

EFFECT OF MORTAR TYPE AND JOINT THICKNESS ON THE COMPRESSIVE STRENGTH OF BRICK MASONRY PRISMS: A FINITE ELEMENT APPROACH

A DISSERTATION
SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE
AWARD OF THE DEGREE OF

**MASTER OF TECHNOLOGY
IN
STRUCTURAL ENGINEERING**

Submitted By:
Mohit Kumar Kulshreshtha
(24/STE/05)

Under the supervision of
Prof. Shilpa Pal



**DEPARTMENT OF CIVIL ENGINEERING
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Shahbad Daultapur, Main Bawana Road,
Delhi-110042, India**

May 2026

**CIVIL ENGINEERING DEPARTMENT
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042**

CANDIDATE’S DECLARATION

I, **Mohit Kumar Kulshreshtha (24/STE/05)**, a student of M.Tech in Structural Engineering, hereby declare that the project dissertation titled “**Effect of Mortar type and joint thickness on the Compressive Strength of brick masonry prisms: A finite element approach**”, submitted to the Department of Civil Engineering, Delhi Technological University, Delhi, in partial fulfillment of the requirements for the award of the Master of Technology degree, is my original work. It has not been copied from any source without proper citation. I further affirm that this work has not been submitted previously for the award of any degree, diploma, associateship, fellowship, or any other similar title or recognition.



Mohit Kumar Kulshreshtha

Place: New Delhi

Date: 30-May-2026

**CIVIL ENGINEERING DEPARTMENT
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042**

CERTIFICATE BY THE SUPERVISOR(S)

This is Certified that **Mohit Kumar Kulshreshtha (24/STE/05)** has carried out his research - work presented in this thesis entitled “**Effect of Mortar type and joint thickness on the Compressive Strength of brick masonry prisms: A finite element approach**”, for the award of Master of Technology from Department of Civil Engineering, Delhi Technological University, Delhi, under our supervision. The thesis embodies results of original work, and studies are carried out by the student himself, and the contents of the thesis do not form the basis for the award of any other degree to the candidate or to anybody else from this or any other University/Institution.



Signature

Prof. Shilpa Pal

Professor

Delhi Technological University

Date:

ABSTRACT

Brick masonry is among the highly versatile and popular construction techniques adopted in India and which have been used in numerous projects over the last decades. There are majority buildings across the nation that have been erected using brick masonry cement mortar technique, while the lime mortar method is predominantly employed in heritage and historical buildings. The strength of masonry construction is greatly influenced by the strength of bricks, mortar, and more importantly, the bond between the brick and mortar. There are cases where masonry fails because of weakness at the interface between brick and mortar.

There are numerous factors that govern the structural strength and stability of masonry walls, such as the characteristics of the mortar itself, the properties of bricks, construction skills, and the thickness of mortar joints. Among all of these, the thickness of the mortar is one major factor that affects the load carrying capacity and strength.

Experimental studies on brick masonry prisms with different mortar thicknesses are available in the literature; however, analytical investigations using detailed finite element modeling are limited. Hence, the present study aims to evaluate the behavior of brick masonry prisms with varying mortar thicknesses through finite element analysis.

The current investigation involves the use of micro modeling concepts in bricks, mortar joints, and interfaces are considered independently. behavior of the brick and mortar material is simulated through DP model, whereas the interface between bricks and mortar is described by intact Cohesive Behavior. The masonry prisms with mortar joint sizes of 13 mm, 20 mm, and 27 mm are analyzed for the condition of axial compression loading when either cement or lime mortar is utilized. This includes analyzing the response of masonry prisms with respect to load-displacement relationship, peak load, compressive strength, stress distribution, and failure modes.

The results indicated that the 20 mm mortar thickness prism exhibited the highest compressive strength for both cement and lime mortar. This suggests that 20 mm mortar thickness provides optimum bond performance and can be effectively used in modern masonry construction as well as heritage masonry structures.

ACKNOWLEDGEMENTS

The completion of this research dissertation, “**Effect of Mortar Type and Joint Thickness on the Compressive Strength of Brick Masonry Prisms: A Finite Element Approach**”, has been a journey marked by learning, challenges, and immense personal and academic growth. I am sincerely grateful to everyone who has contributed to the successful realization of this work.

First and foremost, I am deeply indebted to **Prof. Shilpa Pal**, my supervisor, for her invaluable guidance, constant encouragement, and insightful suggestions throughout this research. Her expertise and mentorship played a crucial role in shaping the direction and quality of this study.

I also extend my sincere thanks to the **Prof. Awadhesh Kumar** Head of the Department, Department of Civil Engineering, Delhi Technological University, for providing a supportive academic environment and the necessary resources to carry out this research. My heartfelt appreciation goes to **Ms. Khyati Saggu, Ph.D. Scholar**, for her continuous guidance, technical support, and constructive suggestions, which greatly assisted me throughout the course of this work.

I would also like to acknowledge **Mr. Anshoo Yadav**, whose research work served as a valuable reference and provided important insights for the development of this study. The knowledge gained from his work significantly contributed to my understanding of the research problem and methodology.

I am grateful to the technical and administrative staff of the Department of Civil Engineering for their assistance and cooperation during this research. I also thank my colleagues and peers for their support, discussions, and encouragement, which made this journey both productive and enjoyable.

Finally, I express my deepest gratitude to my family for their unwavering support, patience, and encouragement. Their faith in me has been a constant source of motivation and strength throughout this academic endeavor.

MOHIT KUMAR KULSHRESHTHA



CONTENTS

CANDIDATE’S DECLARATION	i
CERTIFICATE BY THE SUPERVISOR(S)	ii
ABSTRACT.....	iii
ACKNOWLEDGEMENTS	iv
CONTENTS.....	v
LIST OF TABLES	vii
LIST OF FIGURES	viii
LIST OF SYMBOLS AND ABBREVIATIONS	x
CHAPTER 1	1
INTRODUCTION	1
1.1 GENERAL	1
1.2 BRICK MASONRY PRISM BEHAVIOR UNDER COMPRESSION	2
1.3 NEED FOR NUMERICAL MODELING	3
1.4 PROBLEM STATEMENT	4
1.5 OBJECTIVES OF THE STUDY	4
1.6 OUTLINE OF THE THESIS	4
CHAPTER 2	6
LITERATURE REVIEW.....	6
2.1 GENERAL	6
2.2 LITERATURE REVIEW.....	6
2.3 RESEARCH GAP.....	11
2.4 CONCLUDING REMARKS.....	11
CHAPTER 3	12
METHODOLOGY.....	12
3.1 GENERAL	12
3.2 FINITE ELEMENT ANALYSIS.....	12
3.2.1 EXPLICIT FINITE ELEMENT ANALYSIS.....	12
3.2.2 MASONRY MODELING APPROACHES	13
3.3 CONSTITUTIVE MODELING OF MASONRY MATERIALS	14

3.3.1	DRUCKER-PRAGER PLASTICITY MODEL	15
3.4	MODELING OF BRICK MASONRY PRISM	17
3.4.1	GEOMETRY OF BRICK MASONRY PRISM	17
3.4.2	MATERIAL PROPERTIES	17
3.5	BOUNDARY CONDITIONS.....	19
3.6	MESH SENSITIVITY	20
3.7	LOADING CONDITIONS	22
3.8	VALIDATION.....	22
3.8.1	COMPRESSIVE STRENGTH OF BRICK MASONRY PRISM.....	23
3.9	CONCLUDING REMARKS	24
CHAPTER 4		25
RESULTS AND DISCUSSION		25
4.1	GENERAL	25
4.2	RESULTS	25
4.2.1	ANALYTICAL RESULTS.....	25
4.3	COMPARISON OF ANALYTICAL AND EXPERIMENTAL RESULTS	28
4.3.1	COMPARISON BASED ON PEAK LOAD	28
4.3.2	COMPARISON BASED ON COMPRESSIVE STRENGTH	30
4.4	CONTOURS OF PRISMS WITH DIFFERENT THICKNESS OF CEMENT MORTAR.....	33
4.5	CONCLUDING REMARKS	38
CHAPTER 5		39
CONCLUSIONS AND FUTURE SCOPE		39
5.1	GENERAL	39
5.2	CONCLUSIONS.....	39
5.3	CONTRIBUTION TO SUSTAINABLE DEVELOPMENT GOALS (SDGS) ..	40
5.4	FUTURE SCOPE.....	41
BIBLIOGRAPHY		42
CONFERENCES		42

LIST OF TABLES

Table 3.1 Mechanical Behavior of Brick and Mortar ([24]	18
Table 3.2 Mesh refinement study and corresponding Peak load variation	21
Table 3.3 Validation of Model with Analytical and Experimental Results	22
Table 3.4 Compressive strength of brick masonry prism	23
Table 4.1 Comparison between experimental and analytical results	29
Table 4.2 Comparison between experimental and analytical results	31
Table 4.3 Analytical and Experimental compressive strength of brick masonry prism using correction factor as per IS 1905: 1987	31
Table 4.4 brick masonry prism with different type of mortar.....	36

LIST OF FIGURES

Figure 3.1 Macro Modeling Approach.....	13
Figure 3.2 Simplified Micro Modeling	13
Figure 3.3 Detailed Micro Modeling	13
Figure 3.4 Failure Modes of Joints	14
Figure 3.5 crack in masonry due to compressive loading.	15
Figure 3.6 Linear yield surface of Drucker-Prager Model[19]	16
Figure 3.8 Brick Masonry Prisms with different thickness of cement mortar	17
Figure 3.9 Compressive Strain-Strain Curve of Brick	18
Figure 3.10 Compressive Strain-Strain Curve of Cement mortar	19
Figure 3.11 Compressive Strain-Strain Curve of Lime mortar	19
Figure 3.12 Boundary condition and loading condition.....	20
Figure 3.13 Prism with different mesh size	20
Figure 3.14 Peak Load-Displacement response curve with different mesh size.....	21
Figure 3.15 Experimental Vs. Analytical Results of Brick masonry Prism.....	22
Figure 4.1 Load Vs. Displacement Curve of Brick Masonry Prism with 13mm Cement Mortar thickness.....	25
Figure 4.2 Load Vs. Displacement Curve of Brick Masonry Prism with 20mm Cement Mortar thickness.....	26
Figure 4.3 Load Vs. Displacement Curve of Brick Masonry Prism with 27mm Cement Mortar thickness.....	27
Figure 4.4 Load Vs. Displacement Curve of Brick Masonry Prism with 20mm Lime Mortar thickness.....	27
Figure 4.5 Experimental Vs. Analytical results of Prisms with different thickness of mortar	29
Figure 4.6 Experimental Vs. Analytical results of Prisms with different thickness of mortar in terms of compressive strength.....	30
Figure 4.7 Analytical, Experimental compressive strength of brick masonry prism with different thickness of cement mortar	32

Figure 4.8 Tensile stress distribution in brick masonry prim with 13 mm CM mortar ...	33
Figure 4.9 Tensile stress distribution in brick masonry prim with 20 mm CM mortar ...	34
Figure 4.10 Tensile stress distribution in brick masonry prim with 27 mm CM mortar .	34
Figure 4.11 Compressive Stress distribution in Prisms	35
Figure 4.12 Compressive strength of with varying thickness of lime mortar	37

LIST OF SYMBOLS AND ABBREVIATIONS

FE	Finite element
FEM	Finite element method
FEA	Finite element analysis
CDP	Concrete damage plasticity
FRP	Fiber reinforced polymer
XFEM	Extended finite element method
DP	Drucker prager model
CM	Cement mortar
OPC	Ordinary Portland cement
CM	Cement mortar
LM	Lime mortar
t	Normal traction stress vector
S	Stress deviator (MPa)
r	Third invariant of deviator stress (MPa)
p	Hydrostatic pressure stress (MPa)
β	Material friction angle (degree)
σ	Stress deviator
I	Identity matrix
σ_c	Compressive yield stress (MPa)
d	Material cohesion (MPa)
ψ	Dilation angle (degree)

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Brick and mortar is oldest and mostly used material of building. Masonry has been utilized for constructing buildings, bridges, retaining walls, and other infrastructural components throughout history because of its strength, availability of raw material, and simplicity of construction. Traditional masonry buildings consist of individual building units like bricks, stones, or concrete blocks that are held together by mortar to form a structural component. Brick masonry is among the most popular types of masonry buildings.

There are many strengths in the building of Masonry constructions such as excellent compressive strength, fire resistance, insulation property, and durability. These make masonry still widely used in the development and undeveloped world. But even though there are so many strengths of masonry construction, it is known to be made up of diverse elements, thus its behavior mechanically tends to be complicated.

Masonry behavior is affected by the material properties of its constituent elements, including the strength of bricks, mortar, and bonding, as well as geometric properties such as the thickness of cement-mortar joints. Masonry behavior under compression load is nonlinear because of the formation of cracks, crushing, and inter-relation between bricks and mortars. Brick masonry prisms can serve as prototype specimens for examining the essential mechanical performance of masonry subjected to compression. The analysis of these prisms can be helpful in estimating certain parameters like compressive strength, stiffness, deformation properties, and failure modes. Considering that experimental studies may be expensive and time-intensive, computational methods like the finite element technique have been found useful in studying the mechanics of masonry. Because of the development of computational models such as, micro-modeling of masonry elements can now be achieved.

1.2 BRICK MASONRY PRISM BEHAVIOR UNDER COMPRESSION

Prisms of brick masonry are widely used in experiments on the compression of masonry structures since prisms reflect the fundamental structural reaction of masonry structures to axial loading. Brick masonry prisms are made from bricks joined by mortar joints to create a composite material, which reacts based on the behavior of its components.

