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Finite Element and Experimental Study of Brick Masonry Bonds Under Low-Velocity Impact Load: A Simplified Micro-Modelling Approach

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Abstract
This study employs finite element simulations in Abaqus software to analyse the impact response of different brick masonry walls. This work proposes a simplified micro-model approach that combines the extended finite element with constitutive models based on plasticity. It is demonstrated that using this method to simulate the three-dimensional non-linear behavior of masonry under low velocity impact loads is effective. Considering variations in bricks placement specially choosing right type of brick bonds. The research investigates the structural behaviour under dynamic loading conditions, here, low velocity Impact load. Through comprehensive analyses of point displacement, stress distribution, and failure modes, the study assesses the wall's performance against low velocity impact loads of varying magnitudes on four different brick bonds configuration. The findings contribute to understanding masonry walls behaviour which mainly simulate wall stability analyses in rural areas, having load bearing housing structure. This research underscores the significance of simulation-based approaches in optimizing masonry wall designs for enhanced safety, cost-effectiveness, and structural performance, ensuring their suitability for diverse applications. In Addition, Experimental approach, validates, our results finding through FEM Modelling. This research includes the analysis of non-confined walls and the mechanisms of suspended impact loads, applying the Drucker-Prager failure criterion to enhance the accuracy of the simulations. This approach allows for a more precise representation of how masonry walls respond to dynamic loading conditions, which is particularly relevant for rural areas with load-bearing housing structures.
Keywords: *Brick Masonry, Impact load, Abaqus, Mesh, Stress Distribution, Finite element*

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I. Introduction

Brick masonry walls are integral components of various structures, providing structural support, thermal insulation, and aesthetic appeal. However, these walls are susceptible to damage and failure when subjected to dynamic loading conditions, such as impact loads from blasts or collision events. Understanding the response of brick masonry walls to such loads is essential for ensuring structural safety and resilience in diverse applications, including residential, commercial, and industrial constructions.

For simulating and studying the behavior of structures under dynamic loading circumstances, finite element analysis (FEA) has become an increasingly useful method. In this context, the utilization of Abaqus software enables engineers and researchers to conduct detailed simulations that mimic real-world scenarios, offering insights into the performance of masonry walls under impact loads.

This study aims to investigate the dynamic response of different types of brick masonry walls to impact loads through FEA simulations using Abaqus software.

Due to shortage in impact analysis of brick masonry wall on the basis of different bond arrangement and there is no research yet on this topic, so this can be a start to research on this topic by using different types of simulation method such as micro-modelling, simplified micro-modelling, and macro modelling with validation to experimental approach. Here we use the simplified micro modelling to simulate the given topic. In future we use all other type of fem modelling approach.

Through a comprehensive analysis of displacement, stress distribution, and failure modes, this research aims to provide valuable insights into the behavior of brick masonry walls subjected to impact loads.

In rural areas, housing wall patterns are a significant concern, especially in narrow passages where walls are susceptible to sudden impacts from accidents. These impacts can arise from vehicles, animals, or natural events, causing considerable damage to the structures. Addressing this issue requires developing new construction guidelines that enhance the walls' ability to withstand such impacts. Keeping this in mind, we researched this topic and found that there are few guidelines which tell us what bond arrangement would be correct for an unconfined brick masonry wall that can withstand the low velocity impact load.

Figure 1: Unconfined Brick Masonry walls

Experimental approach is very essential to validate FEM results, although this can have a sufficient but permissible number of assumptions to ensure the model's accuracy and reliability.

[1] Physical experiments are now practically replaced by numerical models. For numerical analysis and to model both linear and non-linear behavior of masonry, a variety of numerical approaches are used, such as the AEM, DEM, limit analysis, and FEM. The finite element method (FEM) is the particular subject of this paper. The two main modelling techniques used in FEM for brickwork are micro- and macro-modelling. The needed degree of intricacy and precision will determine which of these approaches is best. In micro-modelling, brick and mortar are represented as continuum elements, whereas the interfaces between the brick and mortar are represented as discontinuum elements. This allows for a highly detailed simulation. However, as Fig. 1(a) illustrates, this comprehensive Micro-modelling approach requires significant computer power and is therefore limited to the analysis of relatively small masonry pieces. An alternative is to use the streamlined Micro-modelling approach shown in Fig. 1(b) to lessen the disadvantages of the in-depth micro approach. By including mortar thickness, units are made larger in this more straightforward method. The enlarged units are then modelled as a sequence of continuum elements, with the interactions between them represented as a sequence of discontinuum elements. Masonry is handled as a single material in macro-modelling, with no distinction made between mortar and units. Masonry is represented as a sequence of continuum elements, and material attributes are determined from the average properties of masonry constituents.

