Finite Element Analysis of RCC Columns and Footings Using COMSOL Multiphysics

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***Abstract*—Reinforced concrete columns and footing are important parts of a building because they help move the load from the superstructure to the function. Traditional analytical design methods are generally based on fundamental assumptions, including linear elastic material properties and uniform stress distributions, which might not represent the real behaviour of structures. A sophisticated technique for analyzing structures, finite element analysis (FEA) may replicate the actual behavior of structures through nonlinear material features, boundary conditions, and load transmission processes. COMSOL Multiphysics software is used in this study to perform a finite element analysis of reinforced concrete columns and footings. Structural responses, including axial stress, axial load, deflection, axial thrust, and base pressure, are calculated and compared with the analytical solution based on conventional reinforced concrete theory. The percentage error approach is used to validate the outcomes of the COMSOL Multiphysics software. The finite element model is validated by the findings, which show very slight variations.Using COMSOL Multiphysics software,which is a good tool for analysing reinforced concrete structures,can make structural analysis more accurate.**

Index Terms—Finite Element Analysis, Reinforced Concrete Columns, RC Footings, COMSOL Multiphysics, Structural Analysis

I. INTRODUCTION

Structures made of reinforced concrete are at the heart of modern civil infrastructures because of their high strength, durability, and capacity to withstand a broad spectrum of loading conditions. Of all structural members of buildings and infrastructural facilities, reinforced concrete columns and footings are of primary importance for ensuring the safe moments of loads from the superstructure to the supporting soil of the foundation. The primary function of columns is to transfer axial loads and bending moments resulting from beams and slabs, while footings are meant for safe transmission of column loads

to the supporting soil. The structural safety of buildings, bridges, and other civil engineering infrastructures heavily depends on the safe analysis and RC columns and footing design.

Given the quick development of urban infrastructure in recent times all over the world, there has been a greater need to provide more effective analytical methods to examine the behaviour of structures. Statistics on global construction activities indicate that reinforced. Concrete is the most common building material because it is cheap and works well structurally and architecturally. It is anticipated that as more complicated structures have emerged recently, there will be a larger need to create more effective analysis methods to examine how structures behave.

Conventional elastic theory and idealizations based on uniform stress distribution and idealized boundary conditions serve as the foundation for the traditional analytical design methods utilized in the study of reinforced concrete columns and footings. Even while traditional analysis methods are frequently employed in the design of structures, they typically fall short of precisely predicting the behaviour of structures because they are unable to accurately forecast the behaviour of structures under actual loading conditions. Because of things like the yield point of steel in concrete structures and the emergence of fractures in concrete owing to tensile and compressive pressures, reinforced concrete structures typically do not behave linearly.

One of the best ways numerical methods for assessing complicated structural systems is Finite Element Analysis (FEA). Engineers have discovered that the finite element approach is an useful tool for assessing complex constructions with intricate material properties and geometry. By breaking down the complicated structure into small finite elements, the finite element approach can accurately assess the stresses, strains, and deformations that occur in the structure.

One of the most best ways to move forward the field is the finite element analysis method. The finite element method and experimental methods have been employed by several studies to assess the behavior of reinforced concrete columns and footings. According to Vacev et al.'s experimental and computational studies, the finite element approach can accurately mimic the punching shear failure that happens in reinforced concrete column footings [1].

Similar experiments and numerical simulations were conducted by Hegger et al. to look into the punching shear resistance of reinforced concrete footings. The results showed that conventional models tend to underestimate stress concentrations around the column and footing interface, whereas the results from The finite element simulations are more accurate. [2]. Experiments conducted by Hallgren and Kinnunen also gave valuable insights into punching shear failure in column-supported concrete footings and the need for correct numbers modeling in structural analysis [3].

