×10^2 mm, 3.833×10^1 mm in two way and one way slab.

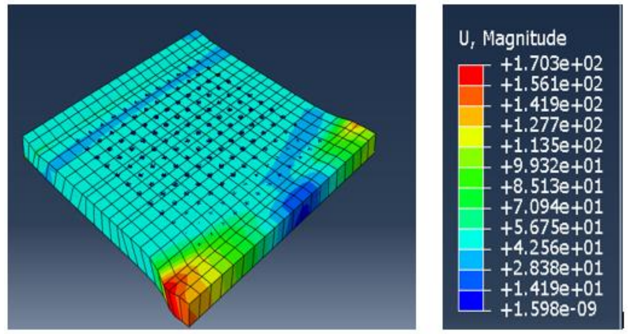


Fig 21: Contour on displacement in 3D view

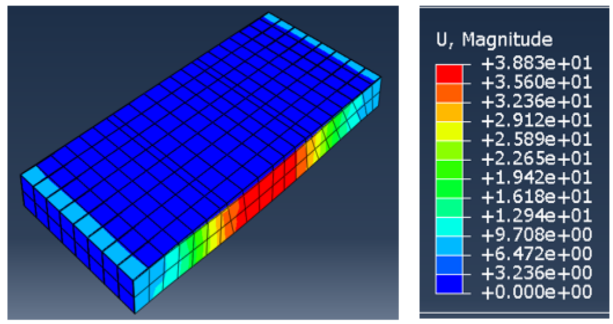


Fig 22: Contour on displacement in 3D view

Load vs mid span Deflection

Finite element analysis (FEA) software such as ABAQUS can help in simulating and analyzing the load-deflection behavior of structures. By incrementally applying loads and solving the structural response, the load-deflection curve can be obtained to evaluate the structural performance and behavior under different loading scenarios.

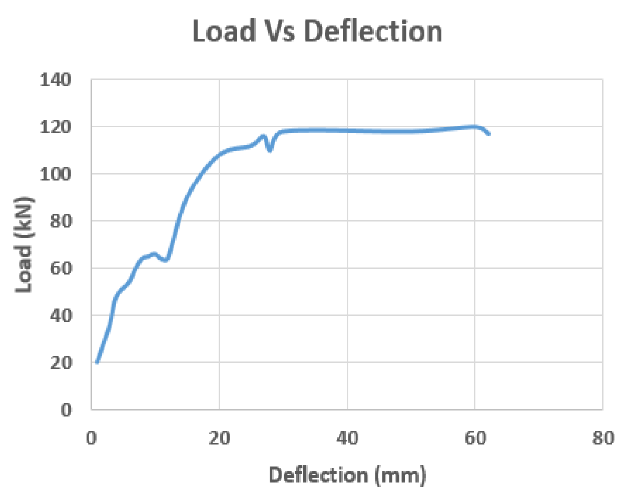


Fig 23: Load vs. Deflection of One-way slab

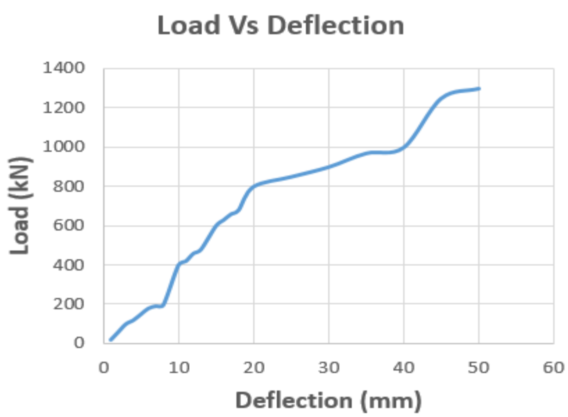


Fig 24: Load v Deflection of Two way slab

VIII.CONCLUSION

1. The numerical model that has been developed and validated by Sagadevan and Rao (2019) accurately aligns with the test results obtained in their study.
2. The high initial stiffness of the numerical model was attributed to the omission of undetectable micro cracks. In the laboratory experiment, prior to the appearance of the visible crack, certain weak sections of the concrete slab experienced the formation of imperceptible cracks. The combination of the applied load and the resulting effect of these hidden cracks ultimately led to the formation of the first visible crack. The numerical model did not account for any potential bond slip failure between the steel and concrete, as observed in the experimental setting.
3. The agreement between numerical and experimental results suggests that numerical investigations can be conducted to explore the flexural behavior of voided slabs.

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