EXPERIMENTAL VALIDATION AND RETROFITTING OF FLY ASH BRICK MASONRY USING EXTENDED FINITE ELEMENT METHOD (XFEM) IN ABAQUS

By

Muhammad Haseeb Amjad

(Registration No. 00000329942)

Department of Structural Engineering

NUST Institute of Civil Engineering (NICE)

School of Civil and Environmental Engineering (SCEE)

National University of Sciences and Technology (NUST)

Islamabad, Pakistan

(2024)

EXPERIMENTAL VALIDATION AND RETROFITTING OF FLY ASH BRICK MASONRY USING EXTENDED FINITE ELEMENT METHOD (XFEM) IN ABAQUS

By

Muhammad Haseeb Amjad

(Registration No. 00000329942)

A thesis submitted to the National University of Sciences and Technology, Islamabad, in partial fulfillment of the requirements for the degree of

Master of Science in Structural Engineering

Supervisor: Dr. Ather Ali

Co Supervisor: Dr. Nilanjan Das Chakladar

School of Civil and Environmental Engineering (SCEE)

National University of Sciences & Technology (NUST)

Islamabad, Pakistan

(2024)

Certificate of Approval

This is to certify that the research work presented in this thesis, entitled "Experimental Validation and Retrofitting of Fly Ash Brick Masonry using Extended Finite Element Method (XFEM) in Abaqus" was conducted by Muhammad Haseeb Amjad under the supervision of Dr. Ather Ali.

No part of this thesis has been submitted anywhere else for any other degree. This thesis is submitted to National University of Sciences and Technology (NUST) in partial fulfillment of the requirements for the degree of Master of Science in Structural Engineering from Nust Institute of Civil Engineering (NICE), School of Civil and Enivronmental Engineering (SCEE), NUST.

Student Name: Muhammad Haseeb Amjad — Signature:-----------------------------

Examination Committee:

a) GEC Member 1: Dr. Azam Khan — Signature:-----------------------------
   Assistant Professor (SCEE, NUST)
b) GEC Member 2 : Dr. Hammad Anis Khan — Signature:-----------------------------
   Assistant Professor (SCEE, NUST)

Supervisor Name: Dr. Ather Ali — Signature:-----------------------------

Co-supervisor name: Dr. Nilanjan Das Chakladar — Signature:-----------------------------

Name of HOD: Dr. Muhammad Usman — Signature:-----------------------------

HoD Structural Engineering
NUST Institute of Civil Engineering
School of Civil & Environmental Engineering
National University of Sciences and Technology

Name of Associate Dean: Dr. S Muhammad Jamil — Signature:-----------------------------

Dr. S. Muhammad Jamil
Associate Dean
NICE, SCEE, NUST

Name of Principal and Dean: Dr. Muhammad Irfan — Signature:-----------------------------

PROF DR MUHAMMAD IRFAN
Principal & Dean
SCEE, NUST

THESIS ACCEPTANCE CERTIFICATE

Certified that final copy of MS Thesis written by Muhammad Haseeb Amjad Registration No. 00000329942 of MS Structural Engineering 2020 Batch (NICE) has been vetted by undersigned, found completed in all respects as per NUST Statuses/ Regulations/ MS Policy, is free of plagiarism, errors and mistakes and is accepted as partial fulfillment for award of MS degree. It is further certified that necessary amendments as point out by GEC members and evaluators of the scholar have also been incorporated in the said thesis.

Signature:--

Name of Supervisor: Dr. Ather Ali

Date:----06-05-2024------------------

Signature (HOD):------------------------------------
HoD Structural Engineering
NUST Institute of Civil Engineering
School of Civil & Environmental Engineering
National University of Sciences and Technology

Date:----13-05-2024-------------------

Signature (Associate Dean):-----------------
Dr. S. Muhammad Jamil
Associate Dean
NICE, SCEE, NUST

Date: 13/5/24------------------------------

Signature (Principal & Dean):-----------------
PROF DR MUHAMMAD IRFAN
Principal & Dean
SCEE, NUST

Date: 14 MAY 2024-----------------------------

iv

Form TH-4

National University of Sciences and Technology

MASTER'S THESIS WORK

We hereby recommend that the dissertation prepared under our Supervision by: (Student Name & Regn No. Muhammad Haseeb Amjad, 00000329942)
Titled: "Experimental Validation and Retrofitting of Fly Ash Brick Masonry using Extended Finite Element Method (XFEM) in Abaqus" be accepted in partial fulfillment of the requirements for the award of degree with (B+ Grade).

Examination Committee Members

1. Name: Dr. Azam Khan Signature:

2. Name: Dr. Hammad Anis Khan Signature: for

Supervisor's name: Dr. Ather Ali Signature:

Date: 06-05-2024

Co-Supervisor's name: Dr. Nilanjan Das Chakladar Signature: NDChakladar

Date: 06-05-2024

HoD Structural Engineering
NUST Institute of Civil Engineering
School of Civil & Environmental Engineering
National University of Sciences and Technology

Head of Department

(Associate Dean)

Dr. S. Muhammad Jamil
Associate Dean
NICE, SCEE, NUST

COUNTERSIGNED

Date: 14 MAY 2024

Principal & Dean SCEE

PROF DR MUHAMMAD IRFAN
Principal & Dean
SCEE, NUST

DECLARATION

I confirm that this research study, entitled is “Experimental Validation and Retrofitting of Fly Ash Brick Masonry using Extended Finite Element Method (XFEM) in ABAQUS’’ solely my own work. The work has not been previously submitted for evaluation elsewhere. The content sourced from external references has been duly recognized and cited.

Signature of Student

Muhammad Haseeb Amjad

00000329942

ACKNOWLEDGEMENT

All praises and thanks to Allah Almighty (The Most Merciful and The Most Beneficent), who is the entire source of all knowledge and guides mankind in darkness with His light. All respects are for the Holy Prophet Muhammad (Peace Be Upon Him), who is the ultimate guide for all of us.

I feel highly privileged to express my deep gratitude to my Supervisor Dr. Ather Ali for not only being a mentor but also for his keen interest, proper guidance, and valuable suggestions during my research and the journey of write-up. Right from the beginning, your guidance has been my strength and without your help and cooperation, I could have never been able to complete my dissertation. Thank you for being patient with me throughout the time. I will always be indebted to you for your act of kindness and humbleness.

TABL OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Pakistan is a highly seismic region, with a long history of devastating earthquakes. Many URM buildings in Pakistan are poorly constructed, with inadequate reinforcement and weak mortar. The Extended Finite Element Method (XFEM) is a powerful numerical tool that can be used to solve engineering problems, such as the behavior of fly ash bricks under different loading conditions. The accuracy of XFEM coupled with continuous micro modeling (which is computationally less expensive and accurate as well) needs to be validated through experimental testing. The aim of this study is to implement an innovative modeling strategy of using continuous micro modeling (CMM) with XFEM crack propagation approach in brick masonry. XFEM method predicted an accurate path of crack initiation and propagation through Quadratic Stress Damage Criteria and Critical Fracture Energy Values of the mortar defined in "material property."

CHAPTER 1

INTRODUCTION

1.1 Background

The research background focuses on the implementation of polypropylene (PP) bands for retrofitting fly ash brick masonry. This is achieved using a continuous micro-modeling method using the XFEM in the ABAQUS software. Fly ash brick masonry, a frequently used construction material, frequently faces challenges related to structural integrity and seismic performance. The application of polypropylene bands for retrofitting is a technique designed to improve the seismic resilience and overall stability of masonry structures. The utilization of the continuous micro-modeling approach with XFEM in ABAQUS offers a sophisticated numerical framework for accurately simulating the complex interactions between the polypropylene bands and the brick structure at a small scale. The study enhances the field of structural engineering by offering a comprehensive review of the retrofitting technique and its impact on the seismic resilience of masonry structures.

The use of fly ash bricks in buildings is increasing due to their environmental benefits and lower costs in comparison to traditional clay bricks. However, the intrinsic brittleness and vulnerability to fracturing of these materials cause concerns over their structural efficacy when subjected to seismic forces or extreme conditions.

The use of retrofitting approaches is crucial for improving the seismic resistance and overall lifespan of existing structures. Polymer-polypropylene (PP) bands are a possible approach to reinforcing masonry walls, offering increased confinement and ductility.

Conventional macro-modeling methods for masonry structures frequently underestimate the impact of individual brick-mortar interactions and micro-cracking behavior. The integration of Continuous Micro Modeling (CMM) along with XFEM within ABAQUS provides a more comprehensive and precise representation of the diverse characteristics of masonry, encompassing micro-cracks, and interactions between bricks and mortar.

The study "PP Band Retrofitted Fly Ash Brick Masonry Using Continuous Micro Modelling with XFEM in ABAQUS" covers a thorough examination of the structural behavior and methods of retrofitting fly ash brick masonry, emphasizing the reinforcing of PP (polypropylene) bands. The scope involves evaluating how well PP bands work to improve the ductility and strength of fly ash brick masonry buildings while considering a variety of loading conditions and failure modes into consideration. Furthermore, the study will investigate how various factors, including material characteristics and band spacing, affect the outcomes of retrofitting. The reason of this study's conclusions is to provide significant fresh details about how to optimize PP band retrofitting for durable and sustainable masonry construction, especially when using environmentally friendly fly ash bricks. By emphasizing these particular components, the study seeks to offer a thorough and perceptive review of PP band retrofitting for fly ash brick masonry walls at the micro-level, thereby providing important information for enhancing the seismic resilience and design of such structures.

This study, although providing useful insights into the retrofitting of PP bands for fly ash brick masonry, acknowledges its limitations. The CMM-XFEM model, in its idealized form, may not effectively simulate actual situations due to the exclusion of elements such as openings and complex boundary conditions. Moreover, concentrating exclusively on fly ash bricks restricts the applicability to other types of construction materials. Moreover, future investigations may require additional refining of material models to accurately represent complex phenomena such as deterioration and hysteresis. The study might experience difficulties in precisely depicting the diversity in material characteristics that are naturally present in fly ash brick construction, such as variances in composition and quality. Furthermore, the complex characteristics of the XFEM approach may require specific simplifications and assumptions while creating the model, which could significantly affect the accuracy and applicability of the outcomes. Moreover, it is possible that the proposed boundary conditions do not adequately represent the dynamic interactions between the retrofitting PP band and fly ash brick masonry when subjected to various loading situations. The study's reliance on laboratory-scale or numerical simulations may bring scaling effects that could restrict the direct transfer of findings to real-world applications. In addition, the research may face limitations due to an absence of validation data for the particular retrofitting technique, which could potentially impact the precision of the model. Furthermore, factors such as the environmental effects, the ability to maintain the retrofitted structure over time, and its long-lasting resilience may not be adequately taken into account. Although there are certain limitations, this research represents a substantial advancement in comprehending and improving the retrofitting of PP bands for enhanced seismic resilience in fly ash brick structures. Recognizing these constraints is crucial for evaluating the research results and directing future studies.

1.2 Research gap

Research on retrofitting PP (Polypropylene) band into fly ash brick masonry using continuous micro modeling with XFEM (Extended Finite Element Method) in ABAQUS represents a niche area within the broader domain of civil engineering and materials science. While this topic presents an intriguing intersection of materials, structural engineering, and computational modeling, there are several potential research gaps that could be addressed:

One significant gap could be the lack of extensive experimental validation of the proposed retrofitting technique. While computational modeling can provide valuable insights, empirical data is crucial to verify the effectiveness and durability of the PP band retrofitting method. Future study could focus on developing thorough experimental setups to validate numerical simulations and evaluate the retrofitting technique's real-world performance.

Another potential research gap lies in the optimization of the PP band configuration. This could include investigating the effects of varying parameters such as band width, thickness, spacing, and material properties on the structural behavior and retrofitting efficiency. Optimization studies could help identify the most effective configuration for enhancing the seismic resistance and overall performance of fly ash brick masonry structures.

Assessing the long-term durability and environmental impact of PP band retrofitting is another area that requires attention. Research could delve into evaluating the resistance of the retrofitting system to aging, environmental factors, and cyclic loading conditions over extended periods. Additionally, conducting life cycle assessments (LCAs) could provide insights into the environmental sustainability of the proposed retrofitting technique compared to conventional methods.

While the proposed research uses XFEM for micro modeling, there may be a gap in integrating multiscale modeling methodologies to capture the behavior of materials and structures at various length scales. Combining microscale models and macroscale simulations may provide a more complete knowledge of the mechanical response of the retrofitted masonry structure under varied loading circumstances.

Conducting a cost-effectiveness and feasibility analysis of the PP band retrofitting technique compared to other retrofitting methods is essential for practical implementation. Research could explore factors such as material costs, installation complexity, retrofitting time, and overall effectiveness to provide insights for decision-making by engineers and stakeholders**.**

1.3 Problem Statement

Fly ash brick masonry provides a feasible and economical substitute for conventional clay bricks in the field of construction. However, the intrinsic brittleness and vulnerability to the cracking of fly ash brick constructions give rise to concerns over their seismic resilience. Although there are retrofitting techniques available to enhance the strength of masonry walls, their effectiveness on fly ash bricks has not been well studied. Additionally, current macro-modeling approaches typically underestimate important micro-level factors such as crack propagation and interface behavior.

Thus, this research seeks to address the primary concern of insufficient knowledge and effective design principles for retrofitting fly ash brick masonry walls with PP bands. This gap restricts the extensive use of this promising approach, which could potentially jeopardize the safety and seismic resilience of existing fly ash brick constructions in earthquake-prone areas. The study incorporates advanced numerical simulations to gain a detailed understanding of how the retrofitting mechanism works at a micro-level. Tackling this issue is not only vital for ensuring the safety and durability of current structures, but it also has greater implications for promoting sustainable building materials and practices in regions susceptible to earthquakes.

Both in rural and urban regions of Pakistan, masonry construction remains widespread owing to the scarcity and expense associated with contemporary construction materials Adobe bricks, rammed earth, stones, clay bricks, and concrete block units are commonly employed materials. Nevertheless, these structures frequently lack adequate design considerations and are classified as non-engineered constructions. The absence of engineers in rural areas and the tendency to avoid involving engineers in urban regions contribute to deficient structural designs, particularly concerning seismic resilience.

Earthquake Engineering has emerged as a discipline that aids in comprehending ground vibrations and forecasting the response of structures subjected to seismic forces. Given its durability, masonry construction necessitates suitable reinforcement strategies to ensure its robust performance during earthquakes. Numerous aged and contemporary masonry structures, spanning both rural and urban locales, necessitate evaluation for performance under seismic conditions. This requirement arises from factors such as non-adherence to design codes, absence of earthquake-resistant design principles, oversight in deciphering seismic regulations, and alterations in seismic zoning.

Masonry structures display notable susceptibility to earthquakes, as illustrated by historical incidents such as the 2005 Muzaffarabad earthquake, the 2010 Haiti earthquake, and the 1976 Tangshan earthquake. These occurrences led to substantial casualties and extensive damage, largely attributed to the widespread deployment of unreinforced masonry, which proved inadequate in resisting the force of earthquake tremors. As a result, comprehending the seismic response of masonry structures and implementing suitable interventions becomes imperative to mitigate the earthquake-related risks prevalent in Pakistan.

1.4 Aims and Objectives

- How much computational effort will be required by different modeling techniques and how much precision will be obtained
- How will fly ash bricks behave in retrofitted masonry compared to red bricks
- How will XFEM, Quadps damage criteria be able to predict crack initiation and growth in respective modeling
- How much difference will be in the results of experimental and numerical models

Chapter 2

REVIEW LITERATURE

2.1 Introduction

Extensive research has been conducted to investigate the reinforcement or strengthening of masonry constructions that lack reinforcement. The goal of retrofitting is to increase the load-carrying capacity or shorten the collapse time of structures when exposed to unexpectedly significant external loads. Several concepts are involved in retrofitting masonry structures, including reducing external forces, upgrading existing buildings, and improving structural integrity.

2.2 Base Isolation

The concept of base isolation includes the separation of the masonry building and its foundation through the installation of flexible pads. This effectively prevents the transmission of seismic movements to the building, or at the very least significantly reduces their impact. During seismic activity, the transmission of vibrations from the foundation to the main structure is limited to a small fraction of the total shaking. Previous research has shown that the careful application of flexible pads can reduce seismic stress by a ratio of five to six when compared to non-base isolated buildings. Low- to mid-rise masonry constructions are especially well-suited for the base isolation technique. Base isolation is an effective method for renovating historically significant structures, as it allows for the keeping of their original position. Conversely, traditional repair methods might be detrimental to the buildings' aesthetic. However, the implementation of this technology is now challenging within the confines of current architectural frameworks. The base isolation system is commonly seen as a means to enhance a structure's ability to withstand seismic forces, without the requirement for further intrusive retrofitting methods.

2.3 Seismic Damper

A mechanical device called a seismic damper is used in buildings to absorb and disperse the energy produced by earthquakes. Seismic energy is transmitted from the lower structure to the upper structure during an earthquake. The vibrations of the building will be lessened as a result of dampers absorbing and dissipating some of the energy.. The implementation of dampers in tall buildings was initially meant to mitigate the impact of wind forces. Subsequently, it was implemented in structures to mitigate the impact of earthquakes. There are various types of seismic dampers that have been created and employed; the most popular types in low-rise buildings include yielding dampers, friction dampers, and viscous dampers. During an earthquake, the viscous dampers dissipate energy by heat and friction, lowering the risk of collapse. The friction damper maintains structural integrity by returning the floors to their former positions, whereas yielding dampers gather and dissipate energy before the floors undergo significant movement. Seismic dampers can effectively mitigate seismic vulnerability and address the complex impacts of unknown and uncertain interventions during the building's lifespan. Traditional retrofitting methods for seismic dampening involve extensive demolition and lengthy construction periods, particularly for masonry structures. As an alternative, a new type of damper called Added Damping and Stiffness dampers has been proposed. ADAS dampers involve the installation of additional external concrete walls equipped with ADAS dampers, thereby minimizing the requirement for extensive modifications to the original building. Furthermore, the brick building was retrofitted utilizing a mixture of steel bracing and dampers. The findings revealed that the dampers effectively dispersed a significant amount of seismic energy, hence preventing excessive deformation and cracking of the masonry. However, there is a concern that this method may not be effective due to the seismic damper's need for significant deformations to achieve efficiency, but masonry structures typically exhibit rigidity. As mentioned before, seismic dampers are frequently used in the repair of framed structures, although they are not widely utilized in masonry structures.

2.4 Surface Treatment

The standard involves the application of reinforcement parts to the existing structure, which are then tightly connected together with mortar connectors. The most frequent method of surface treatment is the use. It is applied by pneumatically spraying a cement, sand, and water combination into a wire mesh that is affixed to the masonry wall's surface. The overlay's thickness typically spans between 70mm and 150mm. Typically these transfer shear forces. Before installing shotcrete, remove the layers of bricks and fill any vacant spots. Furthermore, the stiffness at the point of maximum loading was increased by a factor of three, but the beginning stiffness remained same. According to research, placing shotcrete jacketing on both surfaces can successfully reduce masonry stress by 50%, but employing one-sided shotcrete jacketing reduces strain by roughly one-third. Furthermore, the roughness of the stone surface has a considerable impact on the performance of the retrofit. Changes in shotcrete retrofitting might be made when the substrate surface is noticeably uneven following the removal of loose or degraded parts. Ferrocement is a composite material composed of multiple layers of hardware securely implanted in a thick layer (10-15mm) of high-strength cement mortar. The mechanical properties of ferrocement are regulated by the mesh quality, which improve the material's ability.