The finite element method has also used in more recent studies to analyze reinforced concrete footings under different loads. Numerical simulations carried out by Fouda et al. proved the viability of the model of finite elements in simulating the structural behavior of both strengthened and unstrengthened concrete footings subjected to axial loads [4]. The outcomes of these experiments demonstrated the viability of using numerical simulation models in determining stress concentrations in concrete structures.

The behaviour of reinforced concrete columns under axial load and bending has been extensively studied using finite element analysis. FEA models can be used to simulate the behaviour of reinforced concrete columns subjected to axial load and bending moments, as demonstrated by Papanikolaou and Kappos' nonlinear finite element analysis [5]. Finite element models can be utilized to mimic the behaviour of reinforced concrete structural components, as demonstrated by additional FEA investigations conducted by De Stefano and Pintucchi [8].

Moreover,the actions of reinforced concrete footings has been investigated using three-dimensional finite element analysis, including the effects of soil-structure interaction. Selvadurai and Jayasinghe carried out three-dimensional finite element analysis to examine the behavior of isolated reinforced concrete footings and demonstrate that the behavior of reinforced concrete footings may be simulated using numerical models [7]. The benefits of employing finite element analysis over traditional techniques to examine the behavior of isolated and mixed reinforced concrete footings were demonstrated by additional finite element analysis investigations conducted by Rao and Kumar [6].

With the help of modern simulation software, structural engineers can make use of various multiphysics-based finite element analysis software to forecast the performance of reinforced concrete structures. COMSOL Multiphysics is a potent tool for three-dimensional structural analysis among the different used finite element analysis programs for the examination of reinforced concrete structures.

With the help of COMSOL it is possible with software to model various complex phenomena with high accuracy.

Consequently, we used COMSOL Multiphysics software in the current work to perform finite element analysis of reinforced concrete columns and footings. The main objective of the now research study is to create three-dimensional finite element models of reinforced concrete columns and footings. In addition to this, the structural performance of RC columns and footings will be evaluated. The outcomes of the finite element analysis performed with COMSOL software will be compared with analytical calculations derived from various equations of reinforced concrete theory.

In addition to providing insights into the realistic behaviour of reinforced concrete columns and footings, the study's findings are anticipated to demonstrate the COMSOL Multiphysics software's efficacy as a trustworthy instrument in structural analysis. This study can increase the precision and dependability of structural analysis of reinforced concrete by combining analytical computation with numerical simulation.

II. METHODOLOGY

This study employs the finite element method for numerical analysis to understand the structural behaviour of reinforced concrete columns and footings under load. COMSOL Multiphysics software, a potent tool for three-dimensional structural analysis, is used to simulate the structural behaviour of the RCC column and footing system. To comprehend the real structural arrangement, a thorough three-dimensional model of the RCC column and footing system is provided in this work. The software's Solid Mechanics Module, which enables us to analyze structural components for stress, strain, and deformation, is used to create the model. To replicate the behavior of a structure, the model is given the characteristics of materials that correspond to reinforced concrete. Concrete behavior is represented by parameters like Poisson's ratio and Young's modulus. Boundary conditions are used appropriately to depict a structure's support conditions. To depict the support conditions of a structure, people think that that the footing's base is fixed. To depict the axial load applied to a column, it is assumed that a vertical load is put on the top of the column. An RCC column-footing system's behavior and stress distribution can be assessed with the help of this modeling technique.

The finite element meshing method is then used to mesh the geometry, which makes the results more accurate. Following meshing, the COMSOL Multiphysics solver is used to act like the structural reaction of the column and footing. The stress distribution and deformation response, which demonstrate the structural reaction brought on by the use of the load from the column to the footing, are then obtained by looking the data. The findings of this study can be utilized to verify the precision and effectiveness of the finite element approach in structural evaluation, and to get a better idea of how the structural will respond of RCC columns and footings. Fig. 1 shows the general process used for the finite element analysis.