Brick masonry prism's performance is based on compressive load is intricate owing to the heterogeneity of the masonry material itself. While both the brick units and mortar experience compressive stresses, there are mechanical differences in between these two material like stiffness, strength, and Poisson's ratio. As a result, there will be interactions resulting from the disparity in these mechanical differences between the brick units and mortar. Typically, mortar strains more laterally than the brick units when subjected to compressive forces, leading to tensile forces within bricks.

Compression behavior of the masonry prisms normally displays non-linear properties that include an elastic phase at the beginning, crack development, damage development, and failure of the material. At low levels of loads applied to the material, the prism will display nearly elastic behavior whereby stresses are evenly spread out. With increase in load, stresses concentrate in areas around the interface in between of brick & mortar, causing crack formation. With further increase in load, cracking continues and causes crushing of mortar or splitting of bricks.

There are several parameters which is affect the compressive strength and deformation properties of bricks in masonry prisms, such as strength of brick, strength of mortar, bond quality, shape of the units, and joint thickness. Of these, joint thickness is an important parameter because it determines the stress transfer and compatibility of deformations between the elements of masonry construction.

Modes of failure in masonry prism specimens subjected to compression include splitting of bricks along the vertical axis owing to tensile stresses on a lateral plane, crushing of the mortar joints, and debonding at the brick-mortar interface. The modes of failure illustrate the need for comprehension of the brick-mortar contact surface.

Experimental investigations alone may not be enough to describe the stress state and fracture mechanisms inside masonry prisms, and numerical methods such as the finite element analysis of brick masonry prisms through the software Abaqus can be used. Finite element

analysis is essential in providing insights into stress formation, fracture formation, and failure mechanisms in masonry prisms.

1.3 NEED FOR NUMERICAL MODELING

The mechanics of brick masonry subjected to compressive loads pose difficulties because of the non-homogeneous and non-linear characteristics of the masonry material. The brick masonry is made up of brick units, mortar joints, and interfaces, each with unique mechanical properties that interact in a complex way, leading to the development of stress concentration, cracks, crushing, and degradation of material.

Experimentally conducted researches were mainly done for investigating the mechanical characteristics of masonry prisms; but such type of research is always accompanied by large spending of money and efforts in a laboratory setup. Moreover, experimentally obtained results may provide less information on the internal state of stress within the body, as well as the inception of cracks inside the body itself.

Inclusion of numerical simulation by adopting finite element analysis has been considered a good method for investigation of the behavior of masonry. It will help analyze the behavior of masonry under certain loadings, as well as how the material responds under different parameters that affect its behavior. Parameters affecting the behavior of masonry can be analyzed without any experiments.

Abaqus can be considered an excellent software solution among existing finite element programs for performing nonlinear analyses of structures because of its sophisticated material modeling features, reliable contact algorithms, and the possibility of predicting damage and fracture in quasi-brittle materials. Therefore, it can serve as an appropriate means for performing micro-modeling of masonry elements separately.

Modeling using numerical analysis becomes critical for validation purposes and parametric studies based on various factors like the thickness of the mortar joints, material properties, and interaction at interfaces. Predictions can be made with reasonable accuracy regarding displacement-load curves, stress distributions, and failure modes.

Numerical analysis through Finite Element Analysis is thus a critical technique in understanding the compressive performance of brick masonry prisms, alongside experimental analysis and aiding in the better analysis and design of masonry structures.

1.4 PROBLEM STATEMENT

To create a FE model of brick masonry prism according to the Indian Standards and study the influence of changing the thickness of CM and LM on compressive behavior of the brick masonry prism. Validate the model by using experimental results.

1.5 OBJECTIVES OF THE STUDY

Objectives of present study which is being carried out to study about the effects of type and thickness of mortar joint on the compressive strength and behavior of brick masonry prism through finite element technique are as follows:

- To model the brick masonry prism with varying thickness of cement mortar using FE model.
- To examine the influence of different thickness of LM on the masonry prism using FE Techniques.
- To compare experimental and analytical results of brick masonry prism with varying thickness of CM and LM.

1.6 OUTLINE OF THE THESIS

This thesis belongs to the category of the M. Tech dissertation, and it is mainly divided into five chapters. Following is the brief description of each chapter:

Chapter 1 introduces briefly the topic of masonry structures and compressive behavior of brick masonry prisms. It highlights the significance of mortar properties, thickness and necessity of numerical modeling of masonry structures. Problem statement, objectives, and scope of study have also been clearly mentioned in this chapter.

Chapter 2 is a comprehensive literature review on the experimental and numerical studies conducted in connection with masonry prisms, mortar thickness, interface response, and finite element modeling methods. This chapter gives an overview of key information obtained from numerous research papers and assists in determining the research gap in the present investigation.

Chapter 3 elaborates on the methodology chosen for conducting the research. It covers the aspects of finite element analysis of brick masonry prisms modeled with the use of micro-modeling approach. The discussion includes aspects of geometry generation, material

properties, interaction properties, meshing, boundary conditions, loadings, and model validation based on experimental, analytical and as per IS code.

Chapter 4 deals with the outcome and discussions achieved by performing finite element analysis of brick masonry prisms for varying thickness of mortar joint made of cement mortar and lime mortar under axial compression. Masonry prism behavior has been described based on the load-displacement relationship, maximum load, compressive strength, tensile stress distribution, compressive stress distribution, and failure mode. Comparison among the outcomes of analytical, experimental has also been provided.

Chapter 5 contains the findings made during the current study. This chapter also discusses the future scope of research with regard to the topic. The effect of mortar layer thickness on brick masonry prisms' compressive strength and behavior is discussed in view of the analysis and validation results.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

Literature Review is required to know what results have been found by the past research on behavior of brick masonry prism, mortar and numerical modeling technique. The literature review from past research done by various researchers has greatly enhanced knowledge regarding the mechanics of behavior of masonry structure, failure modes, material properties and influence of mortar joint on structural behavior. Furthermore, literature review is useful to recognize the shortcomings in the past research and areas requiring future research.

The literature review discussed in this research covers past experiments and numerical studies pertaining to brick masonry prisms, the effects of the mortar thickness, cement and lime mortars, and use of finite element method. The results derived from past studies have served as the foundation in formulating and verifying the numerical models in this research.

2.2 LITERATURE REVIEW

Chaimae et al. (2025) performed investigations of brick walls with different patterns of bond under lateral loads using a finite element approach. The study applied a simple micro-modeling approach by analyzing the individual components (bricks and mortar) as a continuum solid. The investigation was aimed at evaluating the influence of the following factors on the performance of masonry walls; Masonry Bond Systems, Openings in Masonry Walls and Fiber-Reinforced Systems [1].

Komürcü (2025) was conducted an extensive numerical examine of failure modes of brick walls through continuous micro-modeling in finite element analysis. Nonlinear analysis was used to examine the stress-strain response, crack propagation, and modes of failure of brick walls with static & dynamic load. One may conclude that the continuous micro-modeling approach is a very strong tool to simulate behavior of masonry wall [2].

Ahiwale et al. (2025). Finite Element Analysis of brick Wall Bonded With FRP Based On Different Structural Bonds. Researchers carried out an investigation regarding application of

FRP in improving behavior of masonry walls. It was carried out using continuum solid elements for modeling brick units and mortar joints. [3].

Elsamak et al. (2025) accomplished a test and numerical analysis of masonry columns subjected to axial compression loading but reinforced with optimized hybrid reinforcement techniques. This work is aimed at improving the mechanical performance of masonry columns, including the increase in compressive strength, stiffness, ductility, and resistance against failure by means of varying hybrid strengthening combinations. Hybrid reinforcement methods were tested on the specimen columns and compared with those that were not reinforced [4].

Kıpçak (2025) carried out a numerical investigation for out of plane rejoinder of dry stack double wythe brick masonry wall reinforced with header bricks. This study seeks to analyze the performance of brick wall subjected to a loading with respect to deformation, stress field, crack formation and failure mechanisms. The results have shown that the walls that have weak connections of header bricks tend to deform easily and lose stability under loading. Therefore, it can be said that using header bricks in masonry walls has significantly improved their out-of-plane capacity and stiffness [5].

Akcan et al. (2025) presented FE method has used to predict behavior of masonry walls under different loading conditions. In macro-modeling approach, masonry has been considered to be a homogeneous continuum material, whereas in the detailed micro-modeling approach, masonry constituents such as bricks, mortar, and interfaces were considered for predicting detailed crack formation [6].

Xia et al. (2024) presented an extensive numerical analysis of the compression performance and multi-dimensional damage evolution of historic brick masonry through a micro-modeling method. The main conclusion of the study indicated that it is important to use an accurate interface and material model when conducting masonry damage analysis [7].

Honnalli et al. (2024) performed a multiscale numerical study of properties of brick prism made by clay bricks via sophisticated finite element modeling methods. The researchers found out that a multiscale modeling approach successfully captured local and global masonry prism behavior. The simulation results agreed with the observed compressive behavior of the masonry prisms [8].

Luo et al. (2023) presented a simplified micro-modeling technique using continuum bodies for conducting nonlinear analysis of masonry panels under loads. This research paper was intended to increase the computational efficiency while providing reliable predictions concerning the stress field, cracking process, deformations, and mechanisms of failures in masonry [9].

Chen et al. (2023) presented an easy to use modeling approach as micro based on nonlinear FE analysis for modeling brick wall under out-of-plane different type of loading scenarios such as blasting. Numerical simulation showed that the proposed simplified micro-model could accurately predict masonry fragmentations and collapse behavior with relatively lower computing cost when compared to other detailed micro-modeling techniques [10].

Shristi et al. (2023) conducted an investigation of effect of thickness of mortar joint reinforcement in improving performance of brick walls through use of numerical analysis methods, specifically using the nonlinear finite element technique. Different mortar joint reinforcement techniques were evaluated to establish their impact on the overall improvement in behavior of brick wall. Outcomes showed that there was an enhancement in the behavior reinforced brick walls related of crack initiation, crack propagation, stress distribution, and overall stability [11].

Yadav et al. (2023) conducted experimental studies on the influence of mortar thickness and mortar type on the compressive response of brick masonry prisms. The thickness of LM & CM with different size used in this research. According to their findings, bricks made from 20 mm thick mortars had the maximum compressive strength among all other types of mortar. In terms of strength performance, the prisms made from cement mortar were better than those made from lime mortar because of their greater stiffness and adhesion properties [12].

Zeng et al. (2021) performed complex nonlinear finite element analyses to study in-plane and out plane responses of unreinforced walls within different loading conditions. This study were pointed at investigating things of material properties, constitutive parameters, and interfacial mechanics between bricks and mortar on the stress condition, cracking pattern, deformation behavior, and failure process in masonry walls. This study employed an advanced finite element modeling approach [13].

Sharma et al. (2021) studied seismic behavior of periodic masonry panels without reinforcement in out-of-plane two-way bending by nonlinear homogenized discrete modeling

approach. The principal purpose of this study was to analyze deformation behavior, cracking, stress distribution, and failure modes in masonry panels exposed to seismic actions. The seismic out-of-plane two-way bending behavior of masonry panels, such as displacement, crack development, stress concentration, and collapse mechanism, was analyzed using numerical simulations. It is shown that discrete homogenized modeling method is capable of simulating seismic behavior & modes of failure of brick panel efficiently [14].

Oliveira et al. (2021) has conducted an experimental and numerical analysis of dry joint properties of refractory masonry structures. The aim of the research was to analyze the mechanical interaction, stress-transfer mechanisms, deformation features, and failure manners of the dry-jointed brickwork structure when loaded under compression and shear loading conditions. From the findings of the study, interface behavior had a considerable impact on stiffness, shear resistance, and stability of refractory masonry structures [15].

Meoni et al. (2021) has conducted experimental and numerical analysis on reconstruction of the strain field and identification of damage in masonry walls under in-plane loads using intelligent bricks. The study has focused on monitoring the phenomenon of cracks development, strain localization, deformation behavior, and damage progression under loading. The research found that incorporating smart sensors with finite element simulation techniques is a practical strategy for structural health monitoring and damage detection of masonry structures. [16].

D'Altri et al. (2019) suggested a destructive block-based numerical model to investigate the cyclic behavior and nonlinear characteristics of full-scale masonry structures loaded laterally. This research was conducted with the aim of assessing stiffness degradation, crack propagation, deformation properties, energy dissipation, and failure modes of masonry structures due to cyclic loading conditions. It was concluded that the destructive block-based numerical modeling technique was very useful in predicting seismic behavior, energy dissipation, and failure of masonry structures due to cyclic loading. [17].

Rahgozar et al. (2017) have conducted both analytical and experimental studies on the behavior of historic mortared brick masonry structures under lateral loads. In this study, efforts have been made to study the stress state, crack development, behavior of deformations, load & displacement curve, and failure modes of masonry wall structures. The comparison of results from numerical analysis with the experimental tests showed good

correlation. Based on the results of numerical analysis, it can be concluded that nonlinear finite element analysis was an effective method for predicting the failure of historic mortared brick masonry structures [18].

Abdulla et al. (2017). has been proposed a novel methodology for the modeling of nonlinear behaviors and failure masonry mode's structures is subjected to monotonic and dynamic loads via Finite Element Analysis. More specifically, the micro-modeling technique has been realized in a manner that involved the modeling of the masonry units with continuum solid elements while the interfaces and mortar joints were modeled using cohesive surfaces in order to account for bond failure, interface debonding, and sliding between interfaces [19].