2.5 Mortar Joint Treatment

Despite the existence of poor or improperly filled mortar, masonry components within buildings can nonetheless be in good shape.The most commonly used methods are grout injection and re-pointing. Grout injection entails the filling of voids and cracks using a variety of grouts, suitable for spaces of diverse sizes, spanning from to sizable and open joints. This technique has demonstrated its efficacy in restoring the original rigidity and strength of masonry structures. However, it does not result in any considerable enhancement in the initial rigidity or strength. While it is possible to substitute the grout with a stronger substance, the enhancement is not significant. Nevertheless, the effectiveness of this method can be enhanced when employed in conjunction with other approaches. A study was conducted to examine the impact of integrating. The findings show that combining the re-pointing process. It is important to highlight that the success of this strategy is dependent on obtaining the mechanical qualities of the mixture as well as assuring. When retrofitting masonry heritage sites, the primary issues are conserving the original beauty and assuring compatibility in terms of physicochemical and mechanical properties. The first refers to the importance of conserving the integrity of masonry heritages after retrofitting, whereas the latter refers to the need to ensure strong compatibility between the masonry and the retrofitting material in terms of their physicochemical and mechanical properties. Using incompatible retrofitting materials can trigger degradation mechanisms and could lead to catastrophic effects. Grout injection and re-pointing processes can efficiently preserve the original appearance of antique masonry structures. As previously stated, the compatibility of physical and chemical qualities between masonry heritage and retrofitting materials is critical. Nonetheless, the exact dynamics of interaction between these materials are unknown. As a result, new investigations into the design and selection of restoration mortar are inextricably related to compatibility assessments, with the goal of preserving the long-term durability of masonry heritage. These studies recommend for a systematic strategy to selecting restorative mortars based on fragility analysis. This approach facilitates the determination of the best suited mortar capable of achieving required compatibility and performance parameters. This method is appropriate for the majority of masonry structures, particularly those with historical significance since it allows for the preservation of their integrity during the retrofitting process. The retrofitting mortar mustn't harm the original masonry. Another suitable application area is multi-leaf masonry walls characterized by weak connections between different layers. This method gains popularity and practicality due to its low cost, simplicity of application significantly.

2.6 External Steel Reinforcement

This technique involves the installation of adjacent to the section, may or may not be connected. During an earthquake, it is anticipated that small fractures will form and expand if the external force applied exceeds the structure's ability to support it. However, the newly implemented steel system exhibits a very high level of rigidity, effectively preventing. In such instances, the more resilient steel system will bear the exterior load component rather than being responsible for supporting the loads. Research has determined that this steel reinforcement system is highly successful in enhancing the resistance, ductility, and energy absorption of masonry construction. Utilizing steel as a retrofitting material is extremely useful in enhancing the load resistance of a structure. Hence, this method is suitable for masonry constructions that are weak or require significant improvement. However, the use of steel would alter the visual appeal of the original masonry structure, making it an unsuitable method for retrofitting masonry heritage. Moreover, the high costs present an additional concern regarding its adoption in developing nations.

2.7 Post-Tensioning

A building's lateral load-resisting framework can be strengthened and made more flexible by using the post-tensioning strengthening technique, which involves placing pre-stressed reinforcements along vertical elements. This method entails drilling masonry pockets and inserting pre-stressed reinforcement vertically, counteracting and augmenting its load-bearing capacity. Researchers found that applying this method to masonry walls quadrupled lateral load resistance, while maintaining ductility. Significant enhancements in strength, stiffness, shear capacity, and energy dissipation were observed, making it applicable not only to bare masonry panels but also to improving seismic performance in RC frames filled with masonry walls. However, there exists a threshold where ductility may diminish due to combined effects of axial force from pre-stressing bars and vertical load. Additionally, the center core method, resembling post-tensioning, involves inserting a reinforcing core vertically into masonry walls, aiming to enhance ductility without altering stiffness.

2.8 Mesh Reinforcement

Mesh reinforcement can overcome some of the limitations of the above approaches such as the addition of mass. FRP is the primary alternative for mesh reinforcement in strengthening unreinforced masonry (URM) structures. FRP composites were first used to repair or reinforce. It has been developed and utilized on additional constructions made of stone and timber and has also been thoroughly examined. Typically, the use of FRP composites to reinforce or retrofit URM walls can enhance the strength of masonry wallets by a factor of 1.1 to 3. An investigation of masonry wallets retrofitted with carbon fiber has shown that their capacity for resistance can be enhanced by 13-84%. The extent of improvement may rely heavily on the structure that is to be renovated. FRP has been demonstrated to enhance the shear resistance of masonry buildings by a factor of 3.25 in the investigated field. Considering both economic and mechanical aspects, it proves more cost-effective to opt for unidirectional FRP laminates or fabric strips over two-dimensional fabrics. A study examined various FRP layouts, including grid arrangements and diagonal strips, finding asymmetrical reinforcement application ineffective in enhancing shear resistance. Grid strips exhibit superior stress dispersion, reducing the likelihood of brittle failure, whereas diagonal strips excel in improving shear capacity. Combining FRP with other strengthening/retrofitting materials yields better results than using each material independently, with notable improvements seen when paired with PP-band. The separation of FRP from the masonry surface significantly impacts retrofitting success; if debonding occurs, it compromises effectiveness, leading to potential failure modes such as masonry crushing, FRP rupture, and debonding.

Reinforcing masonry panels with FRP offers advantages such as minimal added weight, minimal disruption, and significant strength enhancement. However, drawbacks include high costs, the need for specialized technical expertise, and potential alterations to the structure's appearance. The initial expense of FRP is notably higher than that of steel, impacting retrofitting decisions significantly. Moreover, understanding the long-term behavior of FRP materials remains incomplete. Application typically involves externally placing strips or sheets onto the masonry wall, potentially creating a waterproof barrier. Yet, the usage of epoxy-based bonding material can compromise such structures. For regions where FRP costs are prohibitive, alternatives like Polypropylene (PP) bands and bamboo meshes are viable. PP bands, known for their cost-effectiveness and adaptability, have shown promise in strengthening adobe masonry structures, as evidenced in studies in rural Nepal. Similarly, bamboo band meshes have demonstrated effectiveness in retrofitting adobe houses, significantly enhancing their energy absorption capacity. Mesh reinforcement, particularly composite materials incorporating textile fibers, has proven highly effective in strengthening both vertical masonry structures and horizontal elements like vaults and arches. While polymer-reinforced fibers are commonly used, they lack adequate water vapor permeability. To address this, embedding long steel fibers and basalt textiles in mortar has been proposed, resulting in a composite material reinforced with steel and basalt. Comparative studies show both methods effectively enhance the strength of masonry vaults, evident in increased load-bearing capacity and deformation capacity, with basalt reinforcement showing superior strength and flexibility over polymer matrices.

2.9 Confinement of Unreinforced Masonry with Constructional Columns

This approach entails using structural columns to enclose brick walls at corners, intersections, and vertical margins of door and window openings. To improve integrity, connect these structural columns to ring beams at each floor level, effectively restricting the masonry building at the same level. This method shows promise for increasing resistance in both out-of-plane and in-plane directions, with measured increases in lateral resistance of around 1.5 times and improvements in lateral deformations and energy dissipation of about 50%. Experimental testing on half-scale specimens subjected to cyclic loading confirmed these findings, indicating better energy dissipation and deformability in the in-plane direction. While Eurocode 8 recommends this enclosed system for newly constructed masonry structures to preserve integrity, applying it in existing buildings may be difficult and expensive.

2.10 Confinement of Unreinforced Masonry with Ring Beam

Reinforced concrete ring beams are widely used in masonry constructions to improve mechanical performance, especially during seismic occurrences. Masonry constructions reinforced with constructional columns and ring beams are expected to perform well under earthquake conditions. Research has highlighted the critical importance of confining features in retaining the mechanical performance of confined masonry buildings, particularly their ductility and strength. Furthermore, a larger reinforcement ratio and the presence of more restrictive features will improve the structural integrity of the masonry during an earthquake, allowing it to retain more of its strength. In general, if the current ring beam is damaged or lacks strength from the start, it can be retrofitted or strengthened.The masonry structure was improved by the addition of a beam. The data show that the, when, has a good load-carrying capacity. This method, like constructional columns, is simple to put on newly constructed buildings.

2.11 Mechanical Properties of Bricks

Clay bricks have the option of undergoing either kiln firing or sun drying. Figure presents examples of modern clay bricks, encompassing solid pressed bricks, cored bricks, and hollow bricks.

Factors such as compressive strength, tensile strength, and various other mechanical attributes play significant roles in evaluating clay bricks. Nevertheless, it's important to highlight the scarcity of information in existing literature concerning the shear mechanical properties of bricks [1].

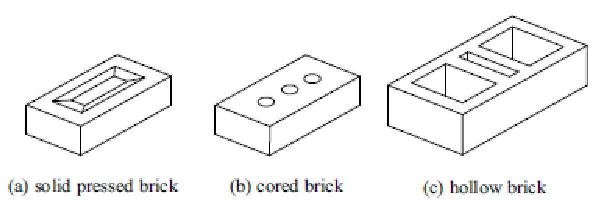


Fig 2.1: Contemporary clay bricks

2.12 Compressive Strength

Evaluating the compressive strength of bricks is a intricate procedure influenced by multiple factors, which include the loading rate, dimensions and geometry of the specimen, as well as the conditions at the tops of the sample. The impact of the restraint effect, occurring at the specimen's ends, holds notable significance in influencing compressive strength.

When subjected to uniaxial compression loads, materials have a tendency to expand in transverse directions, leading to the emergence of transverse compressive confining stresses due to the Poisson's effect. This confining influence results in a state of triaxial compression stress and a subsequent elevation in axial compressive strength, particularly noticeable when employing a firm capping material such as a thin layer of molten sulfur compound or gypsum plaster compound.

To mitigate the impact of platen restraint, alternative approaches can be adopted, such as utilizing softer capping materials like Teflon sheets or platen surfaces coated with grease. An additional strategy involves the implementation of brush platens. This method has proven effective for conducting tests on both concrete and masonry materials [2].

Established standards like CEN (1995) and AS/NZS-4456.4 (2003) encompass an adjustment factor that accommodates the restraint effect. This factor transforms the confined compressive strength into an equivalent unconfined value, serving design and research objectives.

The observed compressive strength of clay bricks can exhibit a range of 20 to 145 MPa (3000 to 21000 psi), contingent upon variables such as the composition of clay, firing circumstances, coring designs, as well as the dimensions and configuration of the bricks. Furthermore, distinct mechanical characteristics like compressive strength, elastic modulus, and Poisson's ratio can display variations when subjected to loads from various directions, underscoring material anisotropy. This phenomenon could potentially arise from uneven firing or manufacturing procedures.

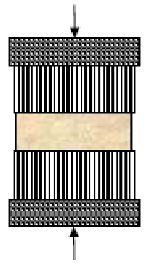


Fig 2.2: Brick uniaxial compression testing using brush platen

2.13 Brick Tensile Strength

Assessing tensile strength via direct tensile tests can present challenges and produce inconsistent outcomes due to difficulties in alignment and the emergence of stress concentrations resulting from the gripping of the test specimen. To address these challenges, indirect tensile tests are frequently utilized, encompassing methods like the three-point bending test for flexural strength and the splitting test. However, it's important to note that the flexural tensile strength often surpasses direct tension results significantly. This divergence can be attributed to the strain gradient occurring in a three-point bending test, resulting in a smaller section of the material encountering elevated stress levels Alternatively, the splitting tension test is commonly employed as an alternative approach to determine a comparable measure of tensile strength. This method provides results with reduced variability and offers greater ease of execution. In the context of a splitting tension test, the tension that emerges across the central section of the unit's height between the loading points closely mirrors a direct tension scenario. As a consequence, the computed average strengths from this test tend to align closely with, or slightly exceed, the outcomes obtained from direct tension measurements [3].

Empirical investigations have revealed that the tensile strength of clay bricks, determined through indirect methods, exhibits an augmentation corresponding to the compressive strength of the bricks. Sahlin (1971) documented a ratio of flexural strength to compressive strength spanning approximately 0.1 to 0.32. Notably, the flexural strength values exceeded those derived from splitting tests by 20% to 50%. Schubert (1988) established that the ratio between longitudinal tensile strength and compressive strength for clay, calcium-silicate, and concrete units typically ranges from 0.03 to 0.10.

Almeida et al. (2002) Employing direct tensile tests, the study aimed to characterize the tensile properties of both bricks and the interfaces between bricks and mortar. The investigation encompassed solid bricks, as well as hollow bricks manufactured in Portugal and Spain. It's worth noting that all test specimens were sourced from original bricks due to limitations posed by the testing equipment. The experiments were carried out with displacement control, maintaining a deformation rate of 0.5 µm/s. This allowed for the measurement of both the tensile strength and the mode I fracture energy. Across all brick types, the outcomes were consistent, revealing an average tensile strength falling within the 3 N/mm² range. Additionally, the average fracture energy varied from 0.0512 to 0.081 N/mm/mm². Nonetheless, the test results displayed significant variability, as illustrated in Figure 2.6. It was observed that specimens possessing greater strength exhibited more pronounced stress decay subsequent to reaching the peak load. Moreover, irregularities were evident in the descending curves of certain specimens. The dispersion seen in the test results was attributed to the development of non-uniform crack opening and crack orientation during the manufacturing processes. This scatter is characteristic of masonry materials under tension [Van Der Pluijm, 1999]. The study also reported a notable proportion of specimens (ranging from 20% to 50% of the total) that experienced failure prior to reaching the ultimate deformation state. This outcome underscores the difficulties encountered during the testing process [4].

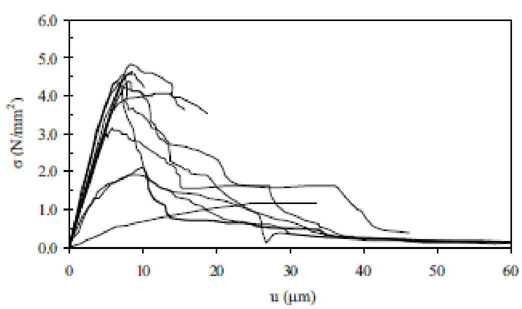


Fig 2.3: Brick direct tensile test responses

2.14 Absorption Rate

A crucial characteristic of bricks that holds substantial sway over the strength of brick masonry is their initial rate of absorption (I.R.A.), also referred to as brick suction. Brick suction plays a pivotal role in establishing bond strength, thereby exerting a noteworthy impact on both the compressive and tensile strength of brick masonry. Drysdale et al. (1982) demonstrated the influence of the brick's initial rate of absorption on shear bond capacity. Attaining an optimal I.R.A. value for bricks is essential in order to maximize the bond strength of the masonry.

Dhanasekar (1985) mentioned that Bricks characterized by a high I.R.A. value have a tendency to absorb a substantial amount of water from the mortar, leaving inadequate moisture for cement hydration. This situation can present difficulties in the brick-laying process. Conversely, bricks possessing lower I.R.A. values might struggle to establish a suitable bond with the mortar, particularly when they have been pre-wetted [5].

2.15 Mechanical Properties of Mortar

In masonry construction, mortar assumes a pivotal role as a binding material. It functions to connect individual masonry units, creating a composite structure capable of enduring applied loads and weather conditions. Throughout history, a range of mortar types have been employed, encompassing lime-pozzolanic, cement-lime, and cement mortar. In most cases, mortar possesses less strength and greater flexibility compared to the bricks it binds.

The weathering attributes of mortar are contingent upon the prevailing local exposure conditions and the thickness of joints. Meanwhile, its fundamental qualities are shaped by various factors, including mixing procedures, curing methods, the passage of time, joint thickness, as well as constituents like cement, sand, lime, or any incorporated admixtures, alongside water. For comprehensive insights into appropriate constituents, you can refer to Dhanasekar (1985). Additionally, Drysdale et al. (1994) delve into discussions about mortar types and their proportions in accordance with ASTM-C-270 (1989). Cement contributes strength, while lime and water enhance workability. Sand, on the other hand, serves as an economical filler.

Concerning mortar, sought-after characteristics encompass satisfactory workability, sufficient bond strength, and suitable overall potency. Successful bonding hinges on achieving a favorable level of brick suction and mortar water retention, whereas workability pertains to the mortar's capacity to flow seamlessly across brick surfaces. While incorporating additional water can enhance mortar flow and workability, it concurrently elevates the water-cement ratio, leading to a decline in mortar strength [6].

This discussion focuses on the compressive performance of mortar due to the scarcity of available data concerning its tensile and shear characteristics. Furthermore, customary mortar test samples are commonly formed in impermeable molds, overlooking the water absorption impact of the masonry component. Consequently, the recorded figures from standard tests do not accurately depict the authentic attributes of mortar within a masonry connection. This situation leads to mortar properties primarily serving quality control objectives rather than genuinely mirroring real-world performance.

In general, studies tend to focus on evaluating and reporting the compressive strength and flexural strength of mortar, as evidenced by various works of Almeida et al. (2002) and Abdou et al. (2006). Some researchers have examined mortar properties by extracting mortar disks from masonry joints, as demonstrated by some reseaechers. However, our understanding of the complete uniaxial behavior of mortar, both in compression and tension, remains limited, as stated by Lourenco (1996).

2.16 Compressive Strength

Mortar's compressive strength can be ascertained using cube or prism tests. According to ASTM-C-109 (1988) guidelines, the suggested mortar specimen is a 50 mm (2 in.) cube cast in a mold that doesn't absorb moisture. Generally, a minimum of three samples are necessary, which are cured under specific conditions and subsequently examined at 7 and/or 28-day intervals [7].

Grim (1975) introduced a correlation to articulate the mortar's compressive strength, factoring in variables like shape, curing technique, age, air content, and initial flow rate of the mortar.

2.17 Brick-Mortar Interface

The tensile strength of the interface between bricks and mortar holds significant importance in the numerical modeling of masonry structures. Diverse testing techniques have been employed and suggested in scholarly literature to quantify this tensile strength. Jukes and Riddington (1998) conducted an exhaustive examination of these testing methods and deliberated on the corresponding difficulties.

A technique proposed by Jukes and Riddington (1998) involves a direct tensile test using paired specimens. In this method, two bricks are linked by a solitary mortar joint, and the load is applied via bolts inserted through drilled holes in the bricks. While this testing approach is advisable for evaluating bond strength in the context of in-plane strength assessments or finite element analysis, it might not be appropriate for scenarios involving a combination of bricks with low strength and mortar joints of high bond strength.

Van Der Pluijm (1992) performed experiments on the direct tensile strength of solid clay and calcium-silicate bricks. The outcomes revealed an exponential reduction in tensile strength under tension, as depicted in Figure 2.7. The mode I fracture energy, which signifies the energy necessary for initiating a crack along the unit/mortar interface, spanned from 0.005 to 0.02 N/mm/mm² across diverse tensile strengths extending from 0.2 to 0.6 N/mm², contingent upon the specific unit/mortar pairing [8].

Almeida et al. (2002) directed a sequence of researches to examine the direct tensile strength of both bricks and the interface between bricks and mortar. The tensile strength and mode I fracture energy were measured for various types of interfaces between bricks and mortar. The average bond tensile strength was roughly 2 N/mm², and the average mode I fracture energy was approximately 0.008 N/mm/mm². Nevertheless, the test outcomes displayed notable fluctuations, encompassing differences in the configuration of the softening branch. The tests were susceptible to instability, with the softening branch being observable in only a limited number of tests. Figure 2.10 illustrates an example of the scatter observed in the reported test results. The scattering of results was attributed to uneven crack opening and the intrinsic characteristics of masonry materials [9].

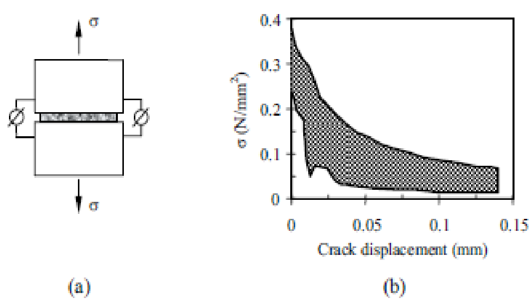


Fig 2.4: Tensile behaviors of brick-mortar interface

Test specimen b) typical response for solid clay brick masonry

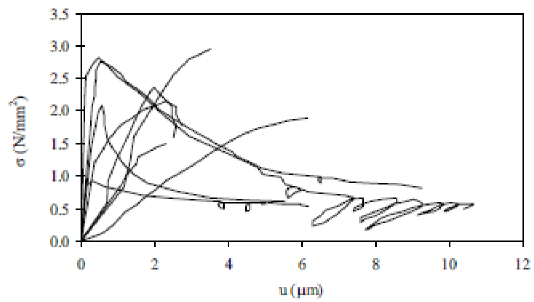


Fig 2.5: Responses obtained from direct tensile tests of brick-mortar interfaces

2.18 Shear Failure

Many researchers have explored shear failure occurring at the interface between bricks and mortar, employing various types of specimens for their investigations.