A. General

To look at how the RCC columns and footings, the current study's technique combines analytical calculations with finite element analysis. The Solid Mechanics module of the COMSOL Multiphysics software program has been utilised to create a three-dimensional finite element model of the column-footing system. The definition of the geometry, the choice of material characteristics, the use of boundary conditions, the use of loading conditions, and the creation of the mesh are all steps in the process of finite element analysis. The model's precision in the examination of the RCC columns and footings under axial loading circumstances has been verified by comparing the numerical outcomes of the finite element analysis alongside the analytical computations.

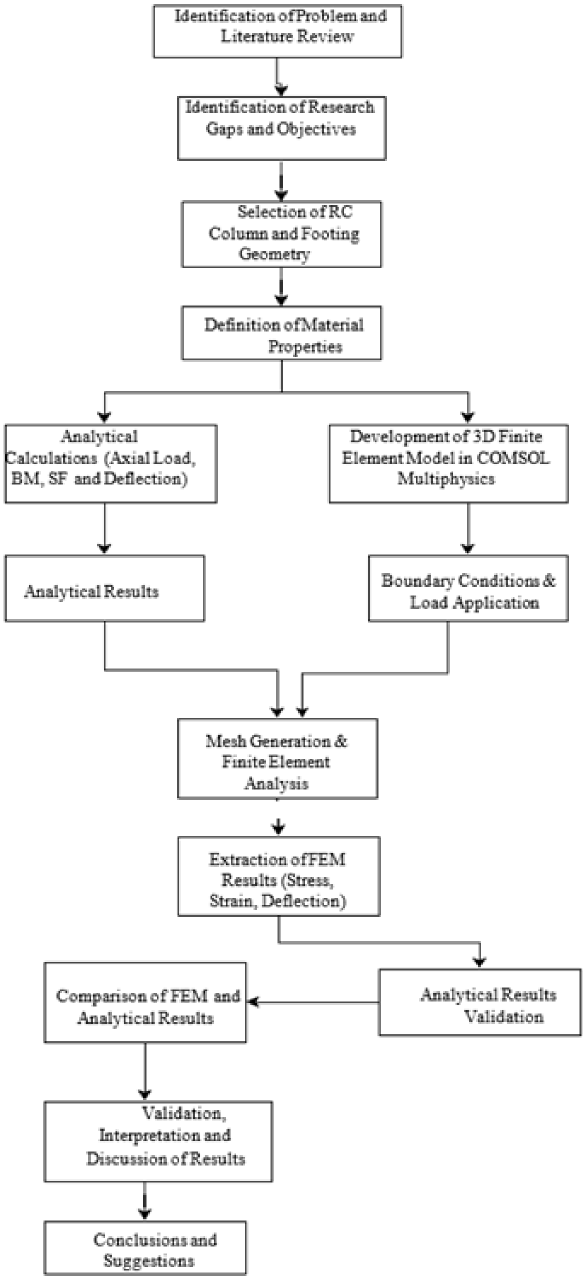

Fig. 1. Flowchart of the research methodology.

B. *Selection of Structural Geometry*

The first step in the analysis is to figure out the shape of the structural system of the reinforced column-footing structure. The geometry is chosen based on standard practices for designing a reinforced column-footing structure. The structural model consists of a reinforced column and a footing that is a foundation member. The column moves loads from the superstructure to the footing. The footing safely moves loads to the supporting soil.The column is placed centrally on the footing to ensure uniform transfer of loads and symmetric behavior of the structure. For precise and trustworthy analytical findings, the geometry is utilized in both computations and finite element modeling.

C. *Material Properties*

The behaviour of the reinforced concrete columns and footings is significantly influenced by the material qualities taken into consideration for the structural components. For the sake of the finite element analysis in this work, the concrete material is regarded as homogeneous and isotropic. for the aim of the finite element analysis, the basic properties of the concrete material, such as density, Poisson's ratio, and the modulus of elasticity, has been taken into account. The standard design rules for reinforced concrete structures, certain characteristics of the concrete material have been taken into account. In order to simulate the behavior of the column-footing system, the traits of the concrete material have been considered for the concrete domain of the finite element model. Both the analytical calculation and the finite element analysis has considered the same characteristics of the concrete material.