Noor-E-Khuda et al. (2016) developed a finite element analysis approach to study the out-of-plane behavior and failure modes of masonry walls under dynamic loading conditions. The objective of the research work was to investigate the displacement responses, cracking phenomena, stress distributions, deformation characteristics, and structural failure modes of masonry walls under severe dynamic loads such as impact and seismic loads [20].

Bolhassani et al. (2015) introduced a simple micro-modeling approach for studying the nonlinear mechanics of partially grouted masonry assemblies via finite element modeling. In this study, crack propagation, stress distribution, deformation characteristics, and failure mechanisms of masonry systems have been examined by reducing the complexity of detailed micro-modeling approaches. Numerical simulation is performed for the load-displacement relationship, cracking, and failure behavior of masonry assemblies under load conditions [21].

Aref, et al. (2013). established a three-dimensional cyclic meso-scale numerical modeling technique for analyzing the nonlinear performance and failure mechanisms of unreinforced masonry structures under cyclic loading. The findings revealed that the proposed meso-scale model successfully estimated masonry cyclic response and seismic damage evolution with high precision under cyclic loads [22].

Kaushik et al. (2007) performed an experimental study to establish a uniaxial compressive stress-strain model for clay brick masonry subjected to axial compressive loads. The study sought to assess the compressive strength, deformation, stiffness properties, stress-strain relationship, and failure modes of masonry prisms made of clay brick and mortar. From

experimental observations, analytical stress-strain relations were established for the prediction of masonry compressive behavior [23].

2.3 RESEARCH GAP

- Limited studies focus on the effect of varying mortar thickness on the compressive behavior of masonry prisms using detailed finite element micro-modelling. The role of mortar thickness in micro-modelling approaches is not sufficiently investigated.
- Insufficient understanding of how mortar thickness influences mechanical performance (peak load, strength, stress distribution) under compressive loading.
- Lack of comprehensive studies that provide direct comparison between experimental results and numerical simulations for validation of masonry behavior.

2.4 CONCLUDING REMARKS

The review of relevant literature presented in this chapter proves that behavior of masonry prisms made from bricks is significantly affected by brick unit characteristics, mortar constituents, joint width, and interface brick-mortar interactions. Masonry is a heterogeneous composite which exhibits very non-linear and complicated behavior when subjected to compressive loads. Prior researches were carried out by many researchers in order to investigate the compressive behavior, fracture patterns, and failure modes of masonry prisms.

CHAPTER 3

METHODOLOGY

3.1 GENERAL

This chapter discusses application of the FE model in the simulation of brick masonry prisms numerically. In this situation, the micro-modeling technique is used where each constituent like brick and mortar is modeled individually. Materials' nonlinearity is represented by DP plasticity model. For analyzing behavior of the masonry prism under compression, explicit finite element modeling was employed. This chapter outlines the process of developing the model which includes geometry, material, interaction, boundary conditions, mesh, loading condition, and result validation.

3.2 FINITE ELEMENT ANALYSIS

The finite element analysis is among the very crucial numerical methods which may be used in making predictions on how structures respond under loadings. The finite element analysis has a vital role in making predictions on the stress distribution, deflections, and even failure of masonry structures. This numerical method works better due to the heterogeneity and nonlinearity nature of brick masonry compared to experiments.

3.2.1 EXPLICIT FINITE ELEMENT ANALYSIS

Explicit finite element analysis is the numerical technique used to obtain solutions through direct computation of the structural behavior without the need to iterate the equilibrium equation globally at each increment.

Explicit solutions are especially appropriate when dealing with systems that involve very nonlinear materials, significant deformations, dynamic loads, impact loads, explosion loads, contacts, crack propagation, fracturing, and structural failure. Because there is no need to iterate for equilibrium, explicit procedures can easily deal with extremely discontinuous behavior and complicated contacts without convergence problems.

3.2.2 MASONRY MODELING APPROACHES

Numerical modeling of masonry buildings can generally be divided into three major categories: detailed micro-modeling, simplified micro-modeling, and macro-modeling. All three modeling approaches have widely been applied in finite element analysis to examine the structural behavior, stress state, displacement pattern, fracture mechanism, and failure mode in the brick masonry buildings when subjected to different load conditions.

Masonry is a heterogeneous and nonlinear composite material comprising brick elements, mortar, and interfaces. There are three modeling approaches that can be applied in analyzing masonry using FEA. They include detailed micro modeling approach, simplified micro modeling approach, and macro-modeling approach.

The macro-modeling technique refers to a numeric technique where the masonry material is considered a homogenous continuum rather than modeling the brick unit, the mortar, and interfaces as shown in Figure 3.1. This is a less computationally intensive method that is primarily used in the analysis of large masonry systems where the focus is on the general behavior of the structure and not localized cracks.

Simple Micro-Modeling refers to a type of modeling technique involving the expansion of brick units and the use of interface elements or contact to simulate mortar joints and brick mortar boundaries as shown in Figure 3.2. Micro-modeling in detail is considered to be one of the most precise methods of numerical modeling for masonry analysis, where individual bricks, mortar, and the interface between bricks and mortar are simulated as shown in Figure 3.3.

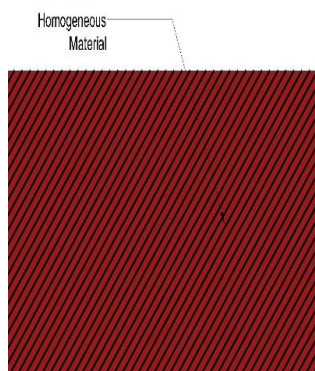


Figure 3.1 Macro Modeling Approach

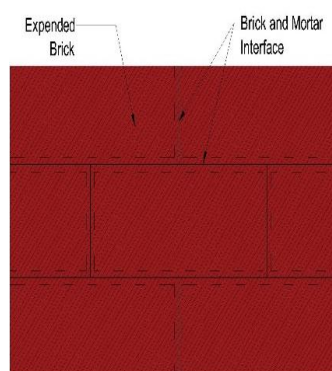


Figure 3.2 Simplified Micro Modeling

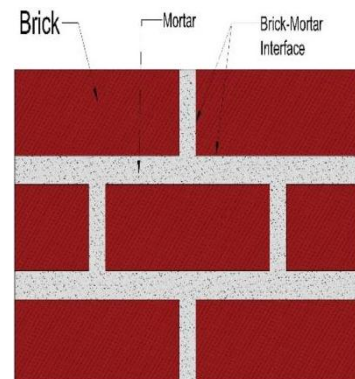


Figure 3.3 Detailed Micro Modeling

For the current study, the concept of micro-modeling was applied for studying the behavior of brick masonry prisms under axial load.

3.3 CONSTITUTIVE MODELING OF MASONRY MATERIALS

Constitutive modeling of masonry materials means the mathematical modeling of the mechanical behavior of brick elements, mortar elements, and their interactions when subjected to various loads. Due to the heterogeneous nature of masonry, being a quasi-brittle material, the mechanical behavior is highly nonlinear.

Drucker–Prager model is Suitable constitutive model for brick masonry prisms subjected to axial compressive loading is considered in current study. Material behavior of brick and mortar under compression is modeled using the Drucker–Prager material model, whereas the behavior between brick and mortar is modeled using **surface-based cohesive behavior**. The Surface-Based Cohesive Behavior Model has been adopted in simulating the adhesive interactions and behaviors along brick-mortar interfaces in masonry structures. Within the framework of this model, the cohesive interaction properties can be assigned.

This surface-based cohesion approach is used to evaluate the structural response of the masonry structure. Consequently, different modes of failure of the joint are captured, including tensile failure Figure 3.4 (a), and shear failure Figure 3.4 (b), and (c).

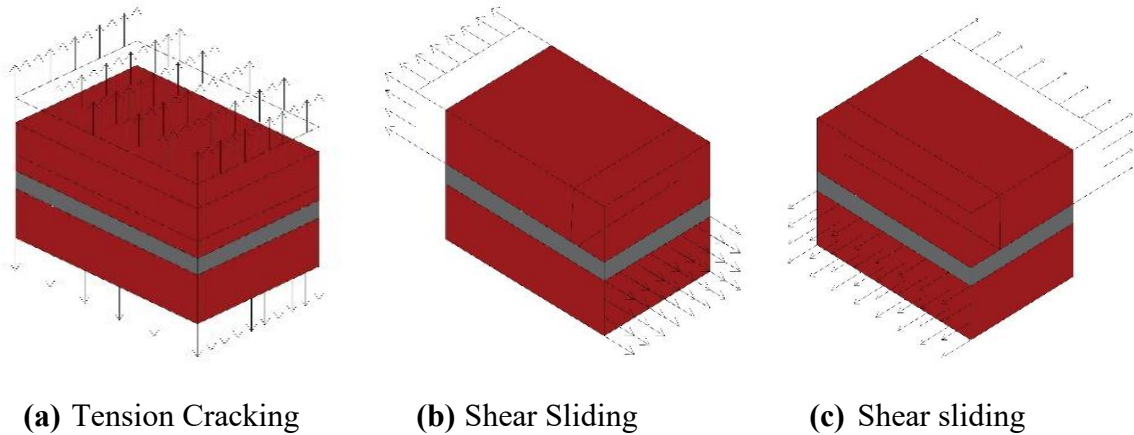


Figure 3.4 Failure Modes of Joints

Plastic deformation in joint contacts is the effect of nonlinear nature of brick-mortar interface beyond the elastic limit under load. In masonry structures, there will be gradual damage, slip, softening, and fracture of the contact surface between brick elements and mortar joints when

the load on the interface exceeds its strength capacity. Nonlinear behavior of the interface greatly affects the cracking pattern, stress distribution, and failure process in masonry structures. Damage initiation will take place when the stress values exceed the preset strengths. Once damage initiation has been accomplished, there will then be an increase in stiffness degradation, which means the amount of load transfer between the brick and mortar will be reduced, and failure will take place [19].

3.3.1 DRUCKER-PRAGER PLASTICITY MODEL

The Drucker-Prager plasticity formulation has been employed for simulating the non-linear behavior of masonry subjected to compression. As per this formulation, isotropic hardening and softening of material due to compression is accounted. This leads to accounting for the possibility of failure of masonry due to compressive loading as shown in Figure 3.5. The Drucker-Prager model was initially formulated by Drucker and Prager by extending the Mohr-Coulomb failure criterion for estimating the failure stress of frictional materials like soils and rocks. Later, the compressive yielding criterion has been extended for hydrostatic compaction loading [19].

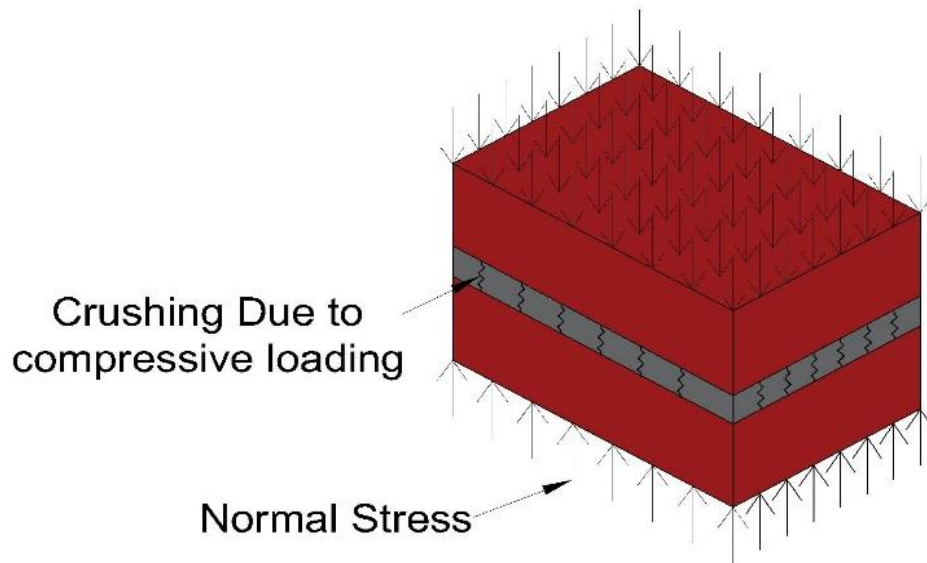


Figure 3.5 crack in masonry due to compressive loading.