For example, Riddington and Ghazali (1988) as well as Lourenco et al. (2004) investigated masonry samples featuring multiple horizontal and vertical joints. Conversely, Hamid and Drysdale (1982) and Jukes and Riddington (2001) concentrated on smaller specimens containing just a single mortar joint [10]. Notably, it has been noted that the shear failure characteristics examined in both types of specimens demonstrate comparable patterns [11].

The failure of masonry joints under shear can be characterized using the Mohr-Coulomb failure law, which establishes a linear correlation between the shear stress (τ) and the normal stress (σ) as follows:

$$\tau = c + (\sigma \times \tan \Phi)$$

In this context, 'c' signifies cohesion, and 'Φ' represents the friction angle. To derive the parameters relevant to shear failure, Van Der Pluijm (1993) introduced a shear test arrangement (Figure 2.9) designed to establish a consistent stress state within the masonry joint. It's important to acknowledge that achieving a consistent shear stress state is difficult due to non-uniform stresses arising from equilibrium restrictions in the specimen. Van Der Pluijm's shear test, however, permits the preservation of a consistent normal confining pressure while undergoing shearing. Van Der Pluijm utilized this test arrangement to examine the shear characteristics of solid clay and calcium-silicate bricks under varying magnitudes of confining stresses level. [12].

Van Der Pluijm observed that the mode II fracture energy (IIfG), which quantifies the region enclosed by the stress/displacement graph and the residual friction shear level, is contingent upon the magnitude of the applied confining stress. The mode II fracture energy spanned between 0.01 and 0.24 $N/mm/mm^2$, while the initial cohesion values varied from 0.2 to 1.9 N/mm^2, according to Van Der Pluijm's findings. Furthermore, he observed that the tangent of the initial internal friction angle (0 tan Φ) ranged from 0.7 to 1.2 across various unit and mortar combinations. The (r tan Φ) remained relatively consistent at around 0.75. Additionally, the angle, which quantifies the upward displacement of one unit relative to the other during shearing, was observed to be a significant factor, depended on the level of confining stress. The mean value of tan Φ varied between 0.2 and 0.7, influenced by the texture of the brick surface particularly under lower confining pressures. The dilatancy angles diminished to zero as the confining pressures escalated, signifying a shift towards pure shear sliding displacement in the residual state.

Furthermore, Drysdale et al. (1982) documented the outcomes of 74 shear tests executed on assemblies of masonry composed of clay bricks. Shear was propagated along the bed joints, both with and without concurrent normal compressive stress. The experiments also encompassed consistent levels of precompression, spanning from 0 to 30% of the compressive strength. An array of mortar types was employed in these experiments. The shear bond failure capacities of the bed joints were impacted by the specific mortar utilized, yet they didn't exhibit a direct correlation with the compressive strength of either the mortars or the corresponding masonry prisms. Under the application of compressive stresses vertical to the bed joints, the significance of the mortar's type and strength was more pronounced in determining the shear strength. Furthermore, the escalation in normal compressive stress did not yield a commensurate rise in supplementary shear resistance. Additionally, the coefficient of friction along the bed joint decreased as the normal compressive stress levels increased [13].

Abdou et al. (2006) undertook a study investigating the impact of perforations on joint mortar behavior. This was achieved through experimentation on half-brick couplet specimens composed of both solid and hollow bricks. A mortar with a relatively high compressive strength (20 MPa) was employed. In both scenarios, the experimental findings suggested the absence of stiffness deterioration, even within the softening phase. Nevertheless, it was noted that the existence of perforations augmented stiffness due to mortar filling, while the internal friction angle of the mortar joint remained unaffected.

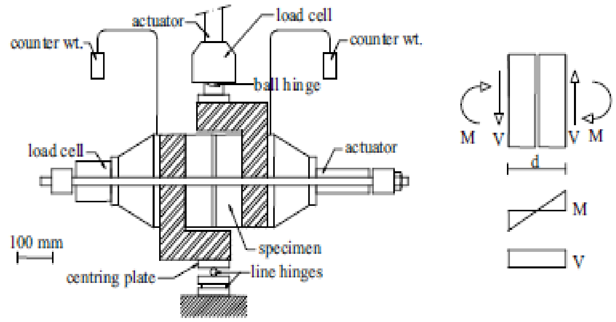


Fig 2.6: Shear test set-up and loading on the specimen

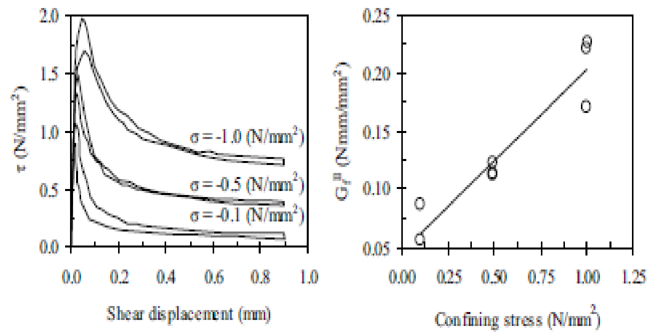


Fig 2.7: Typical Shear behaviors of brick-mortar for clay bricks

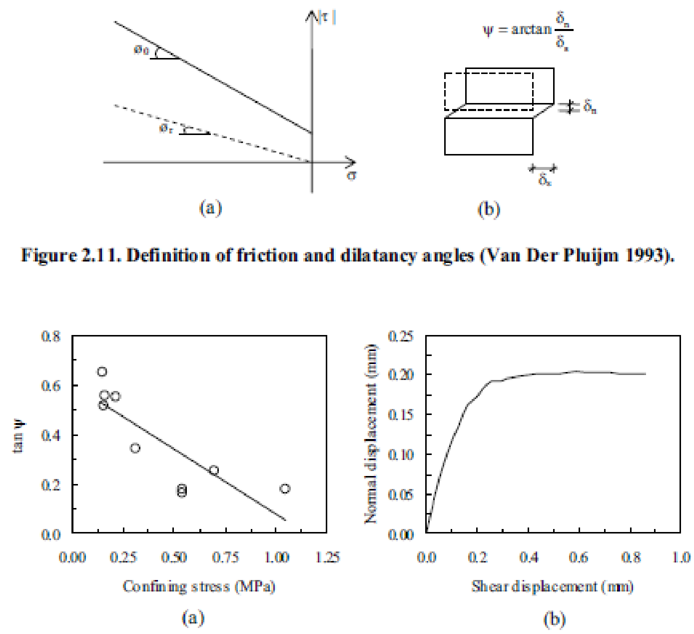


Fig 2.8: Friction and dilatancy angles and brick-mortar interface for clay bricks

2.19 Uniaxial Compressive Behavior

Numerous factors influence the compressive performance of masonry, with a particular focus on the attributes of both bricks and mortar. The disparity in elastic properties between the brick and mortar engenders a collective impact that governs the compressive failure of masonry structures. Under compression, both bricks and mortar undergo lateral expansion at distinct rates due to the Poisson's effect. Ordinarily, mortar possesses a higher Poisson's ratio, causing it to expand laterally more than bricks [14]. Nevertheless, the adhesion and friction at the interface between bricks and mortar curtail the expansion of mortar, leading to a state of triaxial compression within the mortar and compression/biaxial tension within the brick. Hilsdorf (1969), Khoo and Hendry (1973), Dhanasekar (1985), and Chaimoon and Attard (2006) have extensively discussed this phenomenon.

Moreover, according to Hendry (1998), various other factors contribute to the compressive behavior of masonry. These include the quality of workmanship, the coring patterns of extruded bricks that can induce substantial strength reduction due to stress concentration effects, dimensional discrepancies arising from variations in size and inadequate workmanship leading to wall eccentricities, as well as the thickness of mortar joints. With an increase in joint thickness, the compressive strength tends to decrease due to the greater flexibility of the mortar, causing it to spread further and consequently inducing tensile splitting of the brick units at lower applied loads.

The compressive strength of brick masonry holds paramount importance as a material parameter for the analysis and design of masonry structures. This compressive strength can be ascertained either through an estimation involving the strengths of both bricks and mortar or by performing compression tests on masonry prisms. However, Dhanasekar (1985) emphasizes the need for cautious interpretation when employing the approximation method, as it fails to consider potential variations in workmanship. For a more dependable evaluation of compressive strength, utilizing a prism test is recommended. While the genuine uniaxial compressive strength of masonry can be obtained through the RILEM test, it's important to note that this method entails larger and more expensive specimens in comparison to the conventional cube or cylinder tests commonly employed for concrete, as mentioned by Lourenco (1996). Hence, the stacked bond prism is often employed to establish the uniaxial compressive strength. This approach involves the application of correction factors to attain a more accurate representation of the compressive strength. These correction factors account for the effects of pier aspect ratio and the ratio of brick height to joint thickness [15].

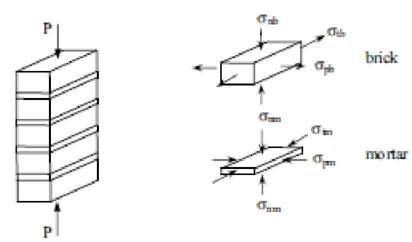


Fig 2.9: Failure mechanism in compression

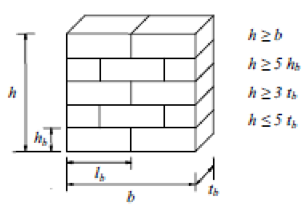


Fig 2.10: RILEM Test

2.20 Uniaxial Tensile Behavior

The uniaxial tensile response of masonry varies based on the loading direction. This distinction arises because, in the latter scenario, either certain bricks must experience fracture, or the failure path needs to follow a staggered route along the bed and head joints.

Lourenco (1996) conducted an examination of the strength, emphasizing that when tensile loading is oriented, failure typically transpires due to the comparatively limited tensile bond strength at the interface between bricks and mortar. The tensile strength of masonry can approximately match the tensile bond strength at the brick-mortar interface. Conversely, when tensile loading is aligned with the bed joints, two distinct types of failure emerge, contingent upon the relative strengths of the joints and units, (Backes 1985). In the first form of failure, cracks traverse in a zigzag pattern through the head and bed joints, resulting in a stress-displacement graph that usually showcases a residual plateau as deformation increases, leading to a stress-displacement curve that demonstrates gradual softening without any remaining strength.

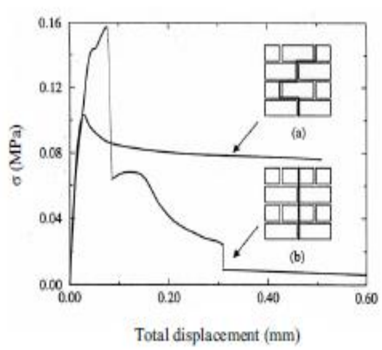


Fig 2.11: Uniaxial Tensile Behavior of Masonry

2.21 Biaxial Behavior

The biaxial behavior of masonry is more complex in comparison to plain concrete. This complexity arises from the intricate interaction between its constituents and the distinct directional characteristics brought about by mortar joints and/or the arrangement of bricks. The collective biaxial behavior stems from a fusion of stress redistribution, localized cracking, and gradual failure in specific regions. Multiple experimental initiatives have been undertaken to explore the comprehensive response of masonry subjected to biaxial stress conditions.

These initiatives primarily concentrated on examining the determination of failure (failure envelope) and the various modes of failure. For instance, Ganz and Thurlimann (1982) proposed a failure surface for biaxial stresses applied to hollow brick masonry. Guggisberg and Thurlimann (1987) investigated the biaxial behavior of masonry units made of clay and calcium-silicate, while Lurati et al. (1990) scrutinized concrete unit masonry.

To illustrate the impact of stress ratio and stress orientation, Dhanasekar (1985) carried out an extensive series of tests on masonry structures subjected to proportional biaxial loading. For this study, half-scale solid clay bricks and mortar with a ratio of 1:1:6 (cement: lime: sand, by volume) were employed. Various bed joint angles and a range of load combinations were taken into account [16].

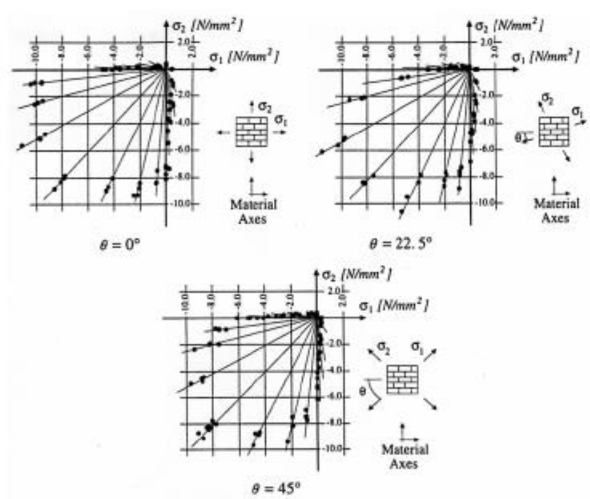


Fig 2.12: Biaxial strength of solid clay

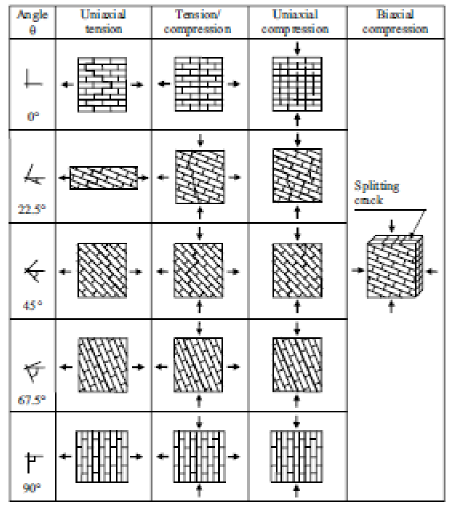


Fig 2.13: Modes of failure of solid clay with biaxial loading

When exposed to uniaxial tension, the failure of masonry is predominantly influenced by the incidence of cracks and descending laterally the head and bed joints. In situations involving tension-compression loading, failure can transpire either by means of joint cracking and sliding exclusively, or by a conjunction of joint and unit failure. Similarly, uniaxial compression also showcases similar patterns of failure.

When confronted with biaxial compression, failure usually presents itself as splitting of the specimen at its midpoint, occurring along a plane parallel to the specimen's exposed surface. This specific failure mode persists uniformly irrespective of the orientation of the principal stresses.

2.22 Modes of Failures for Masonry Structures

The concentration of mass and inertias during an earthquake result in the generation of concentrated lateral forces at roof or floor levels. In masonry constructions, walls assume a pivotal role as principal structural components that bear the weight of the entire structure and enable the transmission of loads from roof or floor levels to the foundation. Hence, it is imperative to grasp the failure modes linked to masonry walls, as discussed below.

There are two primary failure modes for masonry walls during earthquakes:

1. In-plane stresses: These arise due to forces acting in parallel with the wall.

2. Out-of-plane stresses: These manifest as a consequence of forces exerted perpendicular to the wall.

Refer to Figure for a visual representation of the in-plane and out-of-plane directions for walls [17].

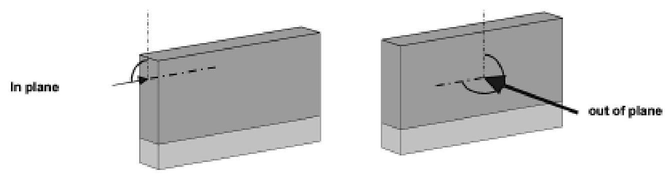


Fig 2.14: In-Plane and Out-Plane directions for walls

Walls are principally engineered to endure lateral loads within their in-plane orientation, wherein their rigidity is notably greater in contrast to the out-of-plane direction. In structures without reinforcement, shear walls serve as pivotal elements responsible for furnishing the requisite lateral strength to withstand horizontal seismic forces. Hence, this study also concentrates on examining the response of cracks in masonry when subjected to in-plane stresses. The failure modes for masonry subjected to lateral forces along the wall plane are outlined as follows:

2.22.1 Shear Crack

Shear cracks become apparent when opposing lateral forces are applied at the upper and lower sections of the wall. This form of failure is the most common and follows the trajectory of load transmission from the roof down to the foundation. It is considered by the emergence of a transverse crack that traverses the wall. Shear cracks commonly arise in walls exposed to substantial vertical and horizontal loads, particularly when the wall possesses an aspect ratio ranging from 1:1 to 2:1, especially under the influence of higher vertical loads [18].

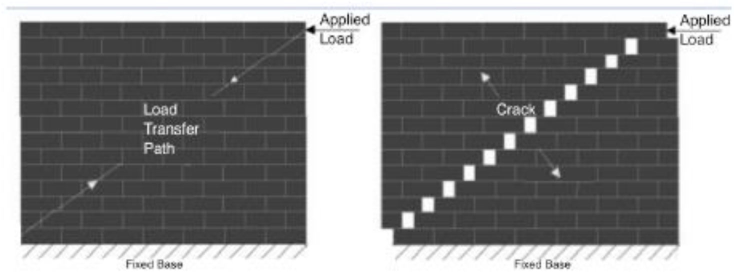


Fig 2.15: Diagonal Shear Crack in wall follow load transfer path

2.22.2 Shear Slip

In the shear slip failure mode, cracks within the wall manifest horizontally amidst the layers of bricks as shown in Figure 2.5. Instead of following the diagonal load path, cracks discover a weaker plane along the brick layer and induce a horizontal shear slip. Walls primarily subjected to horizontal forces can display this form of failure, often occurring in walls with an aspect ratio of (1:1).

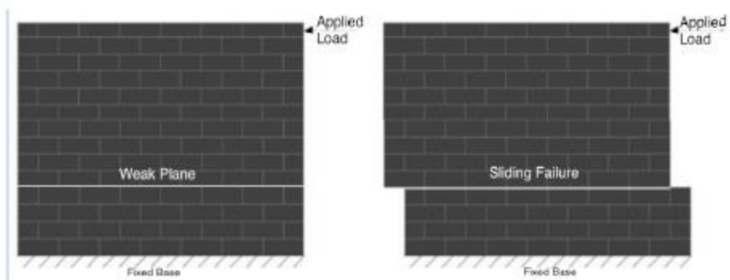


Fig 2.16: Shear Slip due to a weak plane between masonry layers

2.23 Continuous Micro Modeling

Traditionally, the behavior of masonry structures, including those that have been retrofitted with PP bands, has been examined using macro-modeling methods. These models consider masonry as a uniform and consistent material, not considering its inherent variation in composition. These errors may arise when capturing the specific impacts of loads, crack initiation, and material interactions, especially at the interface between bricks and mortar. CMM overcomes these limitations by explicitly representing the different constituents of the masonry system, which include:

- The bricks are individually modeled with separate material properties and geometries, enabling precise representation of their heterogeneity and impact on the overall behavior.
- The particular characteristics of mortar layers are rigorously modeled to accurately capture their critical role in load transfer and crack initiation.
- The interfaces between bricks and mortar are examined separately, enabling the analysis of debonding, micro-cracking, and localized interactions.