[2] Over the last fifty years, a significant amount of work has gone into creating numerical techniques for examining masonry structures. These techniques range from macro-models that view masonry as a continuum to micro-models that view masonry as individual units and joints. In order to analyze masonry couplets and prisms, a comprehensive micro-modeling approach is presented in this study. It represents units and mortar joints as discrete irregular deformable particles that are tightly packed and bound together by interface rules with zero thickness. Failure at brick-and-mortar or brick-mortar interfaces is taken into account by the method. The method's potential was shown by comparing experimental data with computational models, which demonstrated good agreement. This method has the advantage of not relying as much on expensive experimental testing and empirical formulas, and it can accurately simulate cracking and estimate masonry strength.

[3] This study investigates the dynamic behavior of steel plate elements under impact loads using ABAQUS for finite element analysis. It examines parameters including plate thickness, mesh sizes, and impact load velocity. Analyzing models with thicknesses of 60mm, 80mm, and 100mm across mesh sizes from 2mm to 25mm under an impact load velocity of 10m/s, the research focuses on understanding stress patterns over time and mesh size variations.

Findings reveal a slight increase in stresses with finer mesh sizes while reducing impact load velocity decreases plate damage and maximum stresses. Thicker plates demonstrate lower maximum stresses and damage. The study provides insights into optimizing plate designs for impact resistance, suggesting that finer mesh sizes may lead to increased stresses and emphasizing the importance of considering plate thickness in minimizing damage under impact loads.

[4]This paper outlines initial results from an experimental study on the behavior of RC slabs under low-velocity impact loads. Six slabs were tested under impact and static loads, with identical pairs for comparison. Innovative setups were employed for testing, capturing dynamic data to analyze load-displacement relationships and failure modes.

In recent years, researchers have been studying how plates respond to dynamic loads, especially impacts. With growing populations in mountainous areas and global environmental changes, the danger of falling rocks to structures has become significant. This threatens infrastructure and lives, especially when structures aren't designed to withstand impacts. Investigating a structure's impact resistance is crucial for disaster prevention and minimizing damage.

[5]This paper introduces a numerical model for simulating high-velocity impacts on reinforced concrete structures. The model focuses on predicting the behavior of a concrete panel when struck by a rigid steel projectile. Using specific dimensions and meshing techniques, the concrete panel's behavior is analyzed by incorporating a damage model. The steel projectile's characteristics are also considered. Various aspects such as damage, pressure, kinetic, and internal energies are evaluated to understand the impact's dynamics.

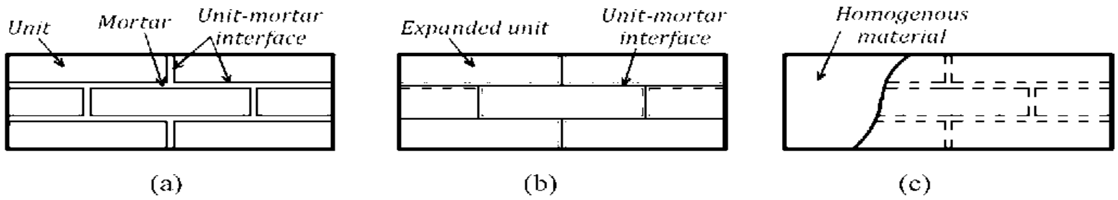


Figure 2-Finite element modelling approaches: (a) detailed Micro-model; (b) simplified Micro-model; (c) Macro-model (based on [1]).

The study provides insights into velocity variations across different points of the projectile and concrete panel during impacts at 540 m/s

[4], [6] Over the past few years, scientists have concentrated their research on how plates react to dynamic pressures, particularly impact stresses. The impact of falling rocks on structures has become increasingly significant due to population development in mountainous areas and changes in the global environment. These latter have an influence on civil structures and pose a major risk to both human life and the infrastructure, particularly if the structures are not built with impact resistance in mind. As a result, investigating building impact resistance is crucial to preventing disasters and minimizing damage.

[7], [8], [9], [10]This investigation examined the impact of explosive forces on reinforced concrete beams through numerical analysis. Findings revealed localized damage in the beams, particularly noting spalling in the tension zone. To validate the numerical results, a single degree of freedom analysis was carried out, with damage curves for different damage levels plotted. The blast effects mirrored those observed in impacts from falling loads.