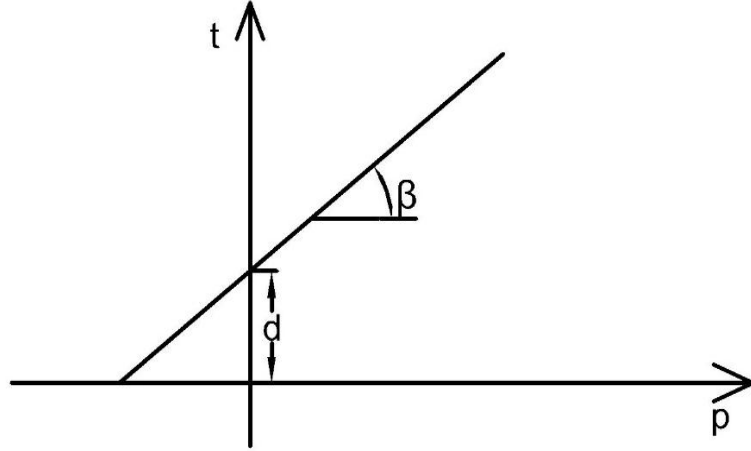


Figure 3.6 Linear yield surface of Drucker-Prager Model[19]

Yield criterion adopted here shown in Figure 3.6 [19]. The development of the yield surface during distortion established using uniaxial compressive strength σ_c of masonry assembly. These parameters include the flow stress ratio R , dilation angle ψ , and friction angle β . The linear yield surface for the DP plasticity model can be formulated by [19]:

$$\mathbf{F} = \mathbf{t} - \mathbf{p} \tan \beta - \mathbf{d} = 0 \quad \dots 3.1$$

Where,

$$\mathbf{t} = \frac{1}{2} \mathbf{q} \left[1 + \frac{1}{R} - \left(1 - \frac{1}{R} \right) \left(\frac{r}{q} \right)^3 \right] \quad \dots 3.2$$

The hydrostatic pressure stress, p , is given by:

$$\mathbf{p} = -\frac{1}{3} \text{trace}(\boldsymbol{\sigma}) \quad \dots 3.3$$

Von Mises equivalent stress, q is given by:

$$\mathbf{q} = \sqrt{\frac{2}{3} (\mathbf{S} : \mathbf{S})} \quad \dots 3.4$$

$$\mathbf{S} = \boldsymbol{\rho} + p\mathbf{I} \quad \dots 3.5$$

$$\mathbf{R} = \left(\frac{9}{2} \mathbf{S} : \mathbf{S} : \mathbf{S} \right)^{\frac{1}{3}} \quad \dots 3.6$$

$$\mathbf{d} = \left(1 - \frac{1}{3} \tan \beta \right) \sigma_c \quad \dots 3.7$$

Compressive plastic behaviour of brick assemblage, which is defined as the dependence on compressive yield stresses on absolute plastic strain.

3.4 MODELING OF BRICK MASONRY PRISM

Brick masonry prism modeling is performed by FE method which is based on detailed micro-modeling techniques. In order to analysis of stress development and failure mechanisms of brick masonry prisms under axial loadings, brick masonry blocks are separated from mortar joints in modeling process.

3.4.1 GEOMETRY OF BRICK MASONRY PRISM

The masonry prism contained five layers of bricks with mortar joints between them. The brick units and mortar joints were considered individually so that the interplay of both units under compressive force could be studied properly. The brick unit sizes selected for analysis were $220 \text{ mm} \times 110 \text{ mm} \times 75 \text{ mm}$, while three mortar joint thicknesses was considered for analysis [12].

The dimension of brick masonry prism with different thickness of cement mortar are shown in Figure 3.8.

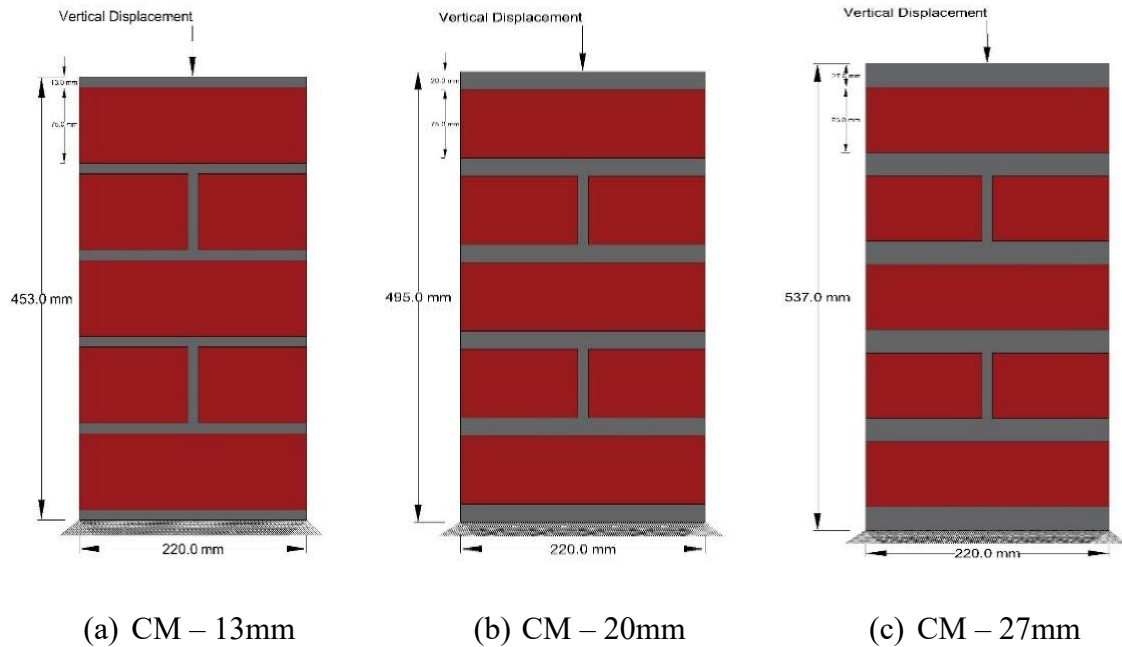


Figure 3.7 Brick Masonry Prisms with different thickness of cement mortar

3.4.2 MATERIAL PROPERTIES

The properties of bricks and mortar were considered through the experimental data and from the literature[12]. The physical properties of bricks and mortar were established with the help of appropriate Indian Standards codes. Bricks' compressive strength was tested based on IS

3495 (Part 1):1992 code, whereas bricks' dimensions were as per IS 1077:1992. OPC-53 cement that conformed to IS 269:2015 and hydrated lime that conformed to IS 1540 (Part 1):1980 were utilized for making mortar. The material properties of brick and mortar shown in table 3.1.

Table 3.1 Mechanical Behavior of Brick and Mortar ([24])

Material	Density (Kg/m ³)	Young's Modulus (MPa)	Poisson's Ratio	Average compressive Strength (MPa)
Brick (5 Nos)	1800	6690	0.15	22.3
Cement Mortar (3 Nos)	2000	4046	0.15	20.38
Lime Mortar (3 Nos)	1600	1000	0.20	5.51

Average compressive strength of brick is more than 12.5 MPa so according to IS code 1077 : 1992 brick classified as a class A brick [25]. Drucker-Prager plasticity model is used for brick elements and joint properties, respectively, to account for nonlinearity of compressive material behavior in masonry. Interaction properties were specified based on cohesive behavior on surfaces to represent bond between bricks and mortar. Furthermore, other mandatory parameter values include ψ , β , and the R. The dilation angle (ψ) has been defined as an estimate lower limit of 11.3° based on, β considered as 36° friction co-efficient of the masonry unit, while $K=1$ [19]. The stress-strain curve for compression of brick, Cement mortar, Lime mortar which is shown in Figure 3.9 that needed to be used to determine the compressive behavior of the models numerically were determined using the test performed in using the ultimate compressive strengths (σ_c) [23].

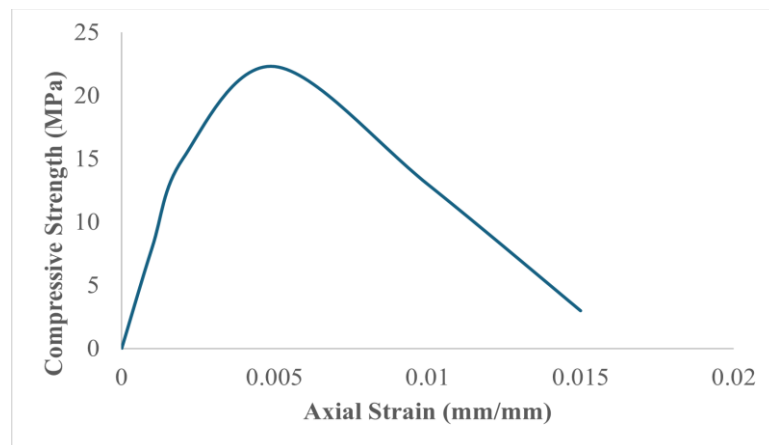


Figure 3.8 Compressive Strain-Strain Curve of Brick

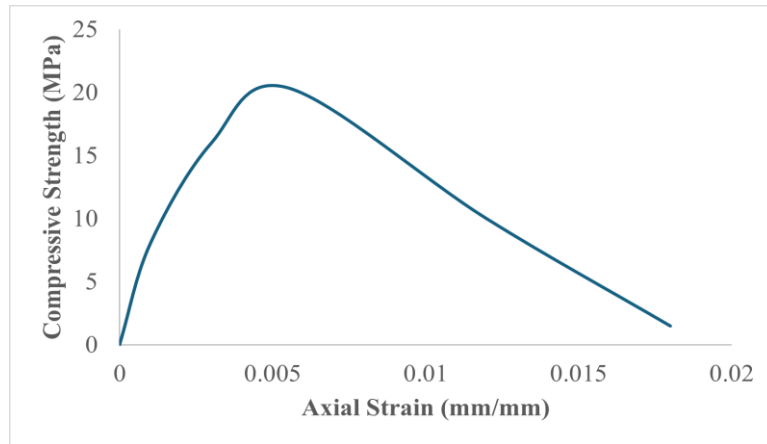


Figure 3.9 Compressive Strain-Strain Curve of Cement mortar

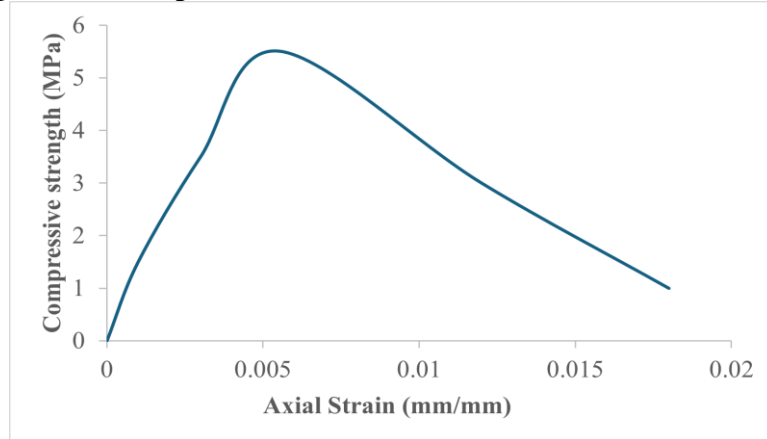


Figure 3.10 Compressive Strain-Strain Curve of Lime mortar

3.5 BOUNDARY CONDITIONS

The boundary conditions were set up for the purpose of simulating the real-life boundary conditions of the masonry prism subjected to compression. The lower end of the masonry prism was completely fixed in all three directions, while the upper end of the prism was subjected to vertical compressive loading as shown in Figure 3.12.

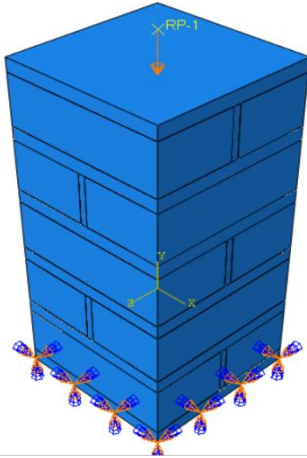


Figure 3.11 Boundary condition and loading condition

3.6 MESH SENSITIVITY

The mesh sensitivity examination supported for identify suitable mesh size for FE analysis and stability and correctness numerical solutions. In the current study, the mesh size analysis has been carried out by considering three different mesh sizes of 5 mm, 10 mm, and 15 mm as shows in **Figure 3.13**. For masonry components, the mesh generation is done with C3D8R elements. The C3D8R is a three-dimensional is used for elements. Such type of elements is extensively used in nonlinear explicit analysis.