The implementation of Continuous Micro Modeling (CMM) offers numerous advantages for assessing the efficacy of upgrading fly ash brick masonry with PP bands:

- The explicit modeling of individual components and their interactions in CMM allows for a more precise description of the complex mechanical behavior of the retrofitted wall. This includes factors like as stress distribution, crack initiation and propagation, and load-bearing mechanisms.
- CMM illustrates the complex processes taken on at the interface between the bricks and mortar, as well as within the PP bands themselves. This study offers a significant understanding of the mechanisms via which PP bands enhance strength, ductility, and crack resistance. Consequently, researchers may effectively optimize the design and application of these bands.
- CMM enables the integration of distinct material characteristics of fly ash bricks and mortar, considering their intrinsic variability and the potential differences from traditional clay bricks. Consequently, this leads to simulations that are more reliable and accurate.
- The model can accurately represent the physical characteristics of the PP bands, such as their dimensions, rigidity, and adhesive properties. This enables the analysis of their distinct impact on the modified wall's function and permits refinement of their configuration.

While offering significant advantages, CMM also presents some challenges:

- CMM models necessitate substantial processing power and resources due to the enhanced complexity of the geometry and material interactions. Such limitations may affect the feasibility of analyzing extensive or complex structures.

- Properly calibrating the CMM model to experimental data is essential for ensuring its reliability. The inherent uncertainty and insufficient research data on fly ash bricks compared to regular clay bricks can make them particularly problematic.
- It is crucial to select appropriate material models for bricks, mortar, and PP bands to accurately represent their nonlinear behavior and interactions. However, the development of precise models for fly ash brick construction is currently ongoing, necessitating additional research and validation.

Within the specific scope of the research thesis, the implementation of continuous micro-modeling aims to explain the relationship between the retrofitting of the PP band and the masonry made of fly ash bricks. Through the simulation of the materials' continuous behavior, researchers can gain useful knowledge about the influence of the PP band on the distribution of stress, the formation of cracks, and their propagation inside the masonry structure. Applying particular attention to this level of detail is especially important in retrofitting instances as the success of the intervention depends on comprehending the complex mechanics of the materials involved at a micro level.

2.24 XFEM in ABAQUS for Masonry Analysis

Conventional finite element methods (FEM) experience challenges when accurately representing the initiation and propagation of cracks, particularly in materials with different characteristics such as masonry. They depend on predetermined crack patterns, which limits their capacity to precisely predict the formation and interactions of fractures within the complex interaction of bricks, mortar, and retrofitting components such as PP bands. The gap between modeling and experience can result in imprecise predictions of structural behavior and limit the improvement of retrofitting approaches.

XFEM addresses these constraints by including enrichment functions in the conventional FEM architecture. These enhancements enable the propagation of cracks throughout the elements, without being limited to predetermined paths. XFEM is capable of accurately representing complex crack patterns in brickwork because of its inherent adaptability.

XFEM is capable of detecting the initiation of cracks at vulnerable locations such as interfaces between bricks and mortar, within bricks, or even within PP bands. The detection depends on the local stress distribution and material properties. The formation of cracks in masonry typically displays complex patterns of branching and merging. XFEM, a simulation technique, can accurately model this behavior, allowing for an accurate representation of possible failure conditions. XFEM enables a comprehensive examination of how cracks interact with PP bands, revealing their effectiveness in preventing crack propagation and enhancing overall ductility.

At a small scale, XFEM visualizations show the detailed mechanisms by which PP bands enhance fracture resistance by highlighting the complex mechanics behind crack patterns. Researchers can examine the initiation, propagation, and interaction of cracks with the bands, which yields vital data for optimizing their design and application. XFEM may identify the fundamental mechanisms via which PP bands enhance load-bearing capability by examining stress distribution changes around cracks and inside these bands. Acquiring this knowledge can result in the development of more effective and focused retrofitting strategies. It can be utilized to anticipate future failure modes by analyzing the patterns of crack propagation. This enables engineers to detect vulnerabilities in the modified structure and apply precautionary actions before the beginning of a catastrophic failure.

It is used in computational mechanics, specifically in finite element analysis (FEA). It serves and is particularly valuable for addressing problems involving intricate crack propagation, discontinuities, and singularities without the necessity to explicitly create meshes for these features. The XFEM reached a level of maturity suitable for commercialization after its initial introduction by Belyschko and Black in 1999. XFEM, built upon idea PoU. It enables representation of breaks within an element for enhancing degrees of freedom using specialized displacement functions [19].

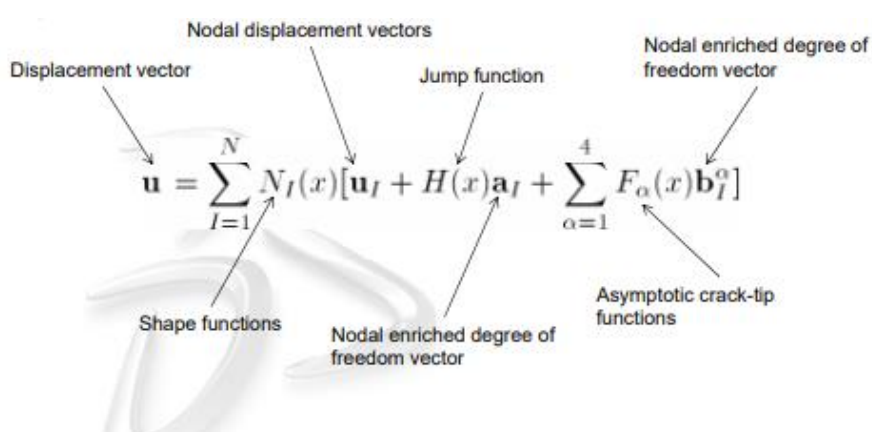


Fig 1.17: XFEM Methods

Finite element analysis (FEA) is extensively, especially for addressing systems characterized by a significant that represent composition. Conversely, modeling seismic behavior of reinforced concrete via intricate demanding. The XFEM necessitates the establishment where cracking occurs, and this contact law is not predefined in the geometric model [20].

It improves calculation through the incorporation of enrichment functions. However, there is a notable distinction: in process applies across. Consequently, only nodes in proximity to the crack tip and those essential for accurately localizing. This approach clearly offers significant benefit.

Their groundbreaking effort introduced for enhancing finite element approximations in a manner enables the solution of crack growth problems with minimal remeshing requirements. This marked a significant milestone in the history of XFEM. Subsequently, more refined formulations have been developed, incorporating features such as enrichment. Moreover, the XFEM has proven to be highly effective. These studies, challenges related to accurately representing cracks and enriching the element. A significant advancement occurred when a comprehensive approach for representing discontinuities, regardless of their location within the domain and independent of the mesh grid, was introduced. It effectively reduces the challenges associated with mesh generation, as it no longer necessitates that the finite element mesh conforms to the crack geometry. The Heaviside functions

This approach helps determine the behavior of the Heaviside function when there are multiple possible normal vectors at a given point.

It occurs along dynamic or moving interfaces, such as in cases involving crack propagation. In such scenarios, FEM offers a powerful numerical framework for simulating the complex behavior of materials and structures as they undergo changes and experience discontinuities over time. This method enables engineers and researchers to analyze and predict the mechanical response of systems subjected to evolving conditions, making it particularly valuable in various fields, including fracture mechanics, geomechanics, and structural engineering.

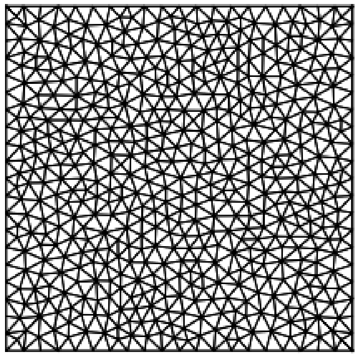


Fig 2.18: Initial Mesh

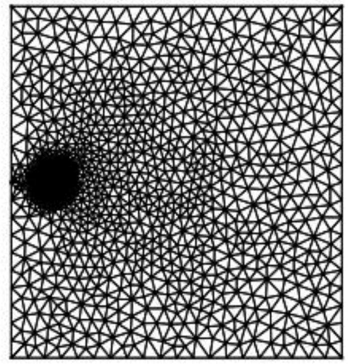


Fig 2.19: Crack appears

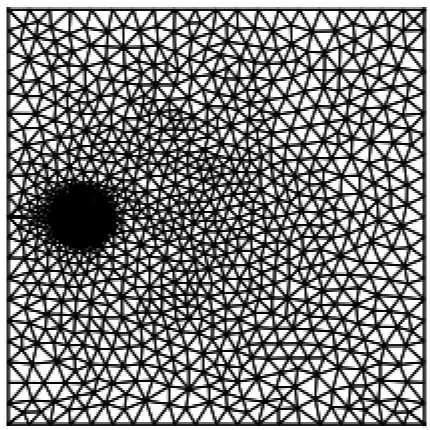


Fig 2.20: Crack Propagates

In many traditional finite element simulations of crack propagation, re-meshing is indeed necessary at every step of the propagation process. This is because as the crack advances, the mesh needs to be modified to accommodate the new crack geometry and ensure accurate modeling of the discontinuity. This re-meshing can be a computationally intensive and time-consuming process, particularly for complex crack paths and three-dimensional simulations.

However, one of the advantages of XFEM, as mentioned earlier, is that it reduces the need for frequent re-meshing. XFEM achieves this by using enrichment functions to represent the crack within the existing mesh, allowing for the simulation of crack propagation without the continuous modification of the mesh. This approach significantly simplifies the modeling process and reduces computational overhead, making XFEM a valuable tool for crack propagation analysis [22].

Researchers can explore fracture propagation inside PP band retrofitted fly ash brick walls at the micro-level by utilizing the features of XFEM in ABAQUS. This marks the starting point of a new period in comprehending the complex dynamics of this retrofitting technique, resulting in enhanced designs, enhanced seismic resistance, and eventually, safer and more sustainable constructions for future generations.

2.25 A review of numerical models for masonry structures

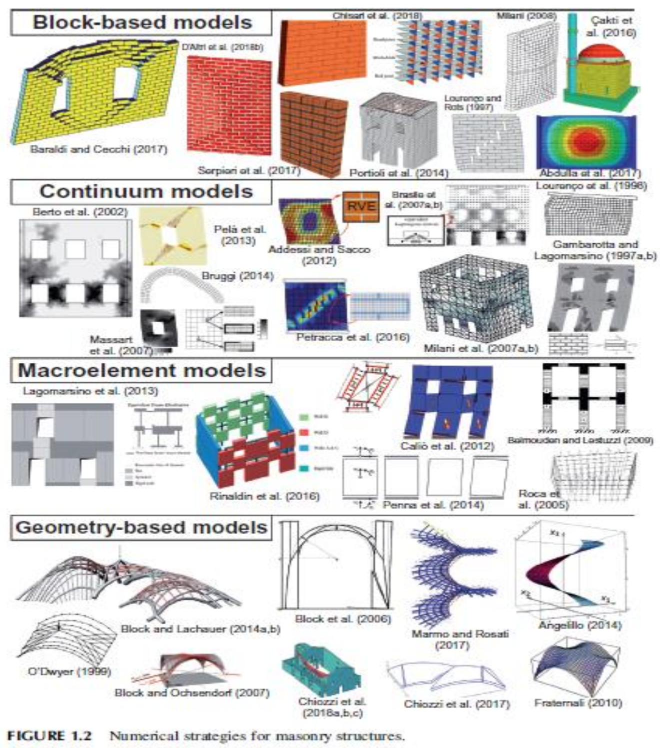


Fig 2.21: Numerical models for masonry structures

Within this section, we introduce a classification of computational methods for masonry structures, following the framework. This categorization organizes the methods used to conceptualize and simulate masonry and/or masonry structures.

Every numerical technique possesses distinct appealing traits that are typically well-suited for particular areas of application. Additionally, various levels of material testing can be utilized to ascertain the powered attributes of the model, contingent upon the scale of symbol adopted in the mold tactic.

Although achieving a wholly uniform labeling of all geometric tackles is unfeasible due to their individual characteristics, the provided classification seeks to systematize the vast array of scientific literature on this subject. We put forth four primary categories of numerical methods for masonry structures.

- Block-by-Block Models (BBMs)

This methodology delineates the structure by simulating individual masonry blocks. It accommodates the definite consistency of masonry. Each block can be preserved as either a rigid or a flexible entity, and the mechanical interface between these blocks can be simulated over diverse formulations [23].

- Continuum Models (CMs)

Masonry is regarded as a continuous entity without differentiating between individual blocks and the layers of mortar. The constitutive behavior of masonry material can be characterized through direct methods, such as constitutive laws derived from experimental tests. Within the multiscale framework, the constitutive relationship in the macroscopic structural model is deduced through a homogenization process, which links it to a microscale material model that encapsulates the key assortments present in masonry [24].

- Macro element Models (MMs)

In this methodology, structural elements at the panel scale, referred to as macroelements, are employed to depict the structure. These macroelements encompass responses that are either phenomenological or derived from mechanical principles. In general, two main macroelements, namely piers and spandrels, are recognized based on the interpretation of the structural configuration. Macro-Modelling (MMs) diverge from models in category (1) by virtue of the fact that the constituent connection of macroelements is designed to replicate the structural response of panel-scale components, as opposed to models in category (2) that replicate the mechanical behavior of masonry material [25].

- Geometry-Based Models (GBMs)

This category employs models utilizing rigid bodies to represent the structure. The methodologies within this class solely necessitate the structural geometry as input data. Commonly, solutions based on lower-bound or upper-bound limit analysis are utilized in this context. Generalized Block Models (GBMs) diverge from block-based approaches found in category (1) by not requiring a detailed description of masonry on a block-by-block basis.

Every category of numerical methodologies is comprehensively assessed in the following sections, where we also critically evaluate the strengths and weaknesses inherent in each approach.

2.26 Block-based models

Block-Based Models (BBMs) are designed to replicate the behavior of masonry at the scale of its fundamental heterogeneity, where blocks are joined using mortar. These models possess the capacity to replicate the authentic texture of masonry, which dictates the material's failure patterns and overall mechanical attributes, encompassing anisotropy.

A seminal contribution to nonlinear Block-Based Models (BBMs) is the research conducted. In this study, masonry is envisioned as a collection of elastic blocks interconnected by mortar joint elements possessing restricted shear strength influenced by bond strength and normal stress. Subsequently, a multitude of BBMs have been devised and introduced [26].

The main advantages of BBMs can be summarized as follows:

- Direct illustration of the actual masonry texture and structural facts.
- Mechanical properties can be resultant from small-scale tentative tests.
- Clear picturing of the crack pattern.
- Anisotropy of the material is directly described for through the representation of masonry's actual texture.

BBMs can instantaneously consider the in plane and out of plane behaviors of masonry, including their interactions [27].

However, there are certain limitations associated with BBMs:

- The computational requirements are substantial, often limiting their applicability primarily to masonry panels. In the literature, there are only a handful of instances where block-based analyses have been extended to encompass full-scale structures

- The precise texture of extant masonry structures, especially monumental edifices, is frequently inadequately understood. As a result, the block-by-block depiction of such structures might be an approximation
- The process of assembling the individual blocks can be time-intensive, thus confining the practical application of these numerical approaches predominantly to theoretical examine

All above, additionally subdivided into various subclasses according to the method employed to simulate the interaction between blocks [28].

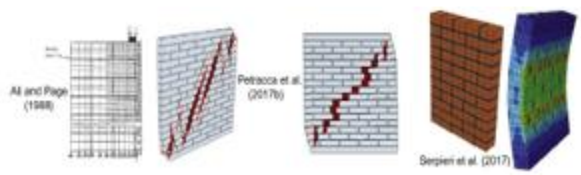


Fig 2.22: Textured continuum-based approaches

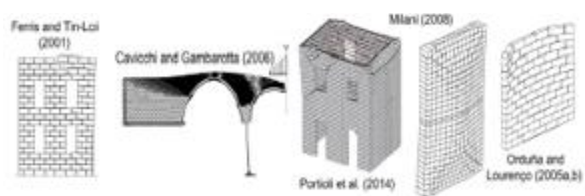


Fig 2.23: Block-based limit analysis approaches

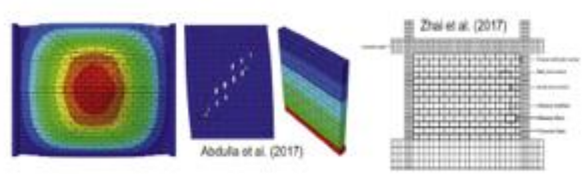


Fig 2.24: Extended finite element (FE) approaches

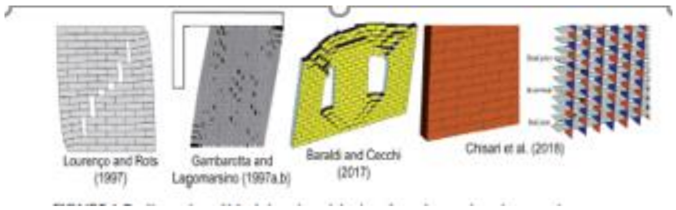


Fig 2.25: Interface element-based approaches

Fig 2.26: Contact-based approaches

1. Interface element-based approaches

The investigation carried out by Lotfi and Shing in 1994 stands as an early illustration of an approach rooted in interface elements for examining the mechanical behavior of masonry structures. Within their study, mortar layers were treated as interface elements with negligible thickness, and the blocks were simulated using a smeared crack constitutive model.

Rots (1991, 1997) investigated further pioneering instances of employing interface element-based methodologies in masonry structures. Rots also devised a technique to expand the blocks using zero-thickness interface elements for mortar layers. Furthermore, Rots (1991, 1997) integrated the inclusion of potential cracks within the blocks.

Gambarotta and Lagomarsino (1997) introduced a cyclic interface model founded on damage mechanics principles. This model employed two internal variables to describe frictional sliding and mortar joint damage. The constitutive equations of this model were formulated to encompass tensile brittle behavior, frictional energy dissipation, and degradation of shear stiffness. Additional cohesive interface models that integrate both damage and friction were to facilitate the analysis of masonry panels.

Frequent methods have been devised, relying on the concept of inflexible blocks relating through nonlinear springs [29]. And introduced a masonry model based on the applied element method. While sharing the fundamental principle with the rigid body spring model (RBSM) originally suggested where the actual characteristics of masonry aren't factored [29]. Conducted an analysis of the in-plane cyclic behavior of masonry walls at a granular level, considering each block individually.

Many of the discussed numerical approaches have primarily concentrated on replicating 2D structures, which limits their applicability to real-world constructions. To overcome this constraint, several 3D models have been devised and handle actual buildings. Specifically designed for 3D masonry structures, two main interface elements have been introduced.

On one hand, an enhanced version of the multisource interface model initially developed by Lourenco in 1997 has been adapted for three-dimensional problems, taking into account geometrical nonlinearity as well. Another approach, introduced and employs a corotational method that allows for the formulation of symmetrical nonlinearity at a discrete level. This modeling approach has found extensive use in masonry structure applications and has incorporated partitioning strategies to enhance computational efficiency. Furthermore, this model has been expanded to analyze the cyclic behavior of masonry structures using a damage-plasticity framework.

On the other hand, Aref and Dolatshahi (2013) introduced an alternative interface model paired with elastoplastic block behavior to conduct cyclic analysis of 3D masonry walls, particularly utilizing solvers. This interface model has been broadly utilized to explore diverse aspects of the mechanical performance of masonry panels.

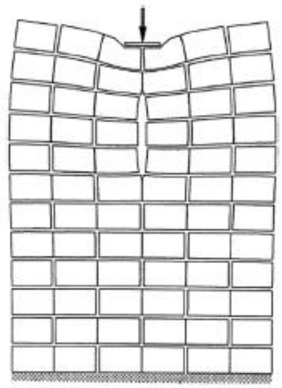


Fig 2.27: Interface element-based approaches

2. Contact-based approaches

Block-Based Models (BBMs) for masonry structures frequently employ contact mechanics. These models often utilize frictional contact laws to depict the interactions among blocks, which may vary in terms of rigidity, deformability, linearity, or nonlinearity. While various custom solutions have been introduced and verified three main categories of contact-based approaches can be distinguished [30].