[11], [12] This study examined RC beams that were subjected to impact loads from objects that fell freely. The investigation demonstrated the same pattern of damage brought on by blast loads that was examined by [9].

[13]The study investigates how different brick arrangements affect how walls respond to sideways forces. Using computer simulations, they examined Header, Stretcher, and English bonds. Initially, all bonds behaved similarly under normal conditions. However, when subjected to sideways pressure, diagonal cracks caused most failures. The research suggests that while brick bonds may not vary much in their initial response, under sideways stress, diagonal cracking becomes a significant factor in failure. This highlights the importance of considering the behavior of brick bonds under various conditions to ensure structural integrity in masonry walls.

The goal of the current study was to increase knowledge about how brick masonry walls behave under impacts at low velocities. Comparing how various brick masonry wall types behaved when subjected to the impact load effect at the wall was one of the study's other goals. The testing procedures for various kinds of brick masonry walls are described in the section that follows, along with the completed test results. The implemented model is novel in that:

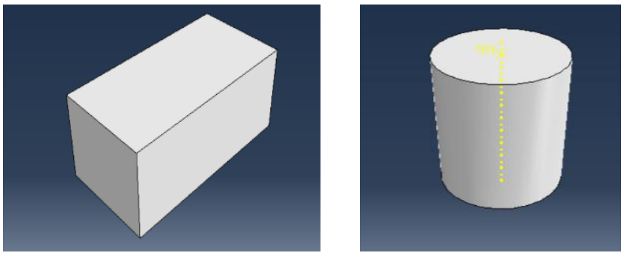
- It simulates how different brick-bond masonry walls react to impact loads keeping all other parameters (i.e. dimension of brick, geometry of walls, properties of materials used, meshing sizes, analysis types etc.)

- It accurately depicts how these walls deform and distribute stress levels, including von-mises stress, maximum and minimum principal stress, using Abaqus software.
- This model follows a simplifies micro-model approach, focusing on overall system as dynamics-explicit analysis along with experimental analysis.
- Experimental study is done using a tripod impact hammer and behavior of different brick bond masonry walls are observed when impact load is applied on them from a well decided location.

II. Methodology

2.1 Model Geometry

Different brick masonry wall types are utilized in geometry modelling, but just three parts of the geometry—brick, Hammer, and PCC—are defined, and each is given a material property. The Hammer weighs 25 kilogram. In a similar vein, these parts' interaction properties are also defined. The dynamic explicit 3D stress element is the sort of element that is used.



a) b)

Figure 3: Geometry a) Brick b) Hammer

2.2 Materials

Generally speaking, we modelled the masonry wall using these three categories of features. These characteristics include Ducker Prager plasticity, elasticity, and density.

Table 1: Brick geometries

Brick	Length	Width	Thickness
Full Brick	230mm	90mm	115mm
Half Brick	115mm	90mm	115mm
Quin Closure	230mm	90mm	57.5mm

The following is the prescribed procedure for assigning these attributes.

2.2.1 Elasticity and Poisson's Ratio

Table 2: Elastic Properties and Poisson's Ratio of Brick

Elasticity	Poisson's Ratio
15500000000	0.2

2.2.2 Ducker Prager Plasticity

Table 3 lists the Ducker Prager plasticity parameters that were utilized in the brick model. In Abaqus, the model has all of these attributes applied to it in the plasticity tab. A plasticity model called Drucker-Prager is used to model the non-linear compressive behaviour of masonry. Under compression, the model permits isotropic hardening and softening of materials.

Table 3: Ducker Prager Plasticity Parameter

Angle of Friction	Flow Stress Ratio	Dilation Angle
36	1	11.3

Also, Ducker Prager Hardening parameter used in this plasticity model which are tabulated in Table 2.

Table 4: Ducker Prager Hardening (Compression behaviour)

Yield Stress	Abs Plastic Strain
7260000	0
7030000	0.00046
5900000	0.0044
4830000	0.006

2.3 Step Define

In Abaqus Software already one step is defined by default (initial step). Now we defined a Dynamic Explicit Step with the time period 0.5 and the time scaling factor 1.

2.4 Assembly and Interaction Property

Brick (either full, half, or Quin closure), PCC, and Hammer are the three pieces that we defined in the part module. To put these pieces together The PCC is positioned at the base of the brick wall using an assembly module, which creates an interaction attribute that allows for tangential behavior with a friction coefficient of 0.25 in penalty.