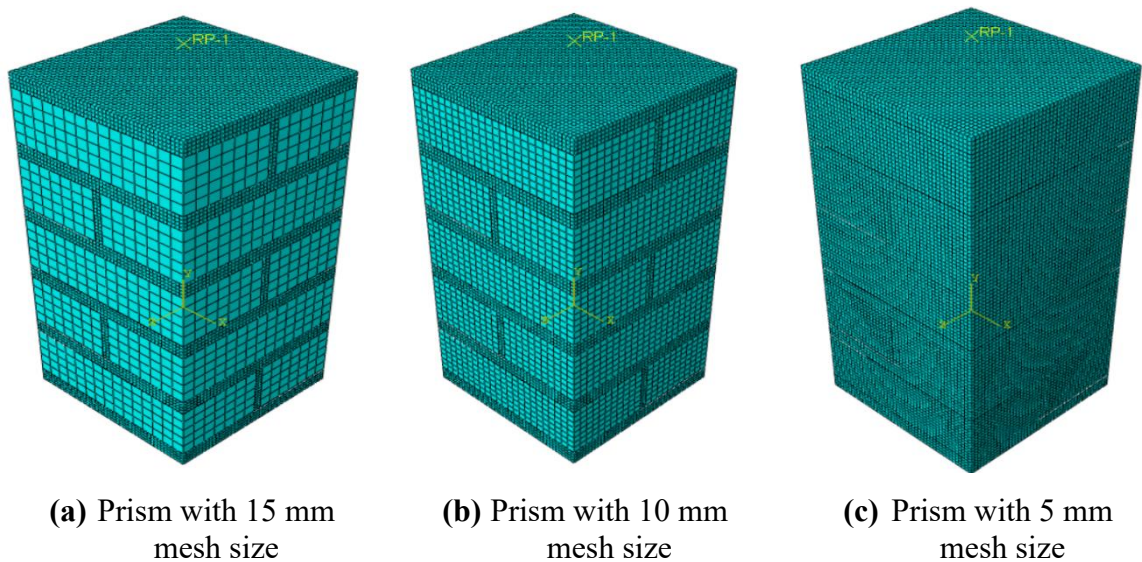


Figure 3.12 Prism with different mesh size

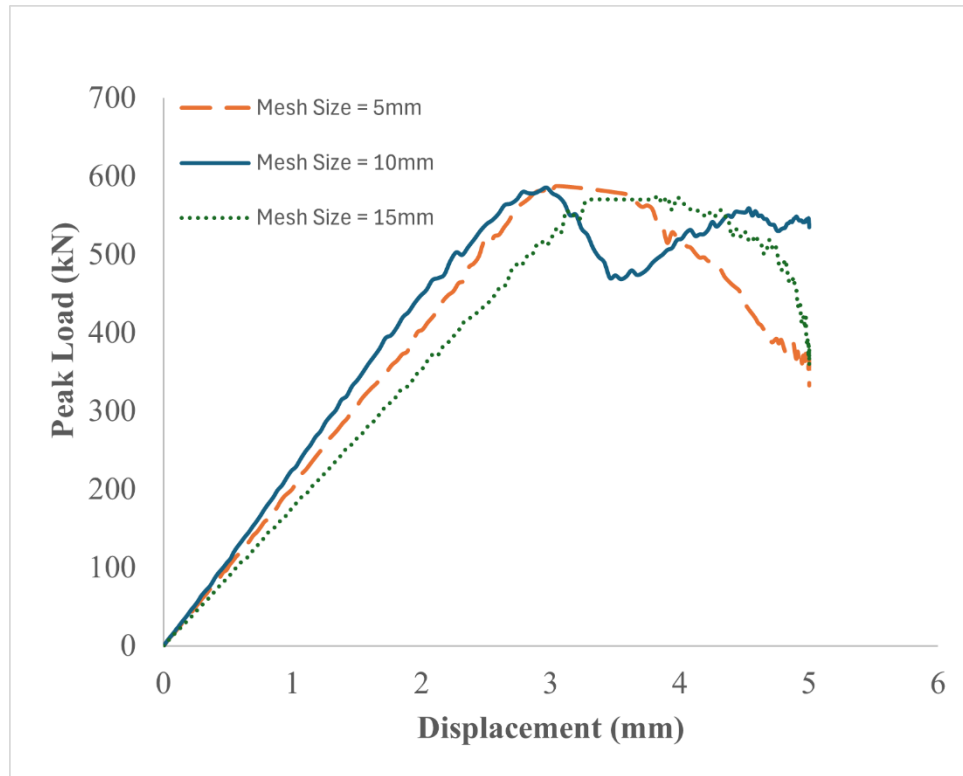


Figure 3.13 Peak Load-Displacement response curve with different mesh size

The comparison of the load displacement curve derived from various mesh sizes is made in order to observe how the size of mesh affects the efficiency of the brick prism under axial compression loading conditions. Figure 3.14 represents the results of the mesh sensitivity analysis obtained through load-displacement curves. As can be seen from figures, all meshes have quite similar behavior because of the gradual increase in load-carrying capacity followed by nonlinearity.

Table 3.2 Mesh refinement study and corresponding Peak load variation

Mesh size	Number of nodes	Number of elements	Element type	Peak load (kN)	Variation (%)
15 mm	85231	62934	C3D8R	575.749	-
10 mm	103471	77924	C3D8R	585.178	1.63
5 mm	250511	209484	C3D8R	587.571	0.40

Mesh sensitivity analysis with different mesh sizes, namely 5mm, 10mm, and 15mm, in order to find the influence of mesh size on the accuracy of finite element analysis. It is clear from

the analysis that the 5mm mesh size produced more accurate results for the peak load; however, the computational time increased substantially. On the other hand, the mesh size of 15mm produced less accurate results while the mesh size of 10mm produced satisfactory results without much computational cost which is shown in Table 3.2. Thus, a mesh size of 10mm was used in the current study.

3.7 LOADING CONDITIONS

To study the compressive response of the masonry prism for the monotonic loading process, the specimen was loaded by compressive forces along the axis of the specimen. In this case, a displacement of 5 mm was imparted to top of surface of the masonry prism, as seen in Figure 3.12.

3.8 VALIDATION

Validation of finite element model is carried out through comparison of the numerical results generated with experimental, analytical, and results of the brick masonry prism having a 13 mm mortar thickness. The validation process involved comparison of results based on peak load.

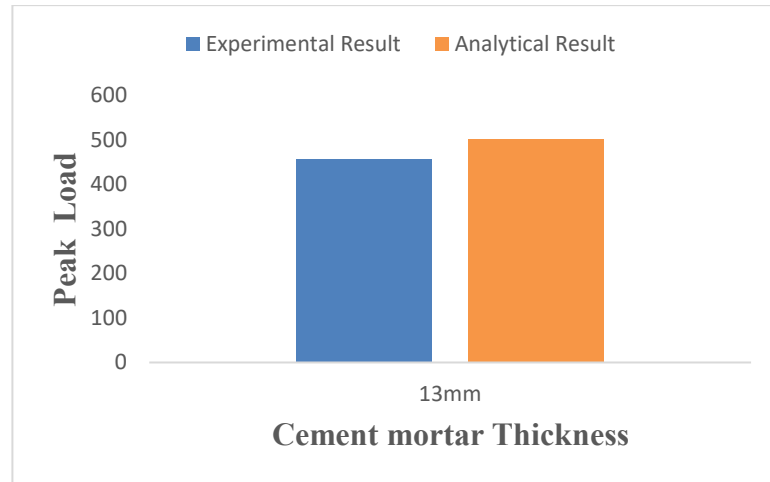


Figure 3.14 Experimental Vs. Analytical Results of Brick masonry Prism

Table 3.3 Validation of Model with Analytical and Experimental Results

Mortar Thickness	Analytical Results (kN)	Experimental Results (kN)	Variation %
13mm	501.93	457	8.95

The comparison in between analytical results and experimental results Peak load of brick masonry prism with 13mm cement mortar thickness is shown in Table 3.3. As observed from the analysis, there was a very good correlation between the analytical and experimental results when it comes to the masonry prism with 13 mm mortar thickness. In this case, the load-carrying capacity based on the analysis was 501.93 kN while the value obtained experimentally was 457 kN. This made the difference between the two values 8.95%, which falls within the accepted range of variations for finite element validation techniques.

3.8.1 COMPRESSIVE STRENGTH OF BRICK MASONRY PRISM

The compressive strength of the masonry prism is a critical value considered while determining the efficiency of masonry construction. The compressive strength of masonry prisms constructed cement mortar is tabulated below in Table 3.4 Since the **height to thickness ratio** of the specimens had been considered while determining the values, the calculated values were multiplied by a **corrective factor**. This correction factor was derived from Table 12 of IS 1905 : 1987 [26], which provides correction factors for certain heights; whereas other heights may require interpolation to calculate their respective correction factors. For instance, in the case of a cement mortar prism specimen, whose height was 450 mm , the correction factor would be 0.730[26].

$$\text{Compressive strength of brick masonry prism} = \frac{P}{A}$$

According to IS 1905 : 1987, Compressive strength = Correction factor X Experimental compressive strength

Table 3.4 Compressive strength of brick masonry prism

Mortar thickness	Analytical results (MPa)	Experimental results (MPa)	Correction Factor	Strength based on experimental results after correction (MPa)	Strength based on analytical results after correction (MPa)	Variation %
13mm	10.37	9.44	0.730	6.89	7.75	9.85

Comparison of Analytical, Experimental, and Corrected Compressive Strength of Masonry Prism with Mortar Thickness 13 mm on the basis of IS 1905 : 1987 has been provided in

Table 3.4. As per the provisions, compressive strength of masonry prism has been calculated using the correction factor for the experimental compressive strength as well as analytical compressive strength. From the above comparison, it can be seen that the variation in between analytical compressive strength of brick masonry prism and experimental compressive strength of brick masonry prism is 9.85% which falls within the accepted range of variations for finite element validation techniques.

3.9 CONCLUDING REMARKS

The geometric configurations, physical characteristics, interaction characteristics, boundary conditions, meshing technique, and loading conditions utilized in the analyses have been extensively discussed. The finite element model generated was validated against the experimental results already reported in literature, and there was satisfactory agreement between both analytical and experimental responses. The successful validation indicated that the developed finite element model was accurate and reliable, thus appropriate for evaluating the compressive behavior and failure mechanisms of brick masonry prisms with varying mortar thicknesses.

CHAPTER 4

RESULT AND DISCUSSION

4.1 GENERAL

This chapter is devoted to the description of results and discussions on finite element analysis performed for prismatic masonry walls with cement mortar and lime mortar under axial compression tests. Response evaluation of brick masonry prism considering stress-strain relationship, deformations, carrying capacity, and failure modes has been done. Responses of masonry prisms using mortars of varied layer thickness have been compared with mortar layer thickness and type of mortar on masonry compressive behavior.

4.2 RESULTS

4.2.1 ANALYTICAL RESULTS

The load vs. deflection graph that depicts the compression characteristics of the masonry prism with 13 mm thick cement mortar shown in **Figure 21**. At first, the load versus deflection curve displays a linear trend for the vertical loads versus displacement, which indicates the elastic nature of the masonry prism because there is efficient stress transmission through the brick-mortar joints without any cracking.

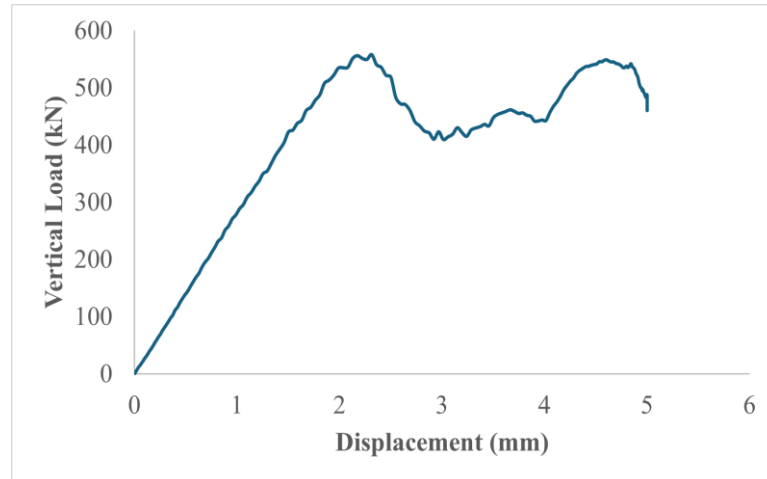


Figure 4.1 Load Vs. Displacement Curve of Brick Masonry Prism with 13mm Cement Mortar thickness

The load-displacement curve for the brick masonry prism with a thickness of 13 mm cement mortar is depicted in Figure 4.1. At first, the load was almost directly proportional to the

displacement, showing that the when applying load on top of prism stresses develop linearly and when the value of load is reach equal to compressive strength of prism that load called as peak load and after that while increasing the load the brittle failure has been occur in the prism . The maximum load attained by the prism was 501.93 kN with a displacement of 2.31 mm.

Once the peak load was attained, a significant drop in load carrying ability was noticed due to cracking and crushing in the masonry elements. When more loads were applied, the nature of the graph started showing fluctuations, implying cracking, stress transfer, and failure at brick-mortar interphases. []

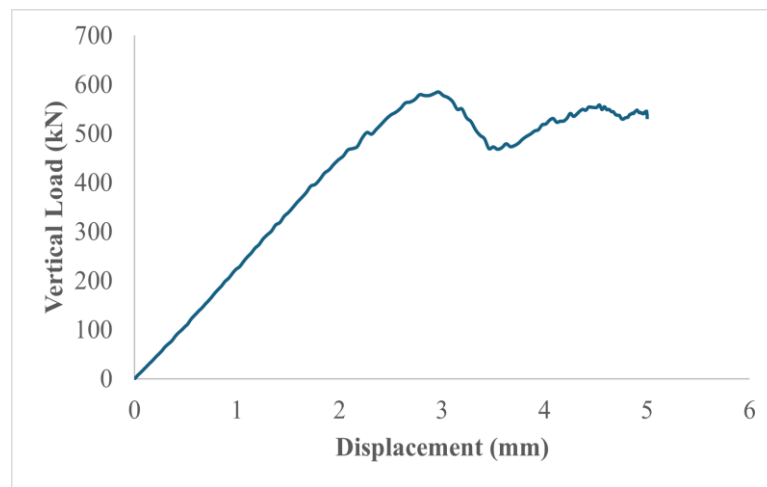


Figure 4.2 Load Vs. Displacement Curve of Brick Masonry Prism with 20mm Cement Mortar thickness

The load-displacement diagram for the brick masonry prism having mortar thickness of 20 mm is shown in Figure 4.2. It can be seen from the graph that initially there is a linear increase in the load with respect to displacement, depicting the elastic nature of the material as well as its stiffness. At a displacement of 2.96 mm, the maximum load attained by the brick masonry prism is 497.401 kN.

After achieving maximum load-bearing strength, there was an observed gradual decrease in the capacity to carry load because of creation of crashes in units. Compared to the 13 mm thick mortar prism, the performance of this prism after the peak load was more gradual, suggesting that there was more uniform stress transfer and more efficient brick-mortar interaction.