- Firstly, the Discontinuous Deformation Analysis financial statement for the deformability of blocks using contained integration approach. It assumes the absence of tensile stress between blocks and prevents blocks from penetrating each other. At all contact points, a Coulomb's frictional law is applied.
- Secondly, a distinct group of models is based on the NSCD method, which was developed by Jean in 1999. This method employs a straightforward nonsmoothed contact implicit formulation and takes into account energy dissipation during block impacts. While it has been effectively employed in various full-scale cases, it appears to have limitations when applied to dry stone masonry structures since it does not consider cohesive responses in mortar layers.

3. Textured continuum-based approaches

The core principle of textured continuum-based models, as introduced by Page (1978), revolves around independently modeling blocks and mortar layers. This is achieved using nonlinear finite elements for each component, and notably, these components are modeled without any physical interface connecting them.

An early example of this strategy can be observed in Figure 1.9 (Ali and Page, 1988), where there is a clear distinction between elements representing blocks and those representing mortar (more precisely, mortar joints). In this approach, a smeared crack model was utilized to simulate cracking within both the blocks and the mortar layers [32].

Recently, a textured continuum-based model has been introduced, as described in Petracca et al. (2017b), which utilizes continuum elements to discretize both the blocks and mortar layers. This model incorporates a damage model for tension and compression.

A highly innovative method for accurately simulating the nonlinear mechanical behavior of mortar layers has been presented in 2017. This novel approach introduces an interphase formulation founded on a multiplane cohesive zone model. As outlined, a multiscale numerical strategy has been employed to characterize the constitutive relationship of mortar joints. This approach facilitates a systematic and replicable adjustment of mortar joint properties [33].

1. Block-based limit analysis approaches

Block-based limit analysis methods are computational techniques used in structural engineering for evaluating the safety and stability of structures subjected to various loading conditions. These approaches prove particularly useful in analyzing structures with intricate geometries and diverse material properties. The core principle underlying block-based limit analysis involves dividing a structure into rigid blocks and examining the equilibrium and compatibility conditions at the interfaces between these blocks to identify critical loads or failure mechanisms.

Structures are discretized into rigid blocks, simplifying the analysis by assuming each block behaves as a single entity without internal deformation. The focus then shifts to examining the interaction between blocks to assess the overall stability of the structure.

Another block-based limit analysis approach was introduced. In this method, they tackled the problem of determining the incorporate no associative friction and tensionless contact interfaces. They achieved this by employing a mathematical program with equilibrium constraints to find the solutions.

This approach was later enhanced by Portioli to accommodate 3D structures and optimized this method using cone programming techniques.

In contrast, A significant advantage of block-based limit analysis is its ability to handle complex geometries and material nonlinearity efficiently. It provides a rational and effective means of evaluating structure safety without resorting to extensive and time-consuming numerical simulations [35]. This computational approach also incorporates considerations for mortar joint cohesion and masonry crushing. Further applications of this model can be found. Its utilization within homogenization measures will be deliberated in the subsequent section.

While these mathematical methods have been successfully applied to evaluate real-world structures, such as masonry bonds in Gambarotta (2006), it's worth noting that they can demand a relatively significant computational effort.

2. Extended finite element approaches

It stands out as an innovative numerical technique in computational mechanics and engineering, expanding the capabilities of the traditional Finite Element Method (FEM). XFEM was developed to tackle challenges posed by problems involving intricate geometries, discontinuities, and evolving cracks or fractures, which are traditionally difficult for standard FEM. Even though only two solutions have been highlighted thus far, these numerical approaches hold significant potential as robust options for conducting accurate analyses of masonry buildings. Their incorporation of XFEM and cohesive behavior models can enhance the fidelity of simulations in capturing the complex mechanical behavior of masonry structures [36].

2.27 Continuum models

In Continuum Models (CMs), utilized to represent masonry. Unlike block-based models, these models do not require the mesh to explicitly represent individual masonry blocks. Consequently, the lattice extent, leading to reduced computational demands compared to block-based approaches.

Constitutive laws for masonry can be developed through two main approaches. The first approach involves direct methods where these laws are formulated based on experimental tests. The second approach utilizes homogenization actions and multiscale approaches [38].

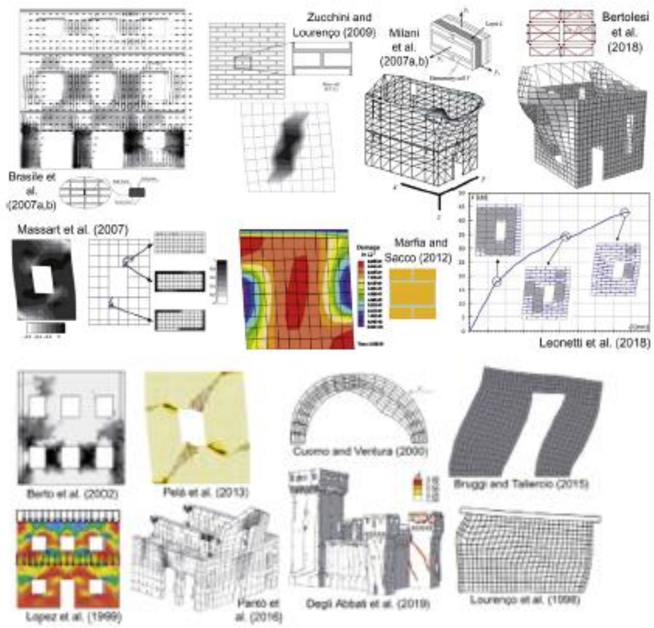


Fig 2.28: Examples of Continuum models

1. Direct approaches

Within direct Continuum Models (CMs), the comprehensive mechanical characteristics of masonry are estimated through the application of continuum constitutive laws. These laws can be derived from experimental tests or other relevant data sources, including investigative asset domains obtained from experiments, obviating the necessity for homogenization processes reliant on Representative Volume Elements (RVEs).

A subset of direct approaches embraces a fundamental concept referred to as the "perfectly no-tension material" hypothesis. According to this hypothesis, masonry is characterized as an isotropic continuum that lacks the capacity to withstand tensile stresses but exhibits linear-elastic behavior in other respects [39]. This simplification is frequently employed as an initial step in preliminary analyses, primarily owing to the inherent difficulties associated with accurately characterizing the tensile behavior of masonry (Maier and Nappi, 1990).

Several variations of the perfectly no-tension material concept have been suggested. Maier and Nappi (1990) introduced a piecewise-linear definition, while a finite element (FE) approach grounded in the complementary energy theorem. Alternative FE simulation methods for no-tension bodies were put forth. In more recent developments, established a framework for FE analysis of no-tension structures through topology optimization achieved a compression-only state of stress by curtailing possible energy [40].

Despite the claim of these non tension approaches to practical case studies, their applicability is not without challenges. Notably, their adaptation to 3D structures has only recently been explored (Bruggi and Taliercio, 2018). Moreover, these methodologies face limitations in capturing the post-peak response of masonry structures, thereby constraining their utility in seismic assessments.

Alternative direct continuum approaches utilize nonlinear constitutive laws rooted in rupture as well as plasticity. Messy crack, plastic, damage, and plastic-damage models have been proposed for the geometric imitation of concrete members and have expanded extensive acceptance in the investigation of masonry structures (Toti et al., 2015). These models exhibit robust performance, are integrated into commercial software packages, and necessitate only a limited set of mechanical properties as input. Isotropic messy crack, damage, and plastic-damage models have proven successful in the analysis of historic monumental masonry buildings, including towers, churches, palaces, and bridges, particularly in 3D models where intricate geometries are involved [41].

Nevertheless, the use of damage models requires the regularization of fracture energy to maintain consistency and reliability. In cases of coarse discretization, incorrect outcomes may arise regarding crack patterns and stress distribution. In response to this challenge, solutions involving crack tracking have been introduced, ensuring mesh-bias independence and dependable crack propagation, especially for quasibrittleness materials. Additionally, orthotropic constitutive laws have been suggested to overcome the limitations of isotropic models, particularly in addressing periodic masonry structures.

To address anisotropy in masonry structures, various models have been developed. Loure´nc¸o et al. (1997) introduced orthotropic softening plasticity models, while Lopez presented fictitious isotropic spaces. Berto et al. (2002) contributed an orthotropic damage model specifically designed for cyclic analysis of in-plane loaded masonry. Additionally, Pel´a et al. (2011, 2013) proposed an orthotropic damage model for masonry walls, utilizing mapped tensors and accounting for unilateral effects.

Although the direct continuum anisotropic models discussed possess scientific merit, their practical application in real-world scenarios is challenging. This challenge stems from the high computational demands associated with these models and the extensive array of mechanical properties required for their setup.

Other methodologies within the realm of Continuum Models (CMs) include numerical cracking analysis employing the strong discontinuity approach finite element (FE) limit analysis utilizing averaged material properties and spring-based solutions. Although these approaches may not strictly adhere to a traditional continuum definition, they are classified as CMs because they emulate continuum-like behavior, where nonlinearities are concentrated in interfaces or springs rather than being explicitly defined block-by-block.

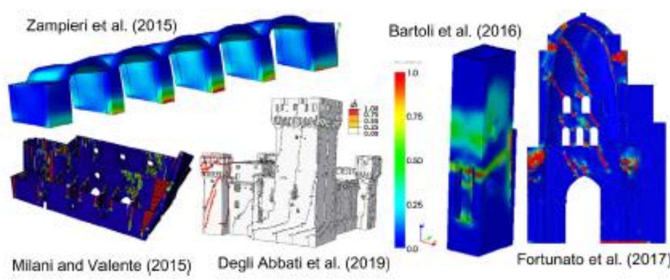


Fig 2.29: Example of direct continuum approaches

2. Homogenization procedures and multiscale approaches

The constituent connection for the operational-measure model can be formulated using homogenization procedures relying on Representative Volume Elements (RVEs). The creation of a suitable RVE is paramount, requiring accurate representation of the heterogeneity inherent in the studied masonry. Various configurations of Volume Elements have been suggested to account for masonry textures [42].

Continuum Models (CMs) comprise a diverse set of models employing homogenization trials and multiscale methods to deduce the constitutive law governing masonry. Three primary categories of models can be identified:

A priori homogenization approaches typically entail two steps. The initial step involves RVE-based a priori homogenization to establish material properties at the structural scale. Subsequently, in the second step, these homogenized properties are integrated into the structural-scale model.

Multiscale approaches conducted in a step-by-step fashion calculate the global structural response incrementally by addressing a boundary value problem on the Representative Volume Element (RVE). The material behavior is approximated step by step within the RVE, and the resulting constitutive relations are then employed in the operational-measure model [43]. Given the effective capture of masonry heterogeneity within the RVE, there is no requirement to incorporate the material substructure into the structural-scale model.

Adaptive multiscale approaches establish a resilient connection between the basic and substantial scales by adaptively integrating the material-scale model into the structural-scale model. This approach provides a flexible means of combining the two scales to attain accurate results.

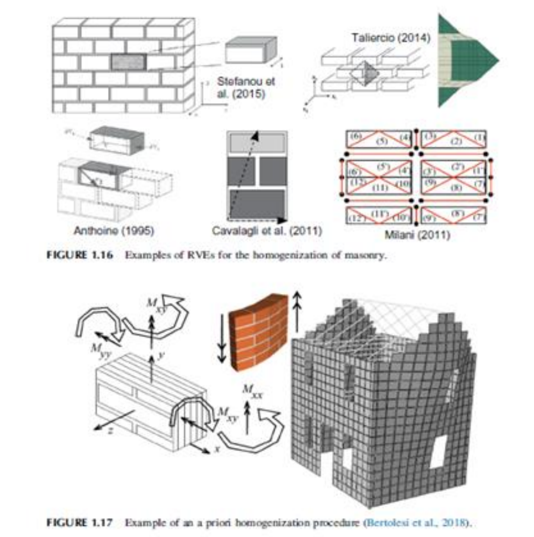


Fig 2.30: Homogenization procedures and multiscale approaches

2.28 Macro element models

Macroscopic Models (MMs) depict structures as configurations of panel-scale structural elements called macroelements. These elements demonstrate generally, MMs are composed of two primary. In contrast straight segments located between two vertically aligned openings, aiding in the interaction between adjacent piers when exposed to horizontal loads.

The main goal of these numerical methodologies is to assess the overall seismic presentation of masonry building [44]. In Macroscopic Models (MMs), the assumption is commonly made that no local failure modes are triggered, especially those related to out-of-plane failures.

In Macroscopic Models (MMs), the identification of piers and spandrels typically relies on damage assessments carried out in earthquake-affected regions. Observations of damage subsequent to seismic events reveal that cracks and structural deterioration often occur in piers and spandrels. Identifying these elements in a masonry building is generally straightforward for facades with evenly distributed openings. However, the task of identifying piers and spandrels becomes more challenging for constructions with erratically agreed starts. The conceptualization of structures into piers and spandrels is essentially impractical for significant constructions characterized by complex geometries.

Macroscopic Models (MMs) stand as the most widely employed numerical strategies and are also preferred by practitioners due to their advantages, including low computational requirements, straightforward model, and uncomplicated description of mechanical properties, contributing to their extensive use. However, MMs also exhibit some limitations. For instance, they frequently assume the absence of local failure modes, potentially leading to overly conservative valuations of the seismic recital of masonry constructions. This is because out-of-plane damage can impact in-plane damage and the other way around. Additionally, MMs may not precisely consider structural details such as the interlocking between vertical boards [45].

While the mainstream of Macroscopic Models (MMs) aligns with equivalent beam-based models (Siano et al., 2018), recent innovations have brought forth spring-based solutions as well. Equivalent beam-based models enjoy extensive usage owing to their advantageous features, such as low computational requirements, straightforward model discretization, and simplified definition of mechanical properties.

1. Equivalent beam-based approaches

Equivalent beam-based approaches are utilized in structural engineering to simplify the analysis of intricate structures by approximating them with equivalent beam elements. This method proves beneficial when dealing with irregular or complex structural systems, offering a more efficient means of modeling and analyzing their behavior [46].

Liberatore (2015) A force-based finite element beam model was developed, consisting of a central linear elastic element, two flexural hinges, and a shear link with an elastic-perfectly plastic response, calculated using a predictor-corrector approach. He proposed a 2D inelastic beam element with concentrated plasticity, employing a bilinear law with strength and stiffness degradation cutoff in the nonlinear range [48].

In recent developments, Raka et al. (2015) introduced an advanced equivalent beam-based macro element designed for nonlinear simulations of masonry structures. The mechanical description of the beam encompassed axile, winding, and shear deformations were grounded. Notably, a fiber-based model were employed to accurately represent the axile and winding responses of the beam [49].

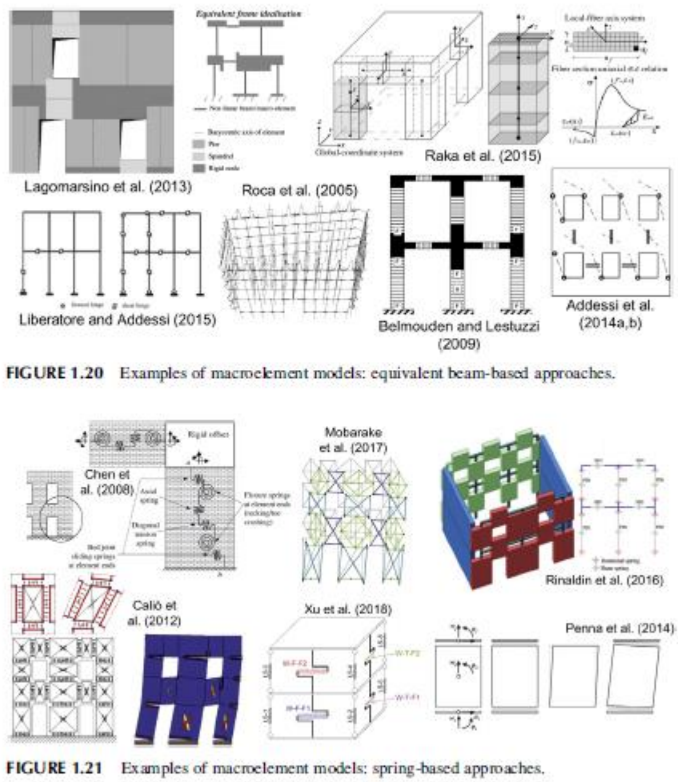


Fig 2.31: Equivalent beam-based approaches

2. Spring-based approaches

Spring-based approaches in masonry elements pertain to numerical modeling methods that utilize spring elements to simulate the mechanical behavior of masonry structures. These techniques are commonly employed in structural analysis to provide a simplified representation of the complex behavior exhibited by masonry components such as walls and arches. The use of springs facilitates an efficient computational approach for the analysis and design of these structures [50].

Gambarotta and Brencich (1998) Springs within masonry-based models can be categorized as linear or nonlinear, depending on the desired level of precision in replicating the material behavior. Linear springs offer simplicity, while nonlinear springs can capture more intricate phenomena such as material yielding and inelastic deformations [51].

Calio et al. (2012) Spring-based approaches can be applied at both macroscopic and microscopic scales. Macroscopic modeling considers the overall behavior of masonry elements, whereas microscopic modeling delves into the detailed interactions at the level of individual bricks and mortar.

Rinaldin et al. (2016) found frequent application in the seismic analysis of masonry structures. They enable the simulation of the dynamic response of the structure to earthquake loads, aiding engineers in assessing seismic vulnerability and designing retrofitting measures.

Mobarake et al. (2017) introduced a fundamental board section composed of six sub-elements, where each pier, spandrel, and node were represented by a chief pane element. The model proposed proved to be effective in simulating the nonlinear static and dynamic behavior of in-plane loaded masonry facades [52].

2.29 Geometry-based models

Geometry-based models (GBMs) conceptualize the masonry structure as a rigid body. These numerical strategies primarily depend on the geometry of the construction and the functional heaps as their main inputs. The goal of geometry-based approaches is to analyze organizational symmetry and potential downfall using static theorem limit analysis-based solutions. Within the framework of GBMs, various innovative solutions have been developed, often based on Heyman's rigid no-tension hypothesis. [53].

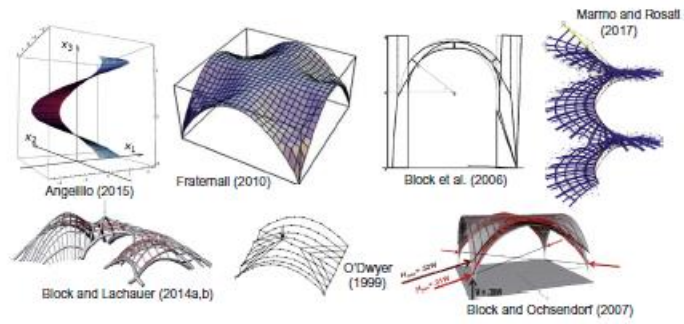


Fig 2.32: Example of geometric based model

Akbas et. al 2013 In study investigated Engineered Cementitious Composites (ECCs) as a distinct subset within high-performance fiber-reinforced cementitious composites, renowned for their exceptional ability to withstand tensile strain-hardening. ECCs display remarkable tensile strain capacity and demonstrate a tendency for multiple microcracks with self-regulated narrow crack widths. Recognizing the importance of ECCs' tensile behavior, researchers developed a hierarchical multiscale modeling approach to comprehensively characterize their mechanical performance under both static and fatigue tensile loading conditions. A specific analytical model was devised to analyze crack bridging in short fiber-reinforced cementitious composites like ECCs, highlighting a unique mechanical trait observed at the microscale and lower mesoscale levels. This analytical model accurately predicts the relationship between crack bridging stress and crack opening displacement. Additionally, a RVE model was introduced to simulate the collective response of the uncracked matrix and multiple cracks within ECCs at the upper mesoscale. The RVE model considers the inherent material variability present in ECCs. In this research, the RVE model underwent analysis using an innovative hybrid approach that combines the Cohesive Zone Model (CZM) with the XFEM. This hybrid CZM-XFEM method enables adaptive simulation of multiple cracks and efficiently describes crack cohesive behavior, drawing insights from the crack bridging analysis conducted at the microscale and lower mesoscale [54].