D. *Analytical Calculations*

Analytical calculations are performed to determine the theoretical structural response of reinforced concrete columns and footings, based on classical structural mechanics theories. For reinforced concrete columns, parameters such as axial stress, bending stress, and deflection are determined by performing conventional analytical calculations. For reinforced concrete footings, analytical calculations are performed to determine parameters such as base pressure, axial thrust, and other load transfer parameters. The analytical calculations performed on reinforced concrete columns and footings provide reference results, This can be applied to verify the numerical outcomes of finite element analysis.

E. *Finite Element Modeling in COMSOL*

COMSOL Multiphysics software, which has the Solid Mechanics module for modeling, can be used to accomplish finite element modeling of reinforced concrete columns and footings. The program can be used to create three-dimensional numerical models that can be used to simulate the distribution of stress, strain variation, and structural deformation. The geometry of the reinforced concrete column and footing system can be created using the COMSOL modeling software, and the structural domain can be assigned the previously specified material properties. The equilibrium equations of the structural system under applied loads can be solved using the method of finite elements.

F. *Boundary Conditions*

Realistic boundary conditions are applied to reflect actual structural support conditions. The help of the structural system from its base is constrained to reflect support from the foundations and prevent rigid body motion. The remaining surfaces of the structural elements are allowed to deform naturally in response to the applied loads. Realistic development of stress distribution and deformation pattern in the reinforced concrete column-footing system is achieved.

G. *Loading Conditions*

Loading conditions are established to mimic real loading scenarios on the structures. A vertical axial load is imposed on the column to mimic the load transfer from the superstructure.The load causes stress on the column, which is then transmitted to the footing. The footing, in turn, transfers the load to the underlying soil via the footing base area. This loading condition allows to assess the column-footing system's stress distribution.

H. Mesh Generation

Since it greatly affects the precision of the numerical findings, mesh production is a crucial component of finite element analysis. The COMSOL Multiphysics software program's automatic meshing function is used to discretize the geometric model of the reinforced concrete column-footing system into tiny finite elements. The structure's geometric domain has been divided into discrete parts using three-dimensional tetrahedral elements. In the regions with greater concentrations of stress, the mesh has been improved.

I. Finite Element Analysis

The finite element analysis is performed using the Solid Mechanics tool available in the COMSOL Multiphysics software. The reinforced concrete column-footing system is put through a static analysis for the given loading circumstances using a stationary analysis tool. The finite element method's solution offers important information on the displacement modes, strain variations, and stress distribution in the structural elements. To determine the precision and utility of the finite element model, such outcomes can be retrieved and contrasted with theoretical computations.

III. RESULTS AND DISCUSSION

A. Stress Distribution Along the Height of Reinforced Concrete Column

The outcomes of the finite element analysis performed by COMSOL Multiphysics software can be used to find out the stress distribution along the length of the reinforced concrete column. Because of the stable support situation and the direct transmission of load from the superstructure, it is evident that larger stresses are concentrated close to the column's base. A uniform distribution of strains can be seen as the distance from the column's base increases.

B. Comparison of Analytical and COMSOL Results

The outcomes of the numerical simulation utilizing the finite element technique (FEM) used in the COMSOL Multiphysics program to compare different reinforced concrete column specimens are compared with the outcomes of the aforementioned analytical computations. To compare the structural behaviour under various loading situations, the comparison is done for particular places on the column length, namely at a quarter span (L/4), mid-span (L/2), and three-quarter span (3L/4). Axial stress and axial deflection are two crucial comparative metrics. These metrics are very important for comprehending how the structure behaves under various loading scenarios. The outcomes of the aforementioned analytical computations are contrasted with the outcomes of the numerical simulation utilizing the COMSOL Multiphysics software's finite element method for different specimens of reinforced concrete columns. To determine the degree of agreement between the outcomes from the two approaches, the percentage error is computed. This kind of comparison is crucial for comprehending the finite element model's dependability and showcasing COMSOL Multiphysics's capacity to faithfully replicate the behaviour of under axial loading, a reinforced concrete column