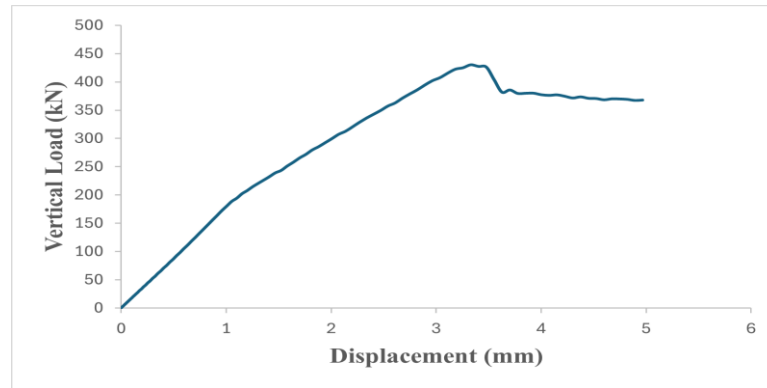


Figure 4.3 Load Vs. Displacement Curve of Brick Masonry Prism with 27mm Cement Mortar thickness

The load-displacement graph for the brick masonry prism having 27 mm thickness of cement mortar is given in Figure 4.3. At first, the load is seen to increase linearly with displacement, which shows that the masonry prism indicate elastic nature. The maximum load obtained from this test is 430.34 kN for a displacement at 3.3 mm, and this value is less than the maximum load obtained for the prism having 20 mm mortar thickness.

Once the peak load was attained, there was an abrupt drop in the ability to carry the load because of the formation of cracks in brick & mortar contact surface. The load was then reduced gradually until failure took place, showing that the post-peak behavior was relatively stable.

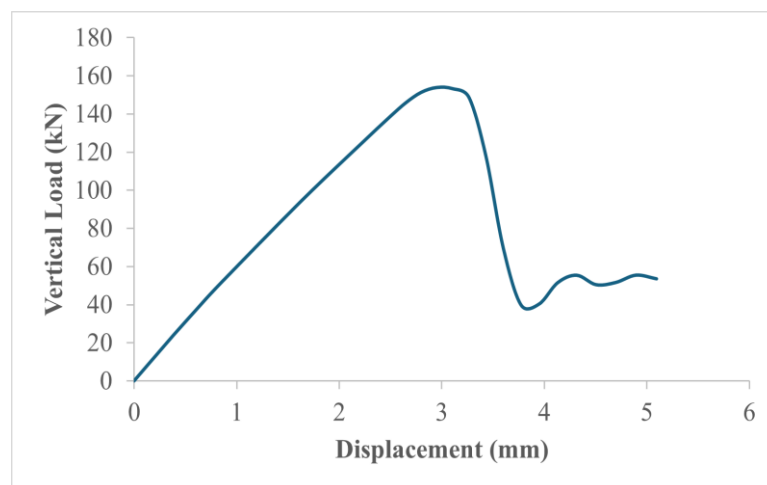


Figure 4.4 Load Vs. Displacement Curve of Brick Masonry Prism with 20mm Lime Mortar thickness

The graph presented in Figure 4.4 Indicates load displacement curve for the brick masonry prism with 20 mm thickness of lime mortar. The load displacement relationship was linear

at the beginning of the test, signifying the elastic nature of the brick masonry prism. It experienced maximum loading of 153.94 kN at displacement of 3.0 mm.

After peak load capacity was achieved, there was a drastic decline in load carrying capability showing that there was brittle fracture and fast growth of cracks through the mortar joints and brick-mortar interface. After the peak load capacity, there were fluctuations showing a low load capacity indicating progressive damage at the interfaces.

4.3 COMPARISON OF ANALYTICAL AND EXPERIMENTAL RESULTS

Comparison with existing experimental data was done in order to test the reliability of the numerical models established through FE analysis performed. Comparison of two types of data was done based on parameters like peak load value, compressive strength, load-displacement curve, and failure mechanism in case of brick masonry prisms of different mortar thickness. There was an acceptable difference between the values calculated using the numerical model and those that have been observed experimentally. Experimental data was taken from research by Yadav & Pal [12].

4.3.1 COMPARISON BASED ON PEAK LOAD

The numerical model evaluating the analytical peak load obtained from finite element analysis to the experimental peak load for prisms made of masonry with various mortar thicknesses. This comparison between the experimental and analytical peak loads is shown in Figure 4.6. This comparison was done based on prisms made of masonry with cement mortar thicknesses under axial compression loading.

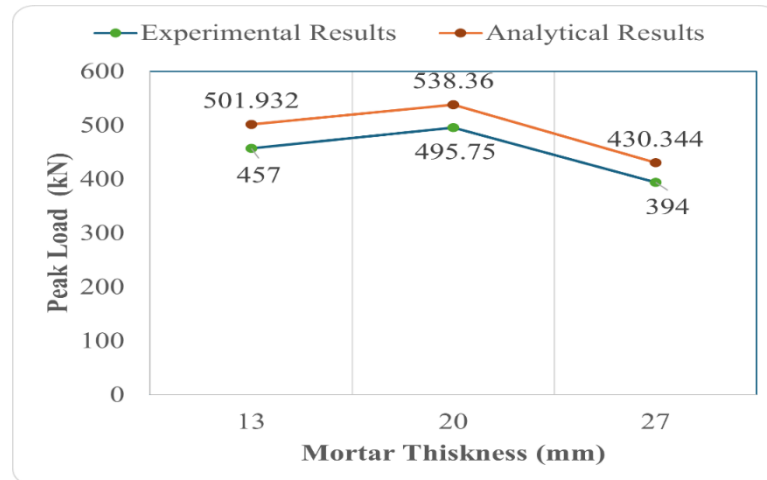


Figure 4.5 Experimental Vs. Analytical results of Prisms with different thickness of mortar

The experimental and analytical peak loads of brick masonry prism subjected to axial compression for mortar thickness are compared in Figure 4.5. Figure 4.5 show that the both experimental and analytical loads have followed the same trend.

The peak load was maximum in the prism having mortar thickness of 20 mm, in both experimental and analytical studies; thus, the results show that the use of 20 mm thickness in mortar yields optimal stress transfer and greater compressive strength. The analytical peak loads of prisms having varying thickness were measured to be 501.93 kN, 538.36 kN, and 430.34 kN, respectively, while their experimental peak loads were 457 kN, 495.75 kN, and 394 kN, respectively.

Table 4.1 Comparison between experimental and analytical results

Mortar Thickness	Experimental results (kN)	Analytical Results (kN)	Variation %
13mm	457	501.93	9.83
20mm	495.75	538.36	8.59
27mm	394	430.34	9.22

The experimental and analytical peak loads for brick masonry prisms with different mortar layers subjected to axial compression loading are provided in Table 4.1. It is observed that the analytical solution is greater than experimental solutions because of in analytical solution we applied ideal conditions but in experiment many factors affecting the solution.

In comparison to all specimens, the masonry prism with a mortar layer of thickness 20 mm had the highest peak load, which showed that there is optimum transfer of stress as well as better bond strength between bricks and mortar layers. The percentage difference between the experimental values and theoretical values has been obtained as 9.83%, 8.59%, and 9.22% for different mortar thickness.

4.3.2 COMPARISON BASED ON COMPRESSIVE STRENGTH

Comparison between the experimental compressive strengths and analytical compressive strengths for brick masonry prism with mortar thickness is shown in Figure 4.6. It can be seen from the graph that the trends followed by both approaches.

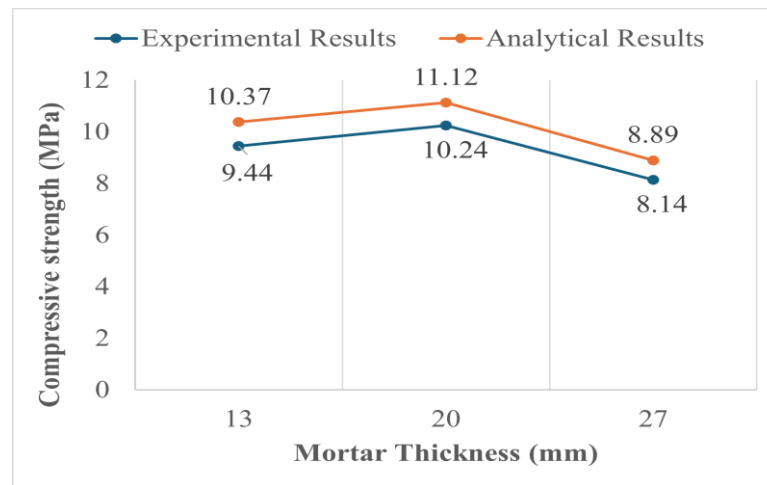


Figure 4.6 Experimental Vs. Analytical results of Prisms with different thickness of mortar in terms of compressive strength

Compressive strength was maximum for the masonry prism with 20 mm thickness of mortar, implying optimal stress distribution and better interface bonding between the brick and mortar. Compressive strengths calculated analytically for varying thicknesses of mortar was found to be 10.37 MPa, 11.12 MPa, and 8.89 MPa, respectively. These values for the same thickness were experimentally determined to be 9.44 MPa, 10.24 MPa, and 8.14 MPa, respectively.

Table 4.2 Comparison between experimental and analytical results

Mortar Thickness	Experimental results (Mpa)	Analytical Results (Mpa)	Variation %
13mm	9.44	10.37	9.83
20mm	10.24	11.12	8.59
27mm	8.14	8.89	9.22

The comparison of experimental and analytical compressive strengths for brick masonry prisms with varying mortar thicknesses tested under axial compression loading is shown in Table 4.2. It can be noted that the analytical compressive strengths of the brick masonry prisms were higher compared to the experimental results.

The maximum amount of compressive strength achieved for prism of masonry having 20 mm thickness of mortar through experimentation as well as by analysis. Percentage differences between the experimental and analytical values were calculated for varying thicknesses of mortar and found to be 9.83%, 8.59%, and 9.22%, respectively.

Compressive strength of brick masonry prism = $\frac{P}{A}$

As per IS 1905 : 1987, compressive strength = Correction Factor X Experimental compressive strength

Correction factor calculated on the basis of height to thickness ratio of brick masonry prism and Compressive strength of brick masonry prism with different thickness of cement mortar are shown in Table 4.3 with respect to Analytical, Experimental and compressive strength with correction factor as per IS 1905 : 1987 [26].

Table 4.3 Analytical and Experimental compressive strength of brick masonry prism using correction factor as per IS 1905: 1987

Mortar thickness	Analytical Compressive strength (MPa)	Experimental Compressive strength (MPa)	Correction Factor	Compressive strength after correction (MPa)
13mm	10.37	9.44	0.73	6.89
20mm	11.12	10.24	0.76	7.83
27mm	8.89	8.14	0.79	6.44

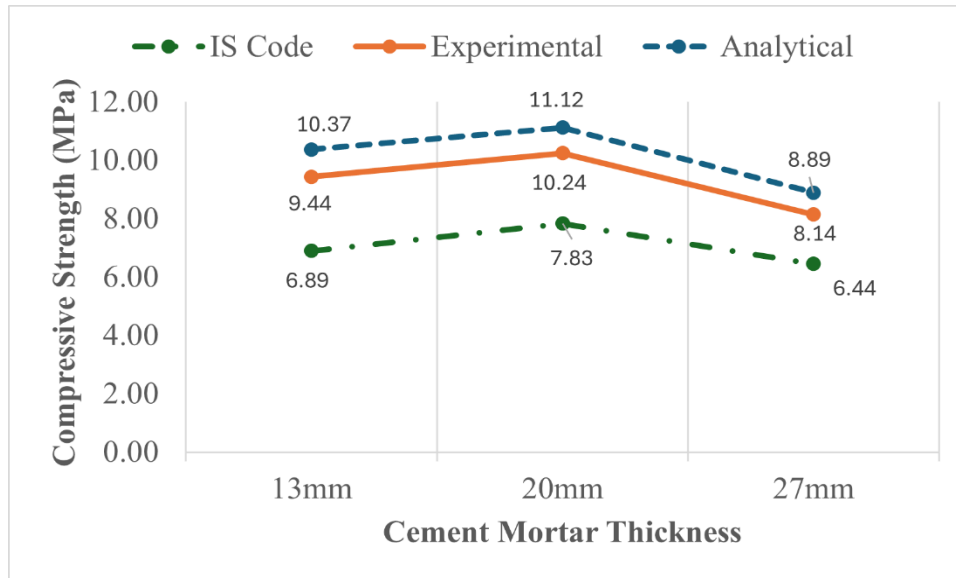


Figure 4.7 Analytical, Experimental compressive strength of brick masonry prism with different thickness of cement mortar

The comparison of analytical & experimental strength of brick masonry prisms for mortar beds of 13 mm, 20 mm, and 27 mm. The compression strength obtained by applying the correction factor from the IS 1905:1987 as shown in Table 4.3.

It is got that strength values derived from Finite element analysis were higher than the experimentally determined and the value after applying correction factor values for all the mortar thicknesses considered. The compressive strength values of 13mm, 20mm, and 27mm mortar thicknesses were calculated to be 10.37 MPa, 11.12 MPa, and 8.89 MPa, respectively. These values were lower than the experimental values, which were 9.44 MPa, 10.24 MPa, and 8.14 MPa, respectively. The corrected compressive strength after applying correction factor as per IS 1905:1987 values were 6.89 MPa, 7.83 MPa, and 6.44 MPa.

Out of all the prisms made from masonry, the prism that had 20 mm thickness of mortar showed the maximum value for compressive strength both analytically and experimentally. It can be inferred that the value of mortar having 20 mm thickness resulted in efficient stress transfer from one brick layer to another. However, for the cases of mortar having 13 mm and 27 mm thicknesses, the compressive strength was low due to stress concentration and deformation.