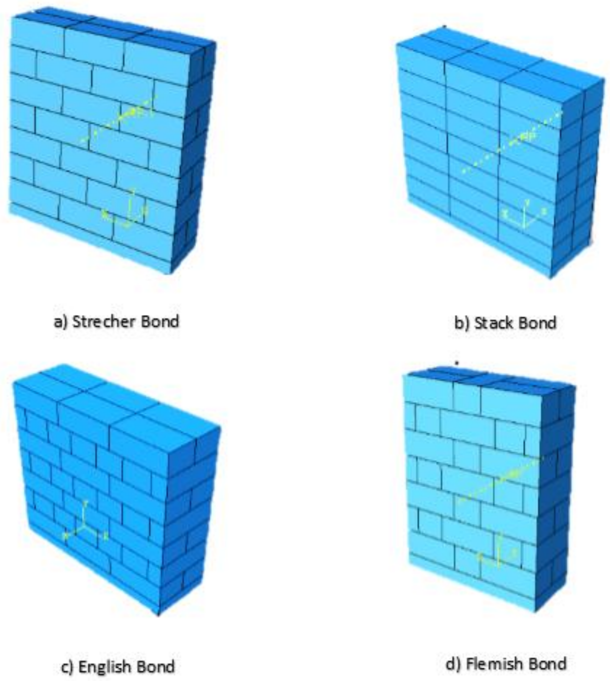


Figure 4: Different types of bonds of Brick Masonry Wall

2.5 Boundary Conditions and Load

Two Boundary Condition is applied to the Brick Masonry Walls. One is applied to the bottom part of the Brick Masonry walls which is ENCASTER type (U1=U2=U3=U4=U5=U6=0) and the other is applied to the Hammer has the velocity is 20m/s in Z- direction which is impact on the Masonry Wall and this Boundary Condition is Velocity/Angular velocity type.

2.6 Element Type

Here we use the C3D8R continuum element type. The C3D8R element is a general-purpose linear brick element, with reduced integration (1 integration point).

2.7 Mesh Analysis and Mesh Sensitivity

The final section is meshing, and a global seed of 5 mm is assigned. Mesh sensitivity refers to the degree to which the results of a simulation or analysis are influenced by the density or size of the mesh used to discretize the model. It is crucial to ensure that the mesh is fine enough to capture important features of the problem accurately. Performing mesh sensitivity analyses helps determine the optimal mesh resolution for obtaining reliable results while balancing computational efficiency.

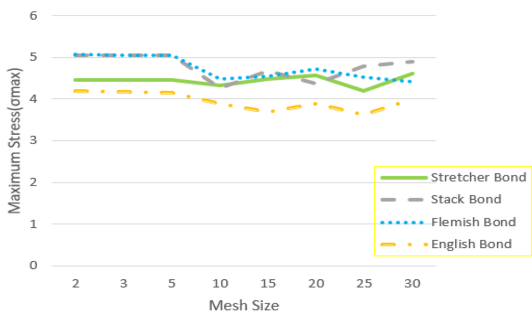


Figure 4: Mesh Sensitivity graph between Maximum Stress and Mesh Size

III. Results And Discussion

The following presents the finite element analysis findings in terms of plastic strains, stresses distributed across the material, and deformed forms at impact.
The model's predicted impact mechanisms, comparable plastic strain, and lowest primary stress distribution under low velocity impact load.

3.1 Stress Distribution and Failure modes

The Stress versus time plot of the dynamic analysis shows that increasing the time period will causes the stresses under the given impact load velocity. The stresses versus time graph can be seen in figure 7 and 8.

A) STRETCHER BOND

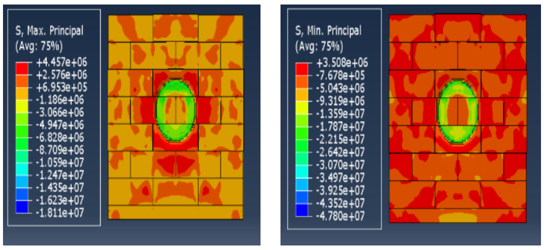


Figure 5: Maximum and Minimum Principal Stress Distribution of Stretcher Bond under impact load