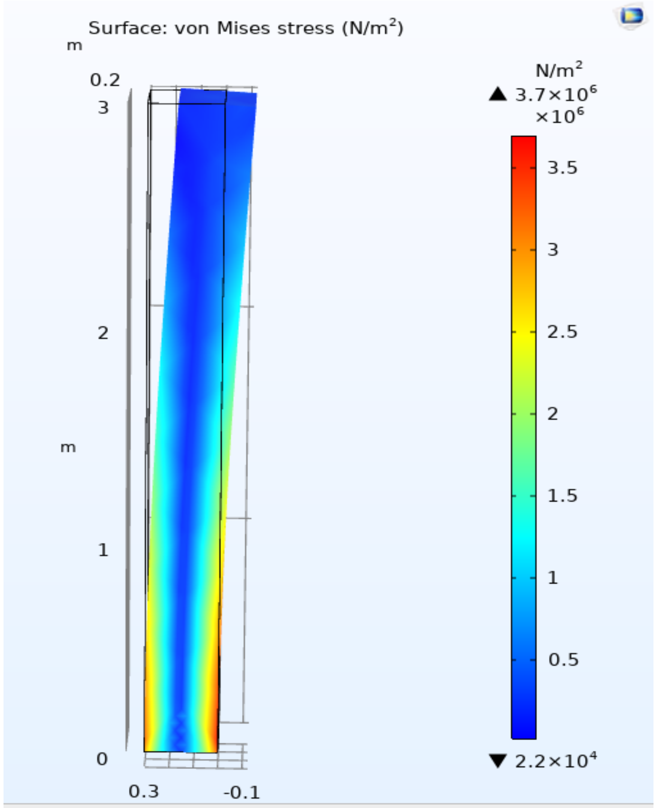

Fig. 2. Stress distribution along the height of RC column obtained from COMSOL analysis.

C. Column Analysis Results

Classical mechanics and structural analysis theories were used to theoretically analyze the column made of reinforced concrete specimens. When put under an axial load along their longitudinal axis, the columns were thought to behave like a prismatic bar. The fundamental equation for stress, which states that the value of stress is same as the load that is applied divided by the cross-sectional area of the column, has been utilised to ascertain the axial stress value predicated on the applied force and the size of the column's cross-section. We used the measurements of the column’s cross-section to figure out the cross-sectional area.

TABLE I. MANUAL AND COMSOL COMPARISON OF RC COLUMN SPECIMEN A1 (B = D = 300 MM, L = 4000 MM, W = 7 KN)

Location	Quantity	Manual	COMSOL	% Error
L/4	Axial Stress (N/mm^2)	0.311	0.311	0
L/4	Deflection (mm)	1.245×10^{-2}	1.235×10^{-2}	0.8
L/2	Axial Stress (N/mm^2)	0.311	0.311	0
L/2	Deflection (mm)	2.49×10^{-2}	2.48×10^{-2}	0.4
3L/4	Axial Stress (N/mm^2)	0.311	0.311	0
3L/4	Deflection (mm)	3.735×10^{-2}	3.724×10^{-2}	0.3
Entire Column	Axial Load (kN)	28	28	0

The axial stress and global axial load have zero error (0%) at L/4, L/2, and 3L/4 points, indicating that these force-based quantities are accurately predicted by the COMSOL software under the given loading and boundary conditions.The deflection results have slightly higher error (0.3 to 0.8%), with the highest error at L/4 and reducing as it progresses to 3L/4. This is due to mesh sensitivity and numerical stiffness in FEA.