The trends derived from analytical results, experimental results, and results after applying correction factor were observed to be alike, thus showing a good match between all the results. Even though the analytical results showed slightly higher values due to ideal

numerical assumptions and simulation, yet the difference was tolerable. Hence, it could be said that the finite element model developed by us could be used reliably for compressive behavior prediction of brick masonry prisms.

4.4 CONTOURS OF PRISMS WITH DIFFERENT THICKNESS OF CEMENT MORTAR

The distribution of the maximum principal tensile stress in brick masonry prisms for varying mortar layers under axial compressive loads is illustrated in Figure 4.10. From the study, it was found that the tensile stresses occurred at the contact surface of the brick and mortar.

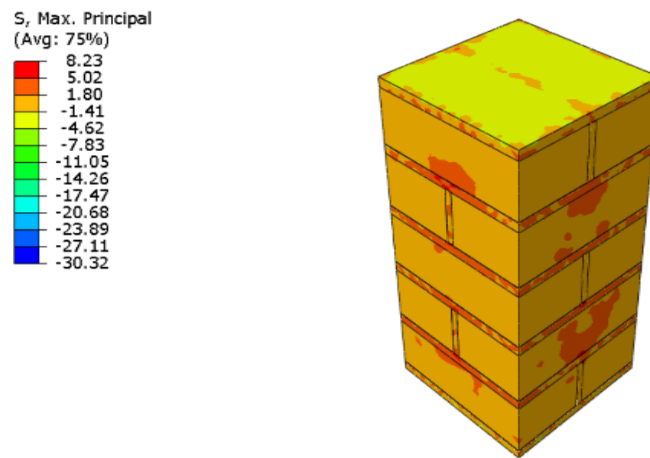


Figure 4.8 Tensile stress distribution in brick masonry prim with 13 mm CM mortar

The tensile stress distribution of the prism with 13 mm mortar thickness as shown in Figure 4.8 that stress was mainly concentrated at the brick–mortar joints. As the applied load increased, these regions experienced higher tensile stresses, leading to the initiation of cracks at the interface. The relatively thin mortar layer provided limited stress redistribution, causing localized damage at the mortar joints. Consequently, failure started with interface cracking and gradually propagated through the surrounding mortar regions.

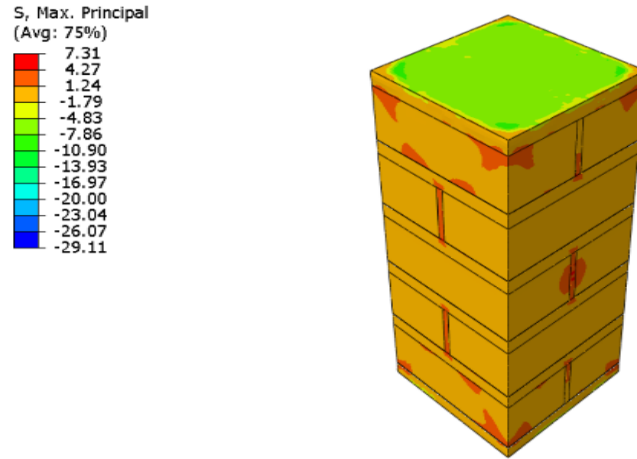


Figure 4.9 Tensile stress distribution in brick masonry prim with 20 mm CM mortar

The prism with 20 mm mortar thickness exhibited a more uniform tensile stress distribution as shown in Figure 4.9 as compared to the other prisms. The stresses were effectively transferred between bricks & mortar layers, resulting in lower stress concentration at the interfaces. Crack initiation was observed at the brick–mortar joints after reaching the maximum tensile stress; however, the propagation of cracks was delayed due to improved bonding and stress transfer. As a result, this prism showed the highest load-carrying capacity and compressive strength.

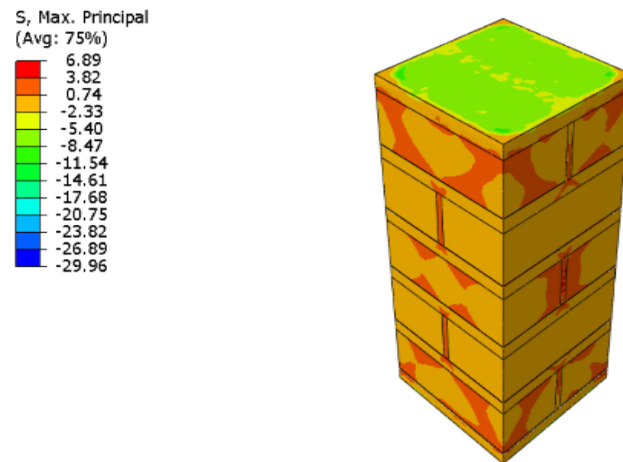


Figure 4.10 Tensile stress distribution in brick masonry prim with 27 mm CM mortar

For the prism with 27 mm mortar thickness, higher tensile stress concentrations were observed at the mortar joints and interface regions as shown in Figure 4.10. The thicker mortar layer underwent larger deformation under loading, resulting in increased stress localization. Since the mortar strength was lower than that of the brick units, cracks initiated

within the mortar joints and along the brick–mortar interfaces. The progressive cracking of the mortar layer reduced the effectiveness of load transfer, leading to premature failure and lower compressive strength

The tensile stress profile of brick masonry prisms having different mortar thicknesses under axial compressive loading. It was found that tensile stress developed mainly in the brick–mortar interface and mortar joint regions. Tensile stress once attains the maximum permissible value, it leads to cracking in the masonry prism. The profile of tensile stress shows that the formation of the first cracks takes place at the mortar joint and brick mortar interface areas due to higher stress concentration and poor bonding. The 20 mm mortar thickness prism is more homogeneous and less stressed compared with other prism samples.

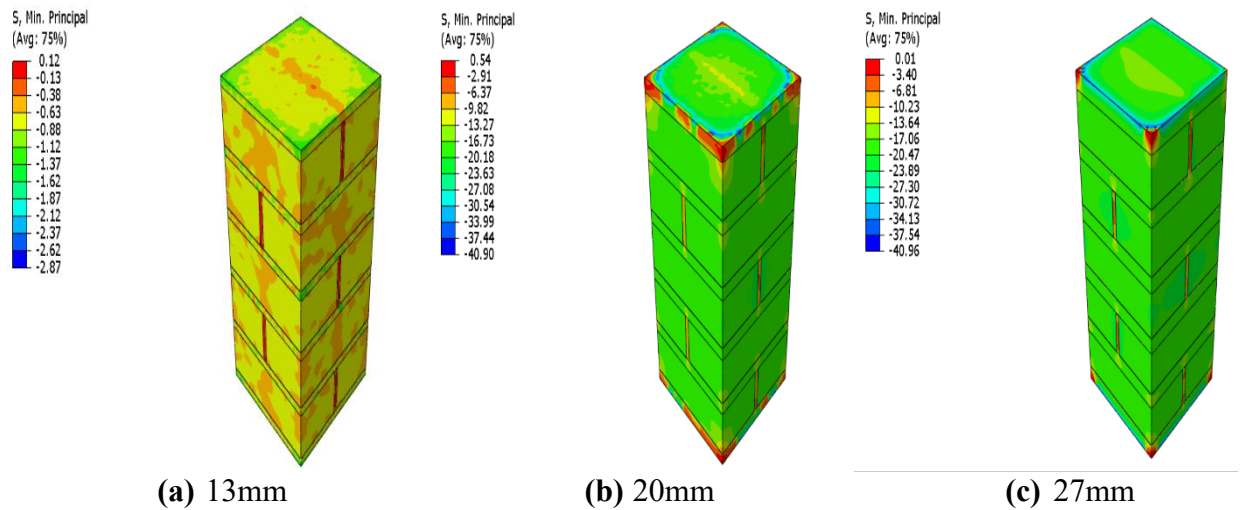


Figure 4.11 Compressive Stress distribution in Prisms

The compressive stress distribution for various mortar thickness of brick masonry prisms subjected to axial compressive loading as shown in Figure 4.11. It can be seen that the compressive stress was mostly concentrated in the mortar joints, loading zones, and brick mortar interface zones. As the compressive stress approached its ultimate level, failure initiated in the form of crushing in the masonry prism. The stress plots reveal that the stress concentration was more in the mortar joints and interface zones because of the uneven stress transmission through the masonry prism. From among all the prisms, the stress distribution was relatively more uniform for the 20-millimeter mortar thickness prism.

The output data derived from the FEA study revealed that mortar thickness act significant part in influencing compressive properties of brick masonry prisms. In comparison with other mortar thickness values studied, the brick masonry prism having a thickness value of 20 mm for cement mortar showed high peak load capacity and compressive strength along with relatively uniform stress distribution. The Finite element model created using Drucker-Prager Plasticity and Surface-Based Cohesive Behavior provided accurate results for analyzing the non-linear properties and stress distribution in cement mortar masonry prisms.

The developed numerical analysis model for cement mortar masonry prisms was first validated after which a similar model was used to study the brick masonry prisms made with lime mortar.

Table 4.4 brick masonry prism with different type of mortar

Lime mortar thickness	Experimental Strength (MPa)	Analytical Strength (MPa)	Variation (%)
13mm	2.39	2.59	7.72
20mm	2.65	2.92	9.12
27mm	2.03	2.225	8.76

Table 4.4 presents the comparison between the analytical and experimental compressive strengths of brick masonry prisms constructed with LM and different mortar thicknesses. The analytical results obtained from the developed Finite element model showed good agreement with the experimental results for all mortar thicknesses, with variations ranging from 7.72% to 9.12%.

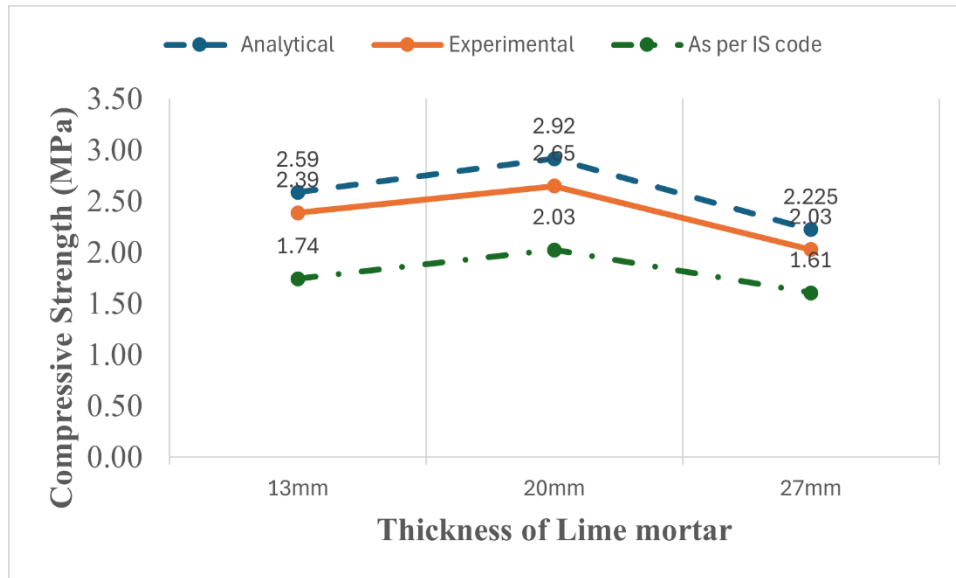


Figure 4.12 Compressive Strength Variation of Masonry Prisms with Different Lime Mortar Thicknesses

The graph in Figure 4.12 shows the compressive strength of brick masonry prisms in terms of analytical value, experimental value, and value after correction with different lime mortar thicknesses. As seen in the graph, it can be concluded that the same pattern is seen in the analytical, experimental, and as per IS 1905 : 1987 the compressive strength of the prisms, and the compressive strength rises up to 20 mm mortar thickness and decreases after that for 27 mm mortar thickness. Among all the lime mortar prisms, 20 millimeter mortar thickness prism exhibited highest compressive strength, with analytical and experimental values of 2.92 MPa and 2.65 MPa, respectively. The prism with 13 mm mortar thickness showed analytical and experimental compressive strengths of 2.59 MPa and 2.39 MPa, whereas the 27 mm mortar thickness prism exhibited the lowest strengths of 2.225 MPa and 2.03 MPa, respectively.

The results indicate that, similar to cement mortar masonry prisms, the optimum compressive performance for lime mortar masonry prisms was achieved at 20 mm mortar thickness. The close agreement between analytical and experimental results confirms the accuracy and reliability of the developed finite element model. Furthermore, the successful validation of the model for lime mortar masonry demonstrates its applicability for analyzing traditional, historical, and heritage masonry structures where lime mortar is commonly used.

4.5 CONCLUDING REMARKS

The results obtained from the finite element analysis revealed that the thickness of mortar is affected the compressive strength, stress distribution, and failure modes of brick masonry prisms. Out of all the prisms, the prism having 20 mm thickness of cement mortar showed maximum compressive strength with improved stress distribution. The developed Finite element model is start to be correct when equated to investigational results. Furthermore, FE model is proficient of catching cracking at interface between bricks and mortar. This model is also suitable for the analysis of lime mortar masonry prisms.