Bordas, Nguyen [55] introduced and demonstrated a comprehensive framework for an object-oriented finite element code enriched with features tailored for XFEM computations. The programming environment offers a robust toolkit for XFEM tasks and embraces a modular and expandable structure. The program's design prioritizes essential qualities such as modularity, extensibility, and robustness. To accommodate interactions between the mesh and geometry, especially in cases involving numerous enrichment items, the code includes a mesh generator and mesh database.

Blasi, De Luca [20] The aim of the present investigation is to devise a hybrid approach that takes into account the influence of concrete cracking on the hysteretic response of reinforced concrete (RC) frames. This approach combines the mechanical performance of concrete based on the smeared cracking approach with the incorporation of discrete cracking surfaces within the geometric model. The behavior of discrete cracking surfaces at the interface is defined by a blend of contact and cohesive elements. This innovative methodology has been incorporated into the ABAQUS software to replicate an experimental test carried out on a double cantilever column, serving as the foundation for fine-tuning the numerical model. Notably, the research replicates a test performed on an RC portal, representing the initial attempt at numerically modeling this particular scenario. To assess the dependability of the proposed model in reproducing the energy dissipation capabilities of RC members under lateral cyclic loading, the numerical outcomes are juxtaposed with experimental data. This comparison involves analyzing the hysteretic force-displacement behavior and cumulative dissipated energy. The hybrid modeling approach presented in this study provides an accurate representation of stress distribution and demonstrates a reasonably satisfying alignment with the hysteretic behavior. Importantly, it achieves this without imposing an excessive computational burden. Finite element (FE) analysis is a commonly used technique in earthquake engineering, especially for handling systems characterized by a large number of degrees of freedom (DOF) that represent the structural layout of buildings.

Challenges related to achieving convergence are encountered, and the paper offers some plausible explanations for the unsatisfactory convergence behavior.

Moës and Belytschko [56] studied the Extended Finite Element Method (XFEM) enables the modeling of displacement discontinuities that do not align with interelement surfaces. This methodology is particularly useful for simulating the expansion of non-conforming cohesive cracks. The advancement of the cohesive zone within the crack is determined by ensuring that the stress intensity factors at the cohesive zone's tip become zero. This approach, based on energy considerations, eliminates the need for evaluating stresses at the theoretical crack tip. To illustrate the effectiveness of this planned tactic, imitations of unified crack growth in concrete are conducted.

CHAPTER 3

METHODOLOGY

3.1 Overview

In the experimental phase of the research, several tests were conducted on bricks and mortars in the laboratory to assess their mechanical properties. The following is an organized and detailed description of the experimental work:

3.2 Objective

Bricks underwent compression testing using a dedicated compression testing machine

- The objective of this test was to assess the compressive strength of the bricks
- The bricks were incrementally loaded until failure, during which the relevant load-displacement data was recorded

3.3 Tests conducted

The research was conducted in the structures Lab at the National University of Science and Technology's (NUST) Civil Engineering Department (NICE). Islamabad.

3.4 Split Tensile Test of Bricks

Utilizing the same compression testing machine, the tensile strength of the bricks was determined using a split tensile test.

- A cylindrical brick sample was positioned horizontally between the compression plates, and an axial compressive force was applied until the specimen underwent fracture
- This test yielded insights into the tensile strength and cracking characteristics of the bricks

3.5 Compression and Tension Testing of Mortar

- Mortar samples were examined to evaluate their mechanical attributes in both compression and tension via flexural loading tests
- The mortar specimens were meticulously crafted to meet the specified dimensions and subsequently subjected to suitable curing procedures
- During the compression test, the mortar specimens underwent progressive compressive loading until they reached the point of failure
- In the tension test, the mortar specimens were subjected to flexural loading to ascertain their tensile strength and deformation characteristics

3.6 Mortar Interface Strength Tests

Two tests were performed to evaluate the strength of the mortar interfaces.

3.6.1 Bond Wrench Test

- Due to the absence of specialized equipment in the laboratory, a custom apparatus was ingeniously devised to carry out the bond wrench test
- This test evaluated the adhesive strength between the mortar and its adjacent materials

3.6.2 Triplet Shear Test

- An additional custom apparatus was fabricated to execute the triplet shear test, given the lack of available equipment in the laboratory

- The aim of this test was to quantify the initial shear strength of the mortar interface

3.7 Construction of Brick Wallets

- A total of six brick panels were erected, with each panel having dimensions of 4 feet by 4 feet
- Out of the six panels, five were assembled using fly ash bricks, while one was fabricated utilizing red bricks, serving as a control specimen
- The rationale behind constructing these panels was to analyze the performance of fly ash brick masonry retrofitted with PP bands and to juxtapose it with the behavior of conventional fly ash and red brick samples

3.8 Retrofitting with PP Bands

- Among the six brick panels, four of them, which were composed of fly ash bricks, underwent retrofitting with PP bands
- The purpose of using PP bands was to augment the lateral confinement of the brick masonry, particularly during seismic activity
- The objective was to assess and quantify the disparity in behavior between the fly ash brick masonry retrofitted with PP bands and the conventional fly ash and red brick samples

3.9 Stress-Strain Analysis

- Throughout the experimental testing, stress-strain curves were generated for both bricks and mortars during compression
- These graphs yielded invaluable insights into the mechanical reactions, stiffness, and deformation traits of the materials under examination

In essence, the experimental endeavors encompassed testing the compression and tensile strength of both bricks and mortars, while also encompassing an assessment of the bond strength and shear strength of mortar interfaces. Furthermore, the creation of brick panels and the subsequent retrofitting using PP bands facilitated an examination of their response during seismic scenarios. The stress-strain curves derived from these tests furnished crucial data for subsequent analysis and comparison with numerical simulations.

Subsequent to the culmination of the experimental phase and the acquisition of the intended material characteristics, the subsequent phase of the research involves the formulation of a software model employing Abaqus. The primary objective of the model is to simulate and analyze the performance of the examined materials, with a specific emphasis on studying the initiation and propagation of cracks within the mortar layer. The following provides an organized and detailed description of this phase:

3.10 Utilizing Material Properties

1. The material properties derived from the experimental assessments of bricks and mortars serve as input parameters for the development of the software model within Abaqus
2. These properties encompass compressive strength, tensile strength, bond strength, shear strength, and other pertinent mechanical attributes of the materials
3. The measured properties play a critical role in achieving precise simulation of the material behavior within the Abaqus model

3.11 Continuous Micro-Modeling with XFEM

- The Abaqus software model employs a continuous micro-modeling approach combined with the Extended Finite Element Method (XFEM)
- Continuous micro-modeling facilitates a comprehensive depiction of material behavior at the microstructural level
- XFEM is employed to capture the inception and advancement of cracks within the mortar layer, thereby augmenting the model's accuracy in contrast to conventional techniques

3.12 Novelty of XFEM in Continuous Micro-Modeling

It's noteworthy to emphasize that the application of XFEM in the context of continuous micro-modeling to investigate the behavior of PP band retrofitted fly ash brick masonry represents a novel and unprecedented endeavor. This inventive fusion of XFEM and continuous micro-modeling provides a distinctive vantage point for comprehending crack initiation and propagation phenomena within the mortar layer.

3.13 Validation of Experimental Results

The established Abaqus model functions as a tool for corroborating the experimental findings derived from the tangible tests. The load-displacement graphs produced through the experimental trials are juxtaposed with the corresponding outcomes acquired through the Abaqus simulations for comparison. This validation procedure guarantees the accuracy and dependability of the software model by evaluating its capability to replicate the observed material behavior in the experiments.

3.14 Load vs Displacement Graphs

The main emphasis of the validation lies in the comparison between the load-displacement graphs originating from the physical experimental tests and those generated by the Abaqus model.

Through an examination of the concordance between the experimental outcomes and the numerical results, it becomes possible to ascertain the dependability and efficacy of the formulated Abaqus model.

In brief, following the completion of laboratory experiments and the acquisition of requisite material properties, the subsequent phase entails the construction of a software model within Abaqus. The model utilizes continuous micro-modeling combined with XFEM to replicate the process of crack initiation and propagation within the mortar layer. This approach holds novelty in the domain of PP band retrofitted fly ash brick masonry. The experimental findings are subsequently authenticated through a comparison of load-displacement graphs derived from the practical tests against those produced by the Abaqus model. This process guarantees the precision and efficiency of the constructed software model.

CHAPTER 4
RESULTS AND DISCUSSION

3.1 Overview

The topic endeavors to explore the efficacy and behavior of retrofitting fly ash brick masonry structures using PP band reinforcement. It employs a sophisticated modeling approach that considers the microstructural characteristics of materials and complex crack propagation using XFEM within the Abaqus software environment. This research contributes to the advancement of retrofitting techniques for masonry structures, particularly those constructed using fly ash bricks, with potential applications in seismic retrofitting and structural strengthening projects.

3.2 Aims

The aim of the research is to investigate and evaluate the effectiveness of retrofitting fly ash brick masonry structures with polypropylene (PP) bands. Specifically, the research aims to assess the structural performance and behavior of these retrofitted structures under various loading conditions, such as seismic events.

Additionally, the study seeks to utilize advanced modeling techniques, including Continuous Micro Modeling with XFEM, to simulate and analyze the behavior of the retrofitted structures at a microstructural level. By employing sophisticated numerical methods, the research aims to provide insights into the mechanisms of crack propagation, deformation, and material interaction within the retrofitted masonry.

The overarching goal is to contribute to the development of more robust and sustainable retrofitting strategies for masonry structures, particularly those constructed using fly ash bricks. This research may have practical implications for enhancing the resilience and safety of existing structures, especially in regions prone to seismic activity or other environmental hazards.

3.3 Brick Wallet Shear Test

The Brick Wallet Shear Test is conducted to assess the shear strength of brick masonry wallettes, small representative portions of masonry walls constructed specifically for testing purposes.

Fig 4.1: Laboratory Test

Fig 4.2: Stepped Cracking of Wallet

3.4 Brick Wallet Compression Test

Fig 4.3: Test Result Controlled Fly Ash Wallet

Fig 4.4: Test Result of 200 mm Spaced Retrofitted Wallet

Fig 4.5: Test Result of 100 mm Spaced Retrofitted wallet

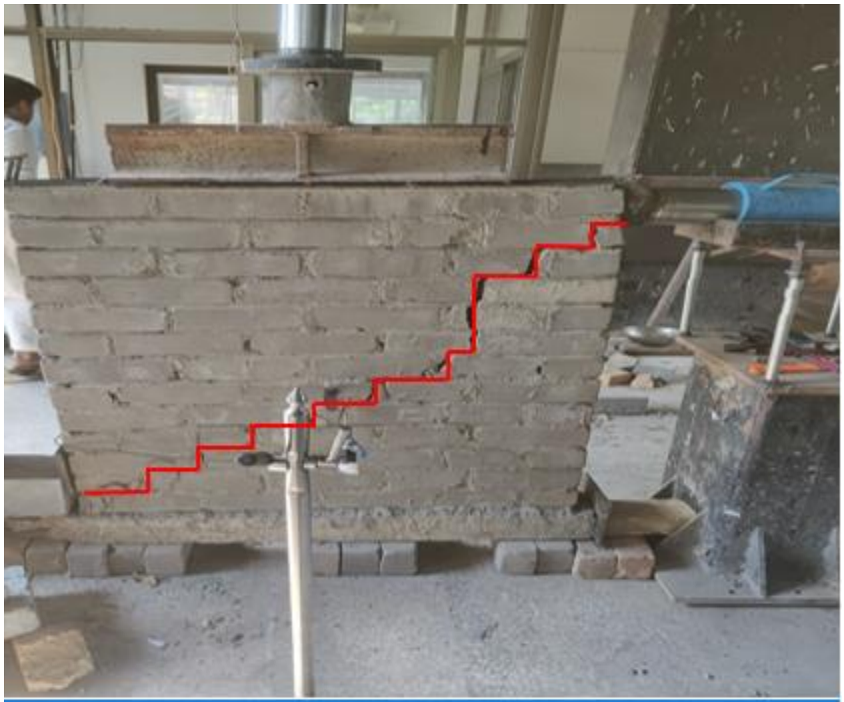


Fig 4.6: Diagonal Stepped Cracking

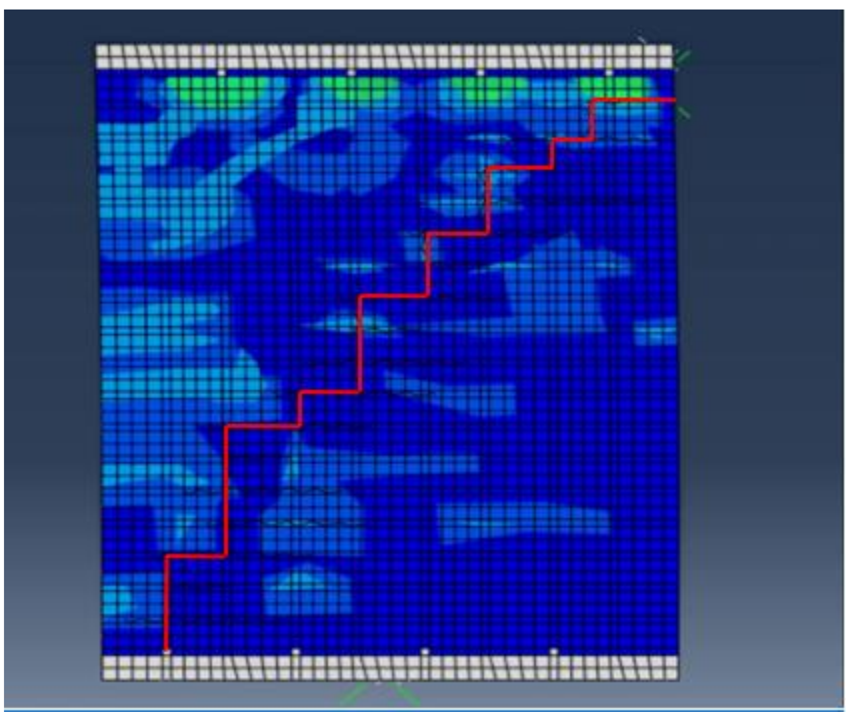
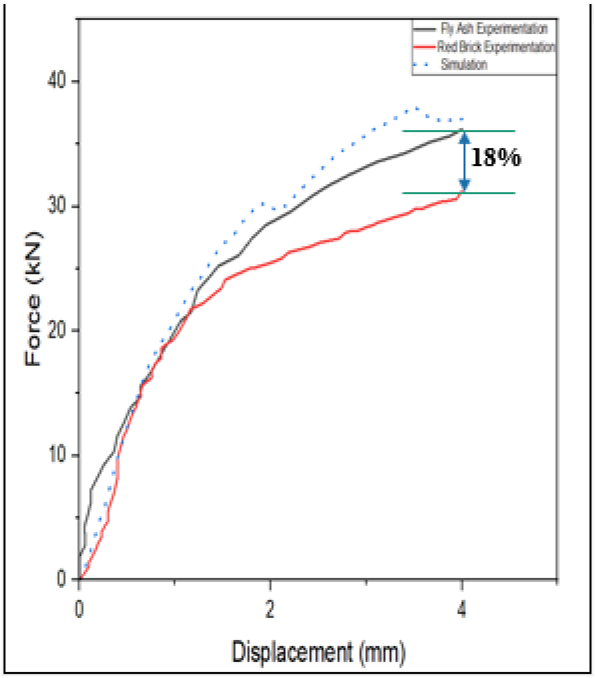


Fig 4.7: Stimulation Result of Fly Ash Brick Wallet



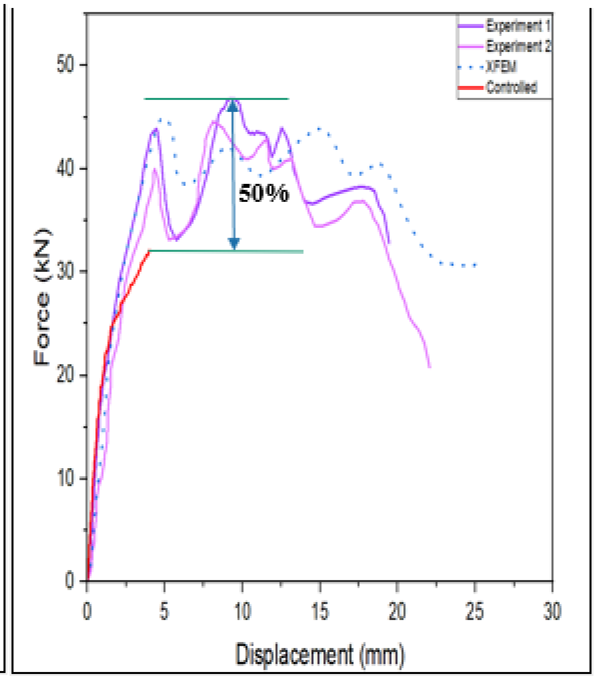


Fig 4.8: Controlled Wallet Graphs

Fig 4.9: 100mm fly ash retrofitted wallet graph

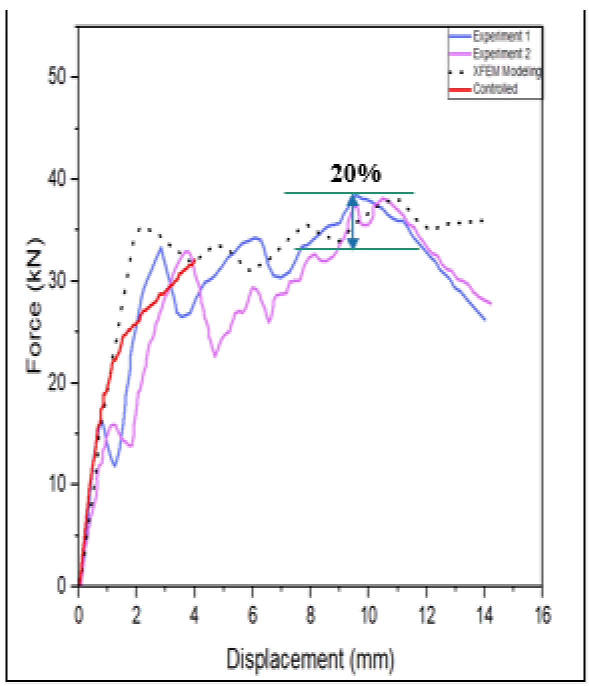


Fig 4.10: 200mm fly ash retrofitted wallets graph

- The peak strength difference between Controlled Red Brick and Fly Ash Wallet is 18% and stimulation result is in close approximation
- The peak strength difference between Controlled Fly Ash Wallet and 100 mm Retrofitted Wallet is 50% and stimulation result is in close approximation
- The peak strength difference between Controlled Fly Ash Wallet and 20 mm retrofitted Wallet is 20% and stimulation result is in close approximation