TABLE II. MANUAL AND COMSOL COMPARISON OF RC COLUMN SPECIMEN A2 (B = D = 300 MM, L = 3000 MM, W = 6 KN)

Location	Quantity	Manual	COMSOL	% Error
L/4	Axial Stress (N/mm²)	0.2	0.1999	0.025
L/4	Deflection (mm)	6×10^{-3}	5.955×10^{-3}	0.74
L/2	Axial Stress (N/mm²)	0.2	0.1999	0.025
L/2	Deflection (mm)	1.2×10^{-2}	2.48×10^{-2}	0.4
3L/4	Axial Stress (N/mm²)	0.2	0.1999	0.025
3L/4	Deflection (mm)	1.8×10^{-2}	1.7956×10^{-2}	0.24
Entire Column	Axial Load (kN)	18	18	0

The error rate for axial stress and axial load is extremely low, ranging from 0 to 0.03%. This suggests that the force-based behavior of the RC column can be accurately modeled using COMSOL.The error rate for the deflection values, which range from 0.24% to 0.74%, is comparatively greater. Mesh discretization, stiffness, and averaging in finite element analysis may be the cause of this.

TABLE III. MANUAL AND COMSOL COMPARISON OF RC COLUMN SPECIMEN A3 (B = D = 300 MM, L = 5000 MM, W = 8 KN)

Location	Quantity	Manual	COMSOL	% Error
L/4	Axial Stress (N/mm²)	0.4444	0.4444	0.01
L/4	Deflection (mm)	4.44×10^{-3}	4.4291×10^{-3}	0.25
L/2	Axial Stress (N/mm²)	0.4444	0.4444	0.01
L/2	Deflection (mm)	4.44×10^{-2}	4.4291×10^{-2}	0.25
3L/4	Axial Stress (N/mm²)	0.4444	0.4445	0.02
3L/4	Deflection (mm)	6.6×10^{-2}	6.6513×10^{-2}	0.13
Entire Column	Axial Load (kN)	40	40	0

The axial stress and total axial load have extremely low error, ranging from 0 to 0.02%, which implies a high accuracy of COMSOL in predicting the force-based response under axial loading.The axial deflection has somewhat greater inaccuracy, ranging from 0.13 to 0.25%, and decreases from L/4 to 3L/4, which could be attributed to mesh sensitivity and numerical stiffness.

D. Loading Condition in Finite Element Model

A uniformly distributed axial load was exerted to the upper surface of the reinforced concrete column-footing system. The load transmission from the top down to the foundation system is represented by this. The load is transferred to the footing and the ground by compressive stress along the column's height.

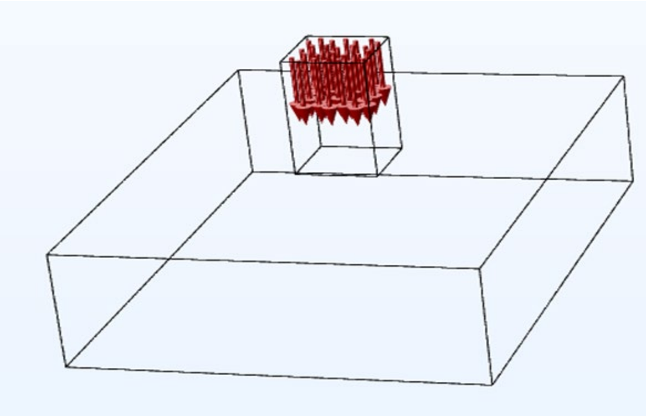

Fig. 3. Axial load applied on the reinforced concrete column in the COMSOL finite element model.