CHAPTER 5

CONCLUSIONS AND FUTURE SCOPE

5.1 GENERAL

The present study deals with the numerical analysis of brick masonry prisms. This chapter discusses the general conclusions derived from the numerical and experimental investigations conducted for brick masonry prisms under axial compressive loads. The experiment was conducted through finite element modeling to analyze the effect of mortar thickness and mortar type on the performance of masonry prisms. Various combinations of mortar thickness of masonry prisms with cement mortar have been studied. The outcomes derived after FE analysis have shown through experimental outcomes.

5.2 CONCLUSIONS

- Micro-model of brick prism was successfully developed with the help of the DP model and contact surface Behavior. It is effectively captured the nonlinear behavior, stress distribution, & modes of failure of masonry prisms.
- The developed finite element model showed good agreement with experimental results, with variations remaining below 10%, demonstrating the accuracy and reliability of the numerical approach.
- The analytical peak loads obtained for masonry prisms with varying cement mortar thicknesses were 501.93 kN, 538.36 kN, and 430.34 kN, respectively.
- The masonry prism with 20 mm cement mortar thickness exhibited the highest peak load of 538.36 kN, which was approximately 7.3% higher than the 13 mm mortar thickness prism and 25.1% higher than 27-millimeter mortar depth prism.
- Analytical strengths obtained for cement mortar masonry prisms with varying mortar thickness were 10.37 MPa, 11.12 MPa, and 8.89 MPa, respectively.
- Maximum compressive strength of 11.12 MPa attained for the prism with 20 mm cement mortar thickness, indicating optimum bond strength and efficient stress transfer between brick and mortar.

- The percentage variation between analytical and experimental compressive strengths for cement mortar prisms was found to be 9.83%, 8.59%, and 9.22% for varying mortar thicknesses, respectively.
- The analytical compressive strengths obtained for lime mortar masonry prisms with 13-millimeter, 20-millimeter, and 27-millimeter mortar thicknesses were 2.59 MPa, 2.92 MPa, and 2.23 MPa, respectively.
- The corresponding experimental compressive strengths for lime mortar masonry prisms were 2.39 Megapascal, 2.65 Megapascal, and 2.03 Megapascal for different mortar thicknesses, respectively.
- Similar to cement mortar masonry prisms with 20 millimeters LM thickness of prism exhibited the highest compressive strength of 2.92 MPa, indicating that 20 mm mortar thickness provides optimum performance irrespective of mortar type.
- The percentage variation between analytical and experimental results for lime mortar masonry prisms was found to be 7.72%, 9.12%, and 8.76% for different mortar thicknesses, respectively.
- The developed finite element model was successfully validated for both cement mortar and lime mortar masonry prisms, confirming its applicability for analyzing conventional masonry structures as well as historical and heritage masonry structures constructed using lime mortar.

5.3 CONTRIBUTION TO SUSTAINABLE DEVELOPMENT GOALS (SDGS)

The present study contributes to the achievement of the United Nations Sustainable Development Goals (SDGs) by promoting sustainable construction practices through advanced numerical modeling of masonry structures.

SDG 9: Industry, Innovation and Infrastructure

The study utilizes finite element analysis to develop a reliable numerical model for predicting the behavior of brick masonry structures. The validated model can assist engineers in designing safer, stronger, and more durable masonry infrastructure while reducing the dependence on extensive experimental testing.

SDG 11: Sustainable Cities and Communities

Masonry structures constitute a major portion of residential buildings and heritage structures in India. Established numerical model is used to assess the structural performance of both

modern cement mortar masonry and historical lime mortar masonry, thereby supporting the conservation and preservation of heritage structures and promoting sustainable urban development.

SDG 12: Responsible Consumption and Production

The use of finite element analysis reduces the need for large-scale experimental testing, thereby minimizing material consumption, laboratory resources, energy usage, and construction waste. This contributes to more efficient utilization of resources and sustainable engineering practices.

SDG 13: Climate Action

By optimizing masonry design and reducing the requirement for repeated experimental investigations, the study indirectly contributes to lowering material wastage and carbon emissions associated with construction activities. The promotion of durable and efficient masonry systems supports environmentally responsible construction practices.

5.4 FUTURE SCOPE

This study was concerned with the numerical analysis of brick masonry prisms having various mortared joint thicknesses using micro-modeling. Even though the finite element model that had been proposed for this purpose yielded satisfactory results as compared to the experiments reported in literature, there are still many aspects regarding the behavior of masonry structures that require further study.

- In this current investigation, only axial compression loading was considered. Further investigation may be carried out in future studies on brick masonry prisms subjected to cyclic loading, seismic loading, shear loading, and combined loading.
- The developed finite element model can further be used for the analysis of full-scale masonry walls, historical buildings, and reinforced masonry systems with various types of bricks, mortars, and bonding methods.
- The use of complex constitutive models such as CDP, XFEM, and damage mechanics may be considered to increase the accuracy in predicting cracking and failure mechanisms in masonry structures.

BIBLIOGRAPHY

- [1] K. Chaimae, E. R. Younes, M. Ouadia, and R. Shamass, "Finite element simulation of masonry wall behavior: Exploring various brick bonds and load conditions," *Structures*, vol. 77, Jul. 2025, doi: 10.1016/j.istruc.2025.109089.
- [2] S. Kömürcü, "A comprehensive numerical study on examining the failure mechanisms of masonry walls via continuous micro modeling," *Eng. Fail. Anal.*, vol. 177, Aug. 2025, doi: 10.1016/j.engfailanal.2025.109680.
- [3] D. D. Ahiwale, D. P. N. Kontoni, and A. V. Jadhav, "FEM investigation of the effect of structural bonding patterns on masonry walls strengthened by FRP," *Engineering Research Express*, vol. 7, no. 1, Mar. 2025, doi: 10.1088/2631-8695/adb3f3.
- [4] G. Elsamak, M. Ghalla, M. H. El-Naqeeb, E. A. Mlybari, R. W. Bazuhair, and M. Emara, "Experimental and numerical assessment of optimized hybrid strengthening techniques for unreinforced masonry columns under axial compression," *Structures*, vol. 81, Nov. 2025, doi: 10.1016/j.istruc.2025.110222.
- [5] F. Kıpçak, "Numerical Study of the Out-of-Plane Response of Dry-Stack Double-Wythe Brick Walls with Header Bricks," *Buildings*, vol. 15, no. 23, Dec. 2025, doi: 10.3390/buildings15234342.
- [6] S. O. Akcan, S. A. Kılıç, İ. E. Bal, and M. C. Yalçın, "Comparison of numerical modeling methods for simulating failure in the in-plane response of unreinforced masonry walls," *Eng. Fail. Anal.*, vol. 182, Dec. 2025, doi: 10.1016/j.engfailanal.2025.110156.
- [7] Q. Xia, T. Liu, Y. Li, Y. Xiong, and Y. Ma, "Simulation and multi-dimensional damage evolution analysis of detailed micro-model representing ancient brick masonry compressive behavior," *Constr. Build. Mater.*, vol. 457, Dec. 2024, doi: 10.1016/j.conbuildmat.2024.139410.
- [8] S. Honnalli, O. S. Vishnu, and G. S. Pavan, "Multiscale numerical modeling of clay brick masonry under compressive loading," *Innovative Infrastructure Solutions*, vol. 9, no. 6, Jun. 2024, doi: 10.1007/s41062-024-01487-5.
- [9] X. Luo, Y. Li, Y. Yang, and H. Pirsaeheb, "A simplified micro-model based on discrete elements and elastic bodies for non-linear static analysis of in-plane loaded masonry panels," *Structures*, vol. 58, Dec. 2023, doi: 10.1016/j.istruc.2023.105383.
- [10] D. Chen, H. Wu, and Q. Fang, "Simplified micro-model for brick masonry walls under out-of-plane quasi-static and blast loadings," *Int. J. Impact Eng.*, vol. 174, Apr. 2023, doi: 10.1016/j.ijimpeng.2023.104529.

- [11] S. Shristi and N. Umamaheswari, “Numerical investigation on strengthening of brick masonry wall using mortar joint technique,” *Mater. Today Proc.*, Sep. 2023, doi: 10.1016/j.matpr.2023.09.192.
- [12] A. Yadav and S. Pal, “The impact of mortar thickness and strength on the brick masonry prism: An investigation,” in *Materials Today: Proceedings*, Elsevier Ltd, 2023, pp. 552–559. doi: 10.1016/j.matpr.2023.10.035.
- [13] B. Zeng, Y. Li, and C. Cruz Noguez, “Modeling and parameter importance investigation for simulating in-plane and out-of-plane behaviors of un-reinforced masonry walls,” *Eng. Struct.*, vol. 248, Dec. 2021, doi: 10.1016/j.engstruct.2021.113233.
- [14] S. Sharma, L. C. Silva, F. Graziotti, G. Magenes, and G. Milani, “Modelling the experimental seismic out-of-plane two-way bending response of unreinforced periodic masonry panels using a non-linear discrete homogenized strategy,” *Eng. Struct.*, vol. 242, Sep. 2021, doi: 10.1016/j.engstruct.2021.112524.
- [15] R. L. G. Oliveira, J. P. C. Rodrigues, J. M. Pereira, P. B. Lourenço, and H. Ulrich Marschall, “Normal and tangential behaviour of dry joints in refractory masonry,” *Eng. Struct.*, vol. 243, Sep. 2021, doi: 10.1016/j.engstruct.2021.112600.
- [16] A. Meoni, A. D’Alessandro, R. Kruse, L. De Lorenzis, and F. Ubertini, “Strain field reconstruction and damage identification in masonry walls under in-plane loading using dense sensor networks of smart bricks: Experiments and simulations,” *Eng. Struct.*, vol. 239, Jul. 2021, doi: 10.1016/j.engstruct.2021.112199.
- [17] A. M. D’Altri, F. Messali, J. Rots, G. Castellazzi, and S. de Miranda, “A damaging block-based model for the analysis of the cyclic behaviour of full-scale masonry structures,” *Eng. Fract. Mech.*, vol. 209, pp. 423–448, Mar. 2019, doi: 10.1016/j.engfracmech.2018.11.046.
- [18] A. Rahgozar and A. Hosseini, “Experimental and numerical assessment of in-plane monotonic response of ancient mortar brick masonry,” *Constr. Build. Mater.*, vol. 155, pp. 892–909, Nov. 2017, doi: 10.1016/j.conbuildmat.2017.08.079.
- [19] K. F. Abdulla, L. S. Cunningham, and M. Gillie, “Simulating masonry wall behaviour using a simplified micro-model approach,” *Eng. Struct.*, vol. 151, pp. 349–365, Nov. 2017, doi: 10.1016/j.engstruct.2017.08.021.
- [20] S. Noor-E-Khuda, M. Dhanasekar, and D. P. Thambiratnam, “An explicit finite element modelling method for masonry walls under out-of-plane loading,” *Eng. Struct.*, vol. 113, pp. 103–120, Apr. 2016, doi: 10.1016/j.engstruct.2016.01.026.

- [21] M. Bolhassani, A. A. Hamid, A. C. W. Lau, and F. Moon, "Simplified micro modeling of partially grouted masonry assemblages," *Constr. Build. Mater.*, vol. 83, pp. 159–173, May 2015, doi: 10.1016/j.conbuildmat.2015.03.021.
- [22] A. J. Aref and K. M. Dolatshahi, "A three-dimensional cyclic meso-scale numerical procedure for simulation of unreinforced masonry structures," *Comput. Struct.*, vol. 120, pp. 9–23, 2013, doi: 10.1016/j.compstruc.2013.01.012.
- [23] H. B. Kaushik, D. C. Rai, and S. K. Jain, "Uniaxial compressive stress-strain model for clay brick masonry," 2007.
- [24] A. Yadav, "INVESTIGATION OF JOINT THICKNESS & MORTAR STRENGTH ON THE MECHANICAL BEHAVIOUR OF BRICK MASONRY MASTER OF TECHNOLOGY IN STRUCTURAL ENGINEERING," 2023.
- [25] B. of Indian Standards, "IS 1077 (1992): Common Burnt Clay Building Bricks - Specification."
- [26] B. of Indian Standards, "IS 1905 (1987): Code of Practice for Structural use of Unreinforced Masonry."

CONFERENCES

[1] Kulshreshtha, M. K., Saggu, K., Pal, S., (2026), “Effect of Mortar type and joint thickness on the Compressive Strength of brick masonry prisms: A finite element approach”- 1st International Conference on Urban Built Environment (ICUBE-2026) held on March 27th – 28th, 2026 at NICMAR Delhi-NCR Campus.



PLAGIARISM REPORT

ORIGINALITY REPORT

6%

SIMILARITY INDEX

3%

INTERNET SOURCES

6%

PUBLICATIONS

1%

STUDENT PAPERS

PRIMARY SOURCES

1

doi.org

Internet Source

<1%

2

"Proceedings of SECON 2020", Springer Science and Business Media LLC, 2021

Publication

<1%

3

Submitted to Aligarh Muslim University, Aligarh

Student Paper

<1%

4

P. Murthi, M. Bhavani, Md.Saqlain Musthaq, Md.Osman Jauhar, V. Rama Devi. "Development of relationship between compressive strength of brick masonry and brick strength", Materials Today: Proceedings, 2020

Publication

<1%

5

"Structural Analysis of Historical Constructions", Springer Science and Business Media LLC, 2019

Publication

<1%

6

S.B. Singh, Pankaj Munjal. "Bond strength and compressive stress-strain characteristics of brick masonry", Journal of Building Engineering, 2017

Publication

<1%

7

Kamran Javed, Muhammad Irfan-ul- Hassan, Muhammad Aboubakar Farooq, Muhammad Burhan Sharif. "Detailed investigation of

<1%