3.5 Comparison and Modelling Graphical Comparison

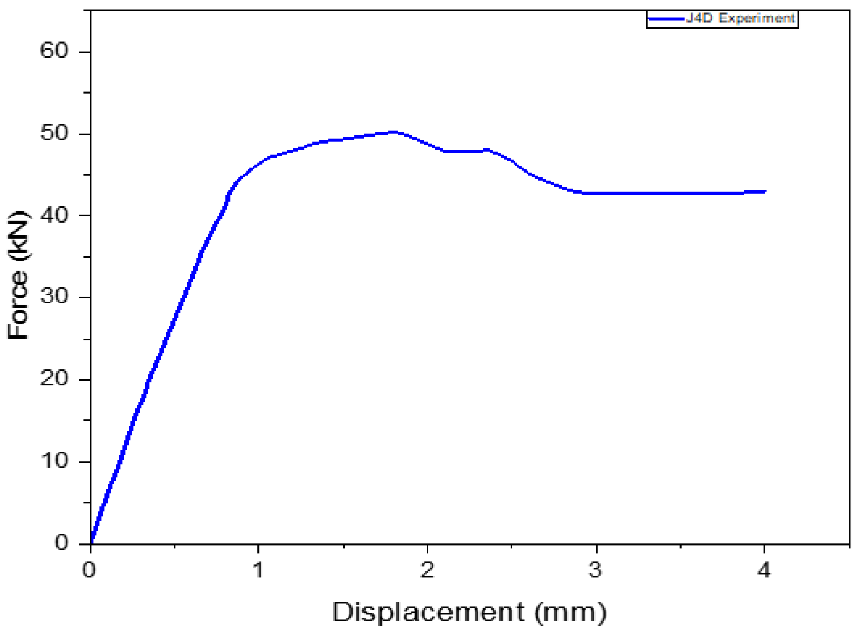


Fig 4.11

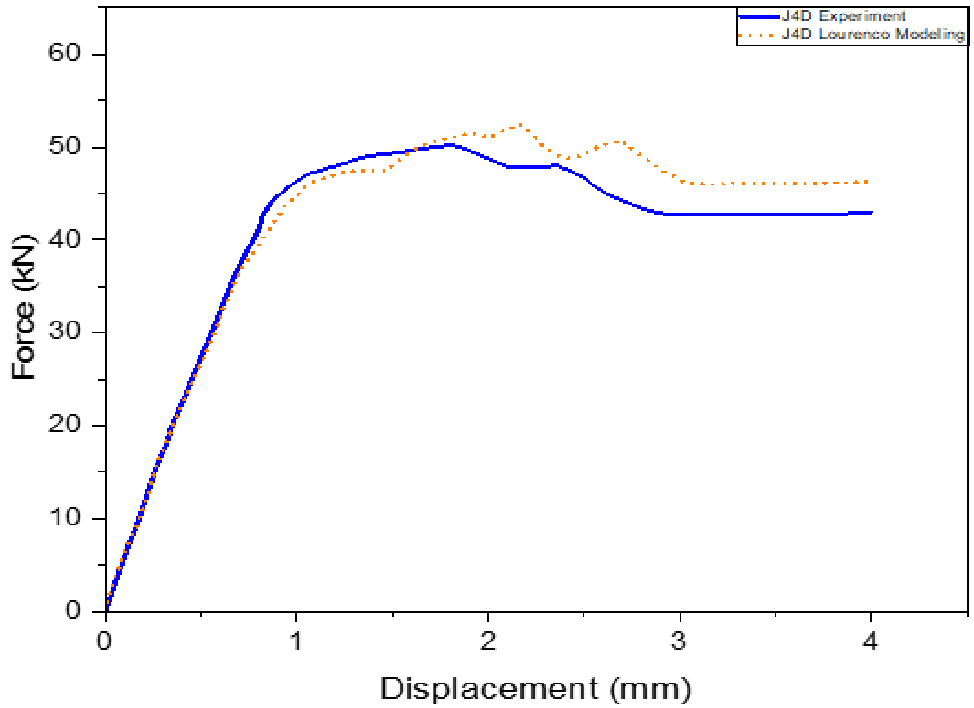

J4D Experiment
J4D Lourenco Modeling
60
50
40
30
20
10
0
Force (kN)
0
1
2
3
4
Displacement (mm)

Fig 4.12

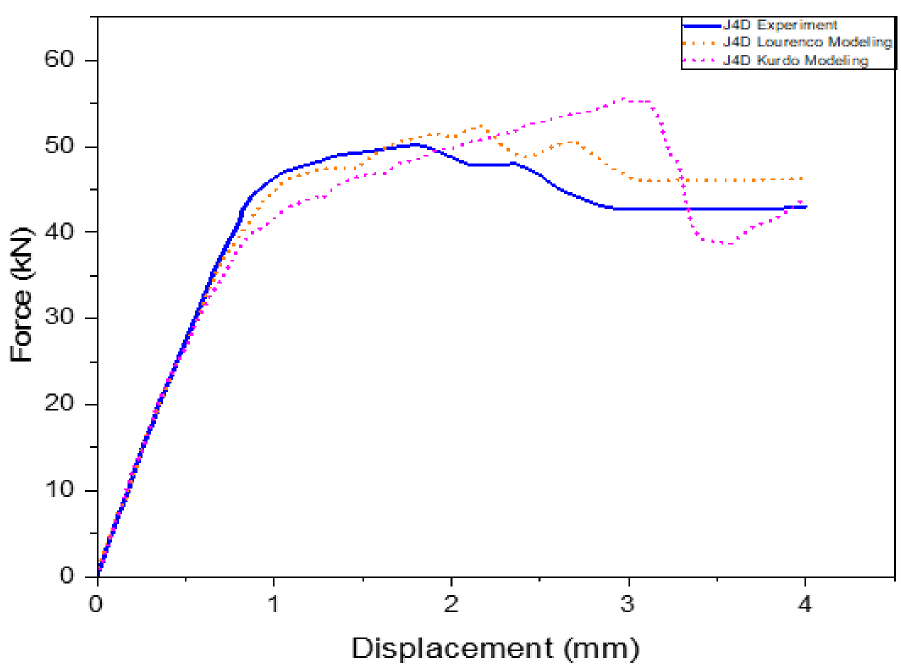

J4D Experiment
J4D Lourenco Modeling
J4D Kurdo Modeling
60
50
40
30
20
10
0
Force (kN)
0
1
2
3
4
Displacement (mm)

Fig 4.13

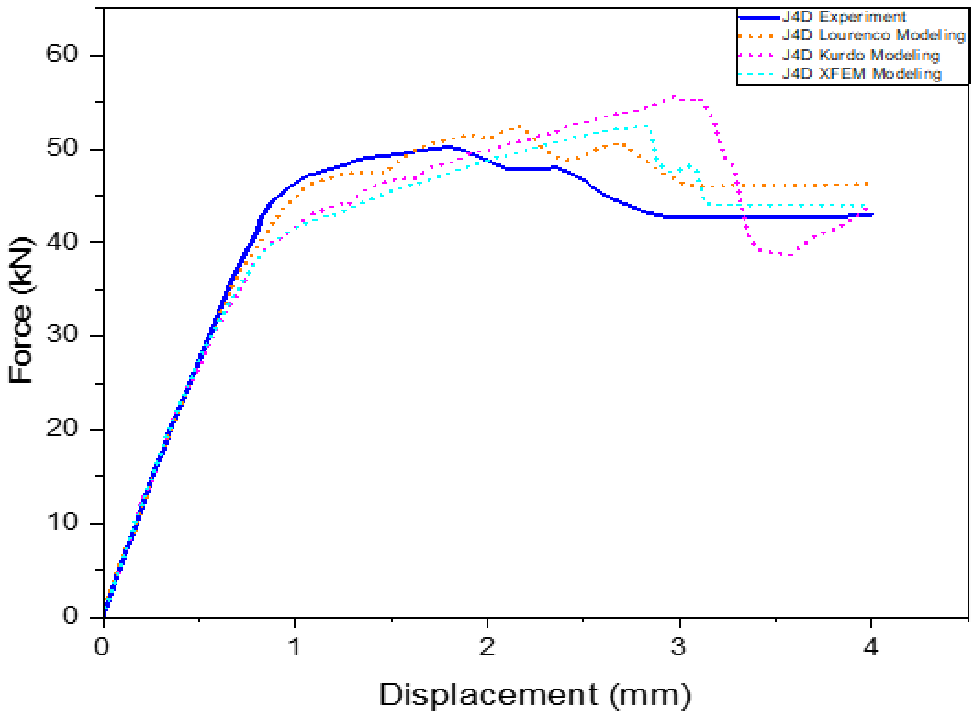


Fig 4.14

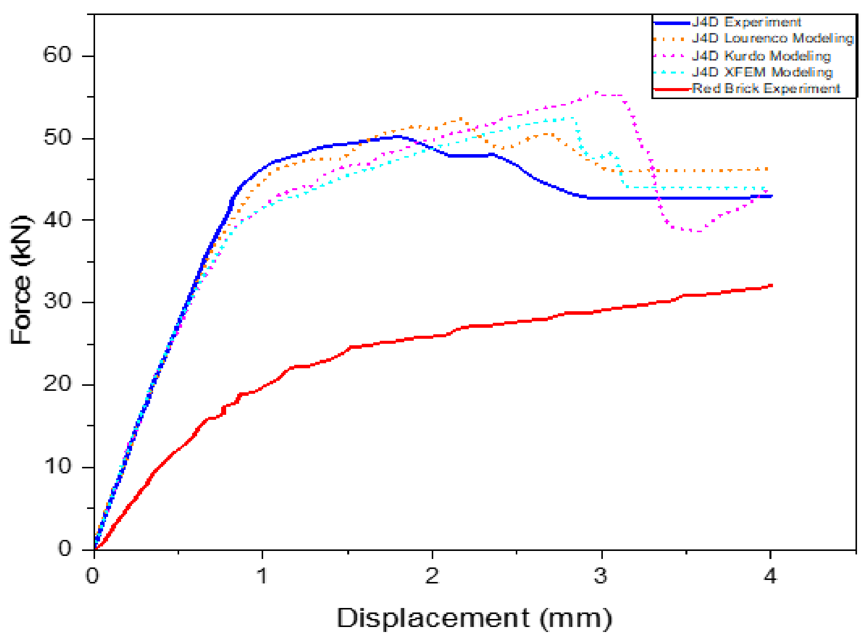


Fig 4.15

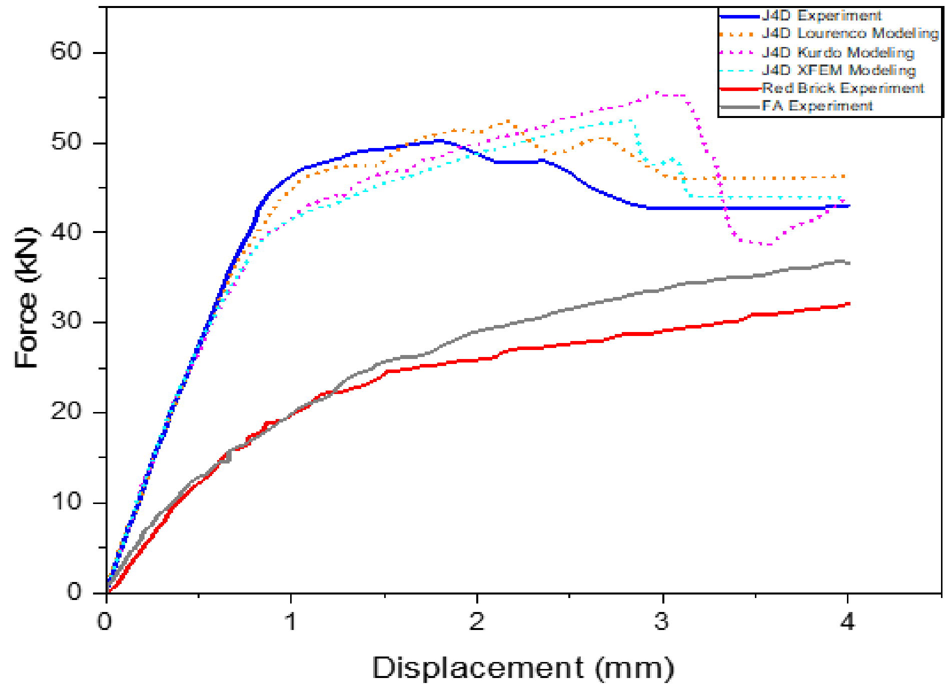


Fig 4.16

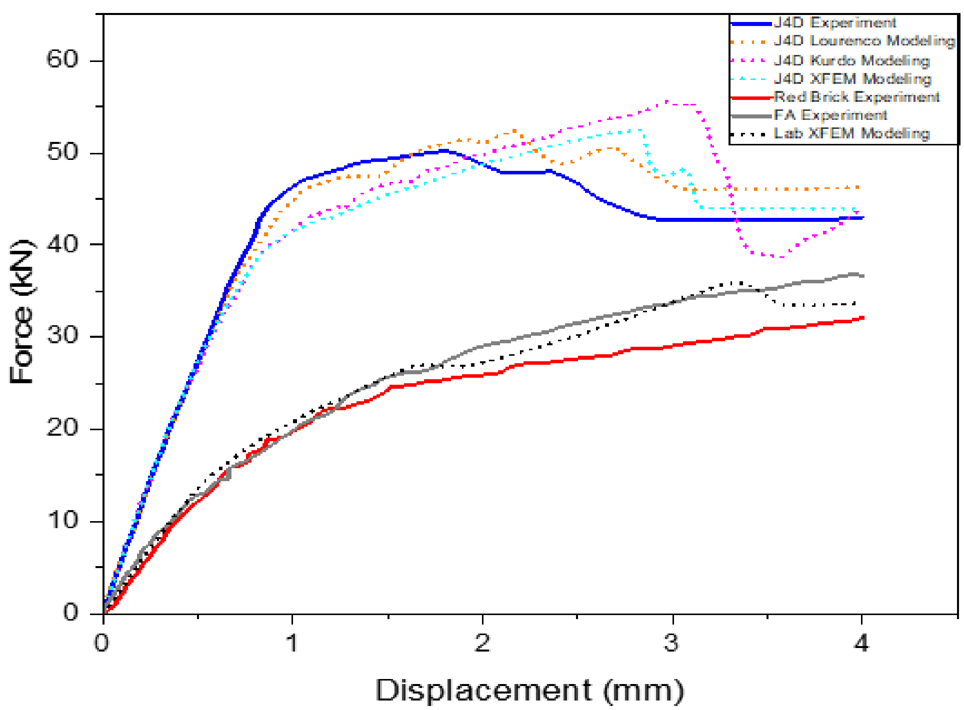


Fig 4.17

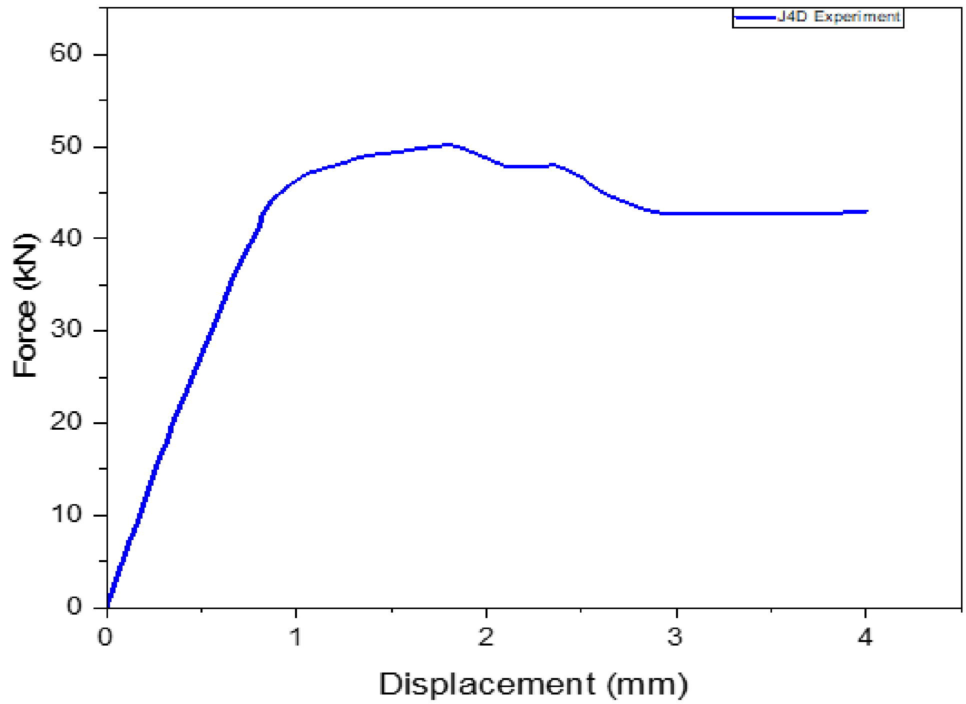


Fig 4.18

Table 4.1: J4D Lourenco Modeling

	% Area Difference
J4D Experiment	
J4D Lourenco Modeling	
(Detailed Micro Modeling)	2.68

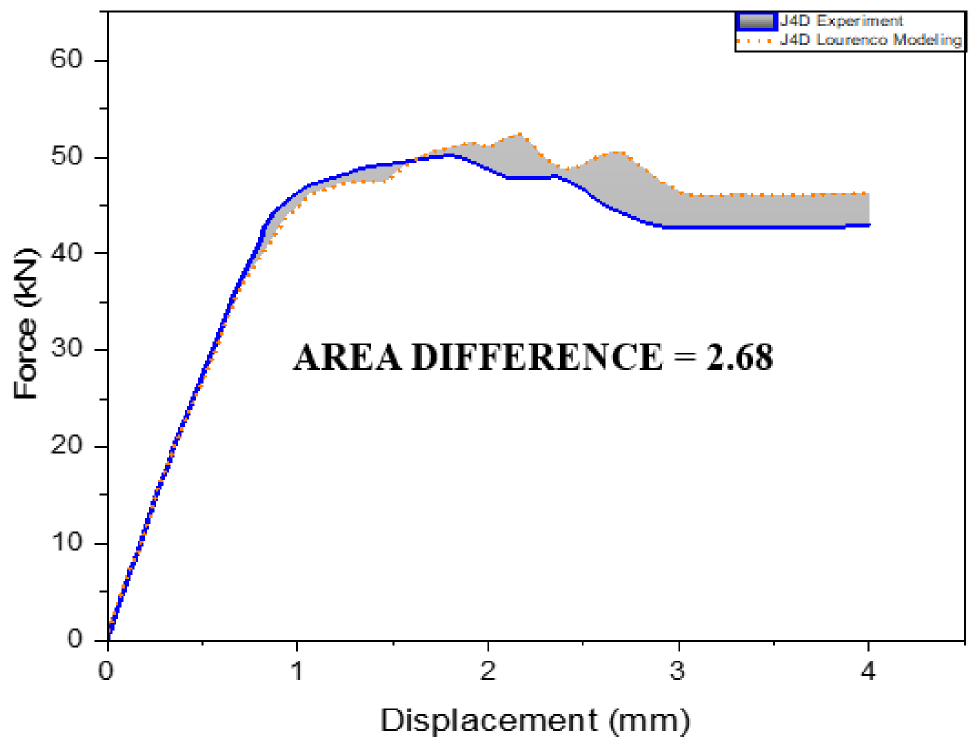


Fig 56

Table 4.2: J4D Kurdo Modeling

	% Area Difference
J4D Experiment	
J4D Kurdo Modeling	
(Simplified Micro Modeling)	5.71

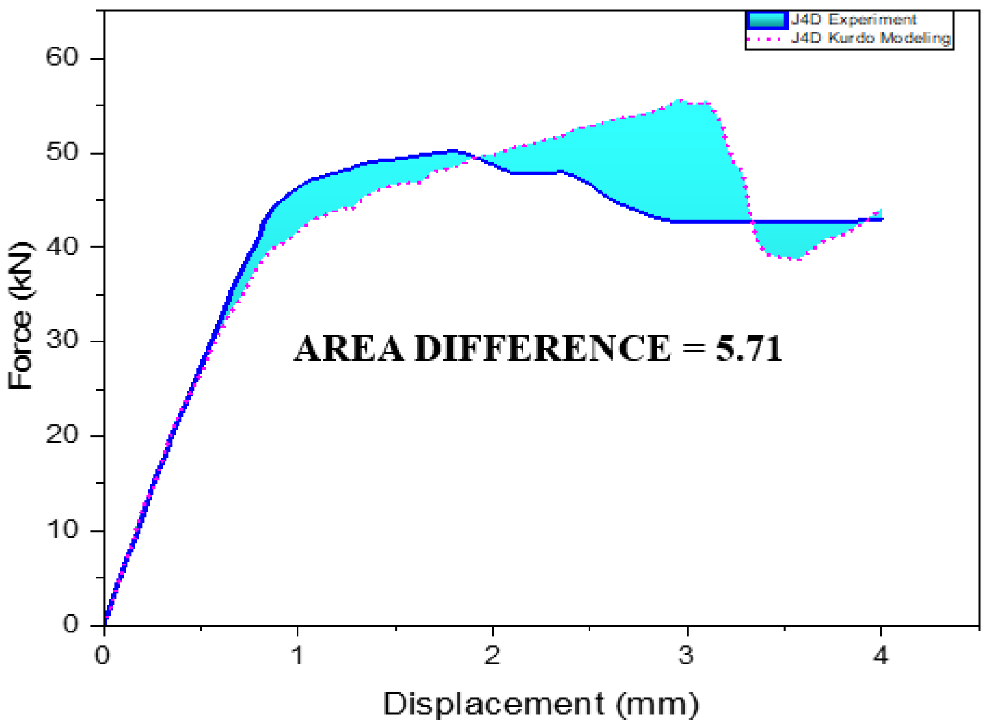


Fig 57

Table 4.3: J4D XFEM Modeling

	% Area Difference
J4D Experiment	
J4D XFEM Modeling	
(Continuous Micro Modeling)	3.19