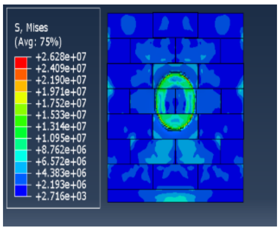


Figure 6: Von Mises Stress of Stretcher Bond under impact load

B) STACK BOND

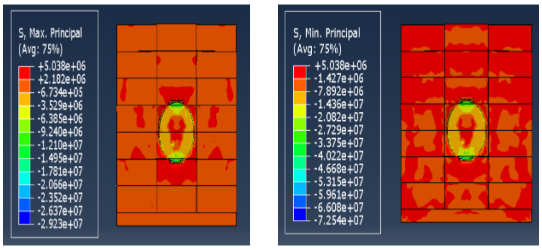


Figure 7: Maximum and Minimum Principal Stress Distribution of Stack Bond under impact load

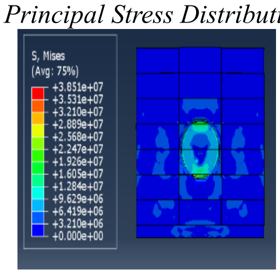


Figure 8: Von Mises Stress of Stack Bond under impact load

C) FLEMISH BOND

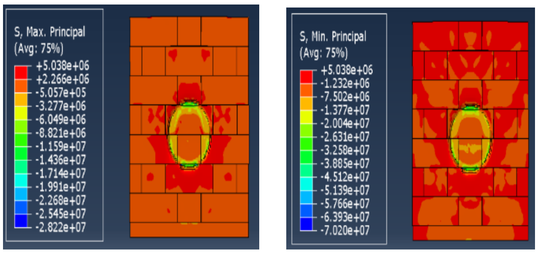


Figure 9: Maximum and Minimum Principal Stress Distribution of Flemish Bond under low velocity impact load

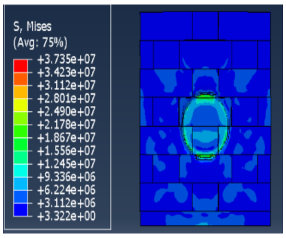


Figure 10: Von Mises Stress of Flemish Bond under low velocity impact load

D) ENGLISH BOND

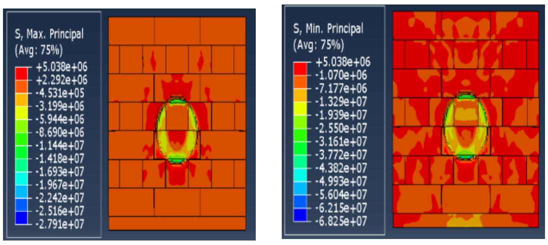


Figure 11: Maximum and Minimum Principal Stress Distribution of English Bond under low velocity impact load

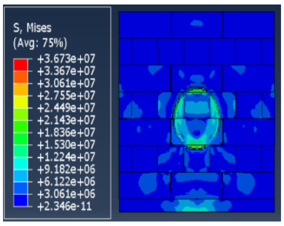


Figure 12: Von Mises Stress of English Bond under impact load

Figure 7 to 14 shows the variation of maximum, minimum principal stresses and mises stresses produced from Abaqus after successful simulation of four types of brick masonry walls subjected under impact loading.

In engineering, von Mises stress is a scalar stress number that is used to forecast how a material will yield under complicated loading circumstances. You designate the shape and mesh of the part as well as the material attributes in Abaqus. After loads and boundary conditions are applied, make sure the output calls for von Mises stress. After running the simulation, examine the von Mises stress distribution to identify possible yielding regions. This stress measurement is essential for figuring out how safe and long-lasting components are under impact load condition. Figure 12 displays Von Mises' stress versus time graph.

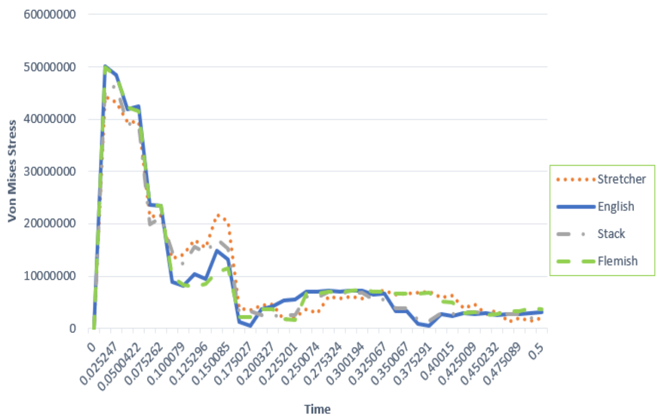


Figure 13: Von Mises Stress verses time graph

3.2 Displacement-Time Graph