E. Footing Analysis Results

Both theoretical calculations and numerical simulations utilizing the COMSOL Multiphysics software package used the finite element method to analyze the findings of the analysis done on the reinforced concrete footing. In order to observe the stress distribution and deformation characteristics under the applied loading circumstances as imparted by the column, the footing was analyzed. By considering the geometry of the footing, the load applied, and the properties of the reinforced concrete material, theoretical calculations were done in accordance with the fundamentals of classical mechanics of structures. The COMSOL Multiphysics software program was used to numerically simulate the footing in three dimensions using the finite element approach. The footing was given the attributes required to carry out the numerical simulation in accordance with the footing structure's actual behavior. The numerical simulation's outcomes offered comprehensive details about the footing structure's deformation and stress distribution.

TABLE IV. COMPARISON OF AXIAL THRUST FOR RC FOOTINGS

Footing Size (mm × mm × mm)	Axial Thrust Manual (kN)	Axial Thrust COMSOL (kN)	Base Pressure Manual (N/mm²)	Base Pressure COMSOL (N/mm²)	% Error
1500 × 1500 × 450	1000	1000	0.556	0.556	0.01
2000 × 2000 × 500	1000	1000	0.313	0.313	0
2500 × 2500 × 600	1000	1000	0.160	0.160	0

According to the study's analysis, both the axial load and the axial thrust have zero percentage error for all footing sizes. This is a gauge of precision, and it is nearly flawless. This confirms that there is no margin of error when simulating the load transfer from the column to the footing using numerical models. This demonstrates that the models used to forecast footing behavior are consistent. The results for base pressure, however, show a somewhat higher percentage error. This is because stress values are used to measure base pressure. Because of the approximations used in the boundary representation in finite element models, mistakes are therefore inevitable. But as was already indicated, this error margin is much below allowable bounds. Additionally, the base pressure readings have a lower standard deviation. Given that all of the results have nearly identical values, this suggests that there is no appreciable error margin. This shows that every technique for figuring out footing behavior has been proven to be accurate. This suggests that finite element method have been proven to be accurate models for evaluating footing behaviour.

IV. CONCLUSION

The COMSOL Multiphysics program was used in this work to perform a finite element analysis of the rectangular footings and the reinforced concrete columns. The accuracy of the numerical results in this study was confirmed by putting them next to the analytical results produced using the IS 456:2000 code and the traditional theory of reinforced concrete design. The structural behavior of the column-footing system under the applied axial loading conditions has been satisfactorily approximated by the constructed finite element models in the current study. The findings obtained using the finite element model are accurate, with very little variance in the percentage range, according to the comparison of the analytical results with the finite element analysis. The accuracy of the finite element model's simulation of the stress distribution throughout the column's length was verified by evaluating the axial stress at the crucial sections, such as L/4, L/2, and 3L/4, along the column's height. The reason for the slight variations in displacement values is that the analytical approach makes assumptions about linear elastic behavior and uniform stress distribution, while the finite element analysis can simulate realistic structural stiffness, deformation, and support constraints.

Furthermore, the study of reinforced concrete footings has demonstrated that the axial load is transferred from the column to the footing since the axial thrust values computed in COMSOL closely match the analytical findings. Due to the consideration of non-uniform pressure distribution and stress concentration in the system, which is typically challenging to account for in an analytical solution, the results obtained for base pressures using the finite element analysis showed a slight degree of variation when compared to the analytical calculations. Furthermore, the column-footing system's stress distribution was well visualized by the finite element model, which is typically challenging to achieve with traditional analysis.

Overall, it can be said that the outcomes confirmed that the created finite element model can be utilized to accurately and consistently predict the structural behavior of reinforced concrete columns and footings under axial loading. The dependability and efficacy of utilizing COMSOL Multiphysics as a numerical tool for structural analysis of reinforced concrete components were confirmed by the observed percentage changes, which were well within acceptable bounds. Even though analytical tools can be used for structural analysis and design of reinforced concrete components, it has been discovered that a better and more thorough understanding of structural behavior can be obtained by combining finite element analysis with traditional methods of structural design and analysis, particularly in critical regions of the structural component.

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