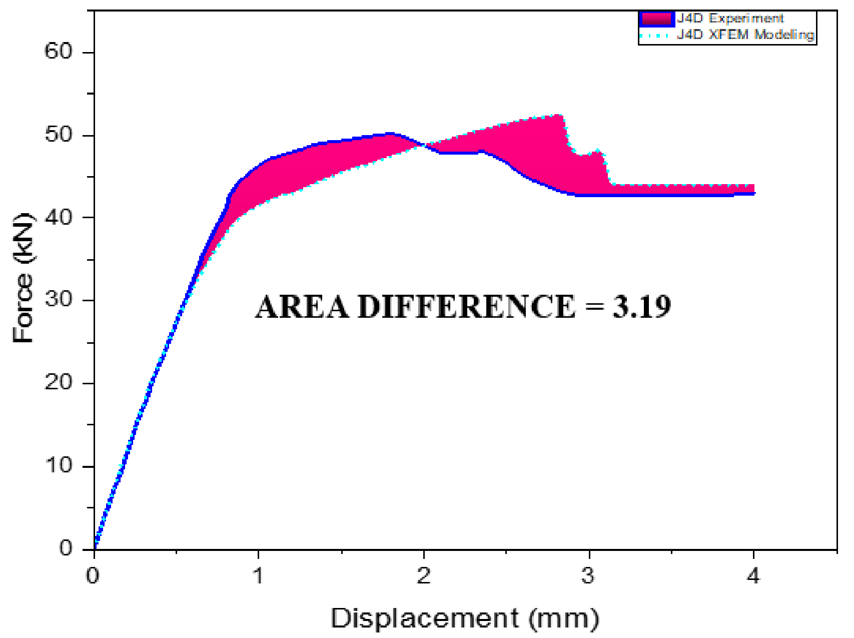


Fig 58

Table 4.4: J4D and Detailed Micro modeling experiments

	% Area Difference	Computational Time
J4D Experiment		
Detailed Micro Modeling	2.68	60 minutes
Simplified Micro Modeling	5.71	15 minutes
Continuous Micro Modeling	3.93	20 minutes

	% Area Difference	% Time Efficiency
Detailed Micro Modeling		
Simplified Micro Modeling	3.03	75
Continuous Micro Modeling	1.25	66.67

Continuous Micro- Modeling is 2 times accurate with only 8 percent loss in time efficiency from Simplified Micro-Modeling

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusive remarks

This research introduces a promising strategy to bolster the seismic resilience and overall structural performance of fly ash brick masonry structures. The integration of polypropylene (PP) bands in the retrofitting process, chosen for their notable tensile strength and durability, represents an innovative solution to address the seismic vulnerability inherent in these environmentally friendly construction materials.

The adoption of the Extended Finite Element Method (XFEM) within the Abaqus software underscores a commitment to advanced numerical modeling, facilitating a meticulous and precise simulation of the structural behavior at the micro-level. This modeling approach is pivotal for comprehending the interaction dynamics between the PP bands and fly ash brick masonry, capturing intricate crack patterns, and analyzing the heterogeneous composition of the materials involved.

The continuous micro modeling methodology, which entails the examination of individual bricks, mortar joints, and interaction zones, contributes to an exhaustive analysis of the retrofitting process. The insights derived from this study not only offer refined strategies for retrofitting fly ash brick masonry structures but also deepen our comprehension of the micro-level mechanics, providing valuable knowledge for future advancements in structural engineering and earthquake-resistant construction practices.

The CMM-XFEM method attains comparable outcomes with reduced computational time, without significantly compromising reliability and precision. Compression tests on wallets reveal that fly ash bricks exhibit 18% greater strength compared to red bricks. The retrofitted fly ash bricks with 100mm spaced polypropylene (PP) bands demonstrate a peak strength that is 50% higher than the controlled fly ash brick wallet. Similarly, the fly ash bricks retrofitted with 200mm spaced PP bands exhibit a strength 20% greater than that observed in the controlled fly ash brick wallet. It is concluded that 100 mm spacing of PP band is better value for retrofitting of brick masonry. The XFEM method accurately anticipates the trajectory of crack initiation and propagation by utilizing quadratic stress damage criteria and critical fracture energy values specific to mortar, as defined in the material properties within Abaqus. The results of Abaqus Modeling were close to the experimental results.

To conclude, the Brick Wallet Shear Test offers crucial insights into the behavior of brick masonry structures when subjected to shear loading. Through analysis of parameters like shear strength, deformation characteristics, and failure modes, this testing method aids in evaluating structural integrity and performance.

Based on the test results, recommendations are proposed to optimize design, enhance construction practices, ensure quality assurance, implement retrofitting strategies, and encourage further research. These recommendations are aimed at fortifying brick masonry structures against shear forces, thereby bolstering their resilience and safety.

In essence, the Brick Wallet Shear Test is instrumental in guiding engineering practices, construction methodologies, and risk mitigation efforts, ultimately contributing to the development of more resilient and durable masonry constructions.

The exploration of "PP Band Retrofitted Fly Ash Brick Masonry Using Continuous Micro Modeling with XFEM in Abaqus" focuses on addressing the seismic vulnerability and overall structural performance of fly ash brick masonry structures. While fly ash bricks are renowned for their environmentally friendly attributes, concerns arise regarding their seismic resistance, particularly in regions prone to earthquakes.

The introduction of PP bands in the retrofitting process represents an inventive strategy to reinforce the masonry structure. Polypropylene materials are selected for their high tensile strength and durability, making them suitable for enhancing the ductility and crack resistance of the masonry system.

The utilization of XFEM in the Abaqus software signals the adoption of a sophisticated numerical modeling technique. XFEM facilitates the representation of intricate crack patterns and material discontinuities, allowing for a more precise simulation of structural behavior under diverse loading conditions. This modeling approach is particularly advantageous for capturing the complexities of the interaction between the PP bands and the fly ash brick masonry at a micro-level.

The continuous micro modeling strategy implies a comprehensive analysis that takes into account the heterogeneous nature of materials and captures local effects within the structure. This may involve studying the behavior of individual bricks, mortar joints, and the interaction zones between the PP bands and the masonry. The objective is to comprehend how these micro-level details influence the overall performance and resilience of the retrofitted structure.

The practical implications of this research could involve the development of optimized retrofitting strategies for fly ash brick masonry structures, contributing to the creation of cost-effective and sustainable solutions for improving their seismic performance. Moreover, insights derived from continuous micro modeling with XFEM may deepen our understanding of the mechanics involved in the retrofitting process, thereby informing future advancements in structural engineering and earthquake-resistant construction practices.

5.2 Future Recommendations

Conduct empirical tests to authenticate the results obtained from the numerical simulations. Physical testing of structures retrofitted with PP bands will provide practical data to validate the precision of the proposed modeling approach.

Undertake parametric studies to explore the impact of various factors such as PP band characteristics, retrofitting arrangements, and material variations. This can offer insights into the sensitivity of the retrofitting strategy and guide the optimization of parameters under different conditions [57].

Extend the research to practical applications by applying the proposed retrofitting method to existing structures. Field studies will enable an assessment of the feasibility, effectiveness, and long-term performance of the PP band retrofitting method in various environmental and structural contexts.

Perform a thorough cost-benefit analysis to assess the economic viability of the proposed retrofitting approach. Compare implementation costs against anticipated benefits in terms of enhanced structural performance, durability, and seismic resilience.

Collaborate with regulatory bodies and standards organizations to incorporate research outcomes into building codes and guidelines. Establish retrofitting protocols based on the study findings, contributing to the development of standardized practices for improving the seismic performance of masonry structures.

Investigate further advancements in numerical modeling techniques beyond XFEM to improve the accuracy and efficiency of simulations. Explore the applicability of other cutting-edge methods or the combination of multiple modeling approaches for a more holistic understanding of structural behavior [58].

Encourage collaboration with researchers and professionals globally to leverage diverse perspectives and experiences. Foster knowledge exchange and joint projects to advance seismic retrofitting for masonry structures using innovative materials and modeling techniques.

Formulate guidelines for the monitoring and maintenance of retrofitted structures over time. Establish protocols for regular inspections, performance evaluations, and necessary maintenance measures to ensure the prolonged effectiveness of the retrofitting solution.

Issues related to convergence and propagation of cracks may be resolved.

REFERENCES

1. Halabian, A.M., L. Mirshahzadeh, and H. Hashemol-Hosseini, *Non-linear behavior of unreinforced masonry walls with different Iranian traditional brick-work settings.* Engineering Failure Analysis, 2014. **44**: p. 46-65.
2. Matysek, P. and M. Witkowski, *A comparative study on the compressive strength of bricks from different historical periods.* International Journal of Architectural Heritage, 2016. **10**(4): p. 396-405.
3. Barros, J.A., J. Almeida, and P.B. Lourenço, *Characterization of brick and brick–mortar interface under uniaxial tension.* 2002.
4. Almeida, J.A., E.B. Pereira, and J.A. Barros, *Assessment of overlay masonry strengthening system under in-plane monotonic and cyclic loading using the diagonal tensile test.* Construction and Building Materials, 2015. **94**: p. 851-865.
5. Shahreza, S.K., J. Niklewski, and M. Molnár, *Experimental investigation of water absorption and penetration in clay brick masonry under simulated uniform water spray exposure.* Journal of Building Engineering, 2021. **43**: p. 102583.
6. La Russa, M.F. and S.A. Ruffolo, *Mortars and plasters-How to characterize mortar and plaster degradation.* Archaeological and Anthropological Sciences, 2021. **13**(10): p. 165.
7. Ghosh, P., et al., *Use of microorganism to improve the strength of cement mortar.* Cement and concrete research, 2005. **35**(10): p. 1980-1983.
8. Fouchal, F., et al., *On the modeling of brick-mortar interface*. 2012, Nova Science Publishers Inc.
9. Brulin, J., et al., *Methodology for brick/mortar interface strength characterization at high temperature.* Construction and Building Materials, 2020. **265**: p. 120565.
10. Ravula, M.B. and K.V. Subramaniam, *Experimental investigation and interface material model for the cohesive–frictional shear response of soft-brick masonry under applied compression.* Journal of Materials in Civil Engineering, 2019. **31**(12): p. 04019311.
11. Shadlou, M., E. Ahmadi, and M.M. Kashani. *Micromechanical modelling of mortar joints and brick-mortar interfaces in masonry Structures: A review of recent developments*. in *Structures*. 2020. Elsevier.
12. Istegun, B. and E. Celebi, *Triplet shear tests on retrofitted brickwork masonry walls.* International Journal of Civil and Environmental Engineering, 2017. **11**(9): p. 1269-1274.
13. Gattesco, N. and I. Boem, *Out-of-plane behavior of reinforced masonry walls: Experimental and numerical study.* Composites part B: engineering, 2017. **128**: p. 39-52.
14. Kaushik, H.B., D.C. Rai, and S.K. Jain, *Stress-strain characteristics of clay brick masonry under uniaxial compression.* Journal of materials in Civil Engineering, 2007. **19**(9): p. 728-739.
15. Manohar, S., N. Chockalingam, and M. Santhanam, *Experimental comparison between salt weathering testing procedures on different types of bricks.* Journal of Materials in Civil Engineering, 2021. **33**(11): p. 04021305.
16. Naraine, K. and S. Sinha, *Cyclic behavior of brick masonry under biaxial compression.* Journal of Structural Engineering, 1991. **117**(5): p. 1336-1355.
17. Erberik, M.A., *Generation of fragility curves for Turkish masonry buildings considering in-plane failure modes.* Earthquake Engineering & Structural Dynamics, 2008. **37**(3): p. 387-405.
18. Comninou, M., *The interface crack in a shear field.* 1978.
19. Du, Z.-z., *eXtended Finite Element Method (XFEM) in Abaqus.* Simulia: Johnston, RI, USA, 2009.
20. Blasi, G., F. De Luca, and M.A. Aiello, *Hybrid micro-modeling approach for the analysis of the cyclic behavior of RC frames.* Frontiers in Built Environment, 2018. **4**: p. 75.

21. Gigliotti, L., *Assessment of the applicability of XFEM in Abaqus for modeling crack growth in rubber*. 2012.
22. Xu, Y. and H. Yuan, *Computational analysis of mixed-mode fatigue crack growth in quasi-brittle materials using extended finite element methods.* Engineering Fracture Mechanics, 2009. **76**(2): p. 165-181.
23. D'Altri, A., et al., *A review of numerical models for masonry structures.* Numerical modeling of masonry and historical structures, 2019: p. 3-53.
24. Lu, X., E. Tsotsas, and A. Kharaghani, *Scale transition: Pore network study of how pore structure affects the macroscopic parameters of the continuum model for drying.* Drying Technology, 2023: p. 1-20.
25. Hong, W., et al., *Finite element model updating of flexural structures based on modal parameters extracted from dynamic distributed macro-strain responses.* Journal of Intelligent Material Systems and Structures, 2015. **26**(2): p. 201-218.
26. Kesavan, P. and A. Menon. *Investigation of in-plane and out-of-plane interaction in unreinforced masonry piers by block-based micro-modeling*. in *Structures*. 2022. Elsevier.
27. Zeng, B. and Y. Li, *Towards Performance-Based Design of Masonry Buildings: Literature Review.* Buildings, 2023. **13**(6): p. 1534.
28. Cascini, L., et al., *Force-based seismic evaluation of retrofitting interventions of historic masonry castles by 3D rigid block limit analysis.* Applied Sciences, 2020. **10**(15): p. 5035.
29. Malomo, L., et al., *FlexMaps: computational design of flat flexible shells for shaping 3D objects.* ACM Transactions on Graphics (TOG), 2018. **37**(6): p. 1-14.
30. Bretas, E.M., J.V. Lemos, and P.B. Lourenço, *A DEM based tool for the safety analysis of masonry gravity dams.* Engineering structures, 2014. **59**: p. 248-260.
31. Malomo, D. and M.J. DeJong, *M-DEM simulation of seismic pounding between adjacent masonry structures.* Bulletin of Earthquake Engineering, 2022: p. 1-26.
32. Ma, D., et al., *Multiscale simulation of polycrystal mechanics of textured β-Ti alloys using ab initio and crystal-based finite element methods.* physica status solidi (b), 2008. **245**(12): p. 2642-2648.
33. Thomaszewski, B., S. Pabst, and W. Strasser. *Continuum-based strain limiting*. in *Computer Graphics Forum*. 2009. Wiley Online Library.
34. Devgan, A. and C. Kashyap. *Block-based static timing analysis with uncertainty*. in *ICCAD-2003. International Conference on Computer Aided Design (IEEE Cat. No. 03CH37486)*. 2003. IEEE.
35. Zhou, J., Q. Chen, and J. Wang, *Rigid block based lower bound limit analysis method for stability analysis of fractured rock mass considering rock bridge effects.* Computers and Geotechnics, 2017. **86**: p. 173-180.
36. Sukumar, N., J. Dolbow, and N. Moës, *Extended finite element method in computational fracture mechanics: a retrospective examination.* International Journal of Fracture, 2015. **196**: p. 189-206.
37. Wang, K., B. Wang, and T. Kitamura, *A review on the application of modified continuum models in modeling and simulation of nanostructures.* Acta mechanica sinica, 2016. **32**: p. 83-100.
38. Liu, Y. and X. Chen, *Continuum models of carbon nanotube-based composites using the boundary element method.* Electronic Journal of Boundary Elements, 2003. **1**(2).
39. Odegard, G.M., et al., *Equivalent-continuum modeling of nano-structured materials.* Composites Science and Technology, 2002. **62**(14): p. 1869-1880.
40. Tadmor, E.B., R. Phillips, and M. Ortiz, *Mixed atomistic and continuum models of deformation in solids.* Langmuir, 1996. **12**(19): p. 4529-4534.
41. Moghaddam, A.A., *Parameter estimation and assessment of continuum models of drying on the basis of pore network simulations*. 2017, Dissertation, Magdeburg, Universität, 2017.

42. Geers, M.G., et al., *Homogenization methods and multiscale modeling: nonlinear problems.* Encyclopedia of computational mechanics second edition, 2017: p. 1-34.
43. Charalambakis, N., *Homogenization techniques and micromechanics. A survey and perspectives.* 2010.
44. Marques, R. and P.B. Lourenço, *Unreinforced and confined masonry buildings in seismic regions: Validation of macro-element models and cost analysis.* Engineering Structures, 2014. **64**: p. 52-67.
45. Wood, D.M., *Macroelement modelling*, in *Mechanical Behaviour of Soils under Environmentally Induced Cyclic Loads*. 2012, Springer. p. 399-439.
46. De Santis, S. and G. de Felice, *A fibre beam-based approach for the evaluation of the seismic capacity of masonry arches.* Earthquake engineering & structural dynamics, 2014. **43**(11): p. 1661-1681.
47. Franza, A., et al., *An equivalent beam approach for assessing tunnelling-induced distortions of frames with infills.* Tunnelling and Underground Space Technology, 2022. **129**: p. 104686.
48. Wijesundara, K., R. Nascimbene, and G. Rassati, *Modeling of different bracing configurations in multi-storey concentrically braced frames using a fiber-beam based approach.* Journal of Constructional Steel Research, 2014. **101**: p. 426-436.
49. Tomás, R., et al., *Review of linear optics measurement and correction for charged particle accelerators.* Physical review accelerators and beams, 2017. **20**(5): p. 054801.
50. Giannopoulos, G., P. Kakavas, and N. Anifantis, *Evaluation of the effective mechanical properties of single walled carbon nanotubes using a spring based finite element approach.* Computational Materials Science, 2008. **41**(4): p. 561-569.
51. Gottron, D. and A. Henk, *Upscaling the Mechanical Properties of a Fractured Rock Mass Using the Lattice-Spring-Based Synthetic Rock Mass (LS-SRM) Modeling Approach—Comparison of Discontinuum, Continuum and Empirical Approaches.* Geosciences, 2022. **12**(9): p. 343.
52. Riccio, A., et al., *Development of a combined micro-macro mechanics analytical approach to design shape memory alloy spring-based actuators and its experimental validation.* Sensors, 2021. **21**(16): p. 5506.
53. Lee, C.-H., C.-Y. Shih, and Y.-S. Chen, *Stochastic geometry based models for modeling cellular networks in urban areas.* Wireless networks, 2013. **19**: p. 1063-1072.
54. Akbas, R., *Geometry-based modeling and simulation of construction processes*. 2003, Stanford University.
55. Bordas, S., et al., *An extended finite element library.* International Journal for Numerical Methods in Engineering, 2007. **71**(6): p. 703-732.
56. Moës, N. and T. Belytschko, *Extended finite element method for cohesive crack growth.* Engineering fracture mechanics, 2002. **69**(7): p. 813-833.
57. Singh, R.K. and P. Shanmugam, *A multidisciplinary remote sensing ocean color sensor: Analysis of user needs and recommendations for future developments.* IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 2016. **9**(11): p. 5223-5238.
58. Ghandriz, R., K. Hart, and J. Li, *Extended finite element method (XFEM) modeling of fracture in additively manufactured polymers.* Additive Manufacturing, 2020. **31**: p. 100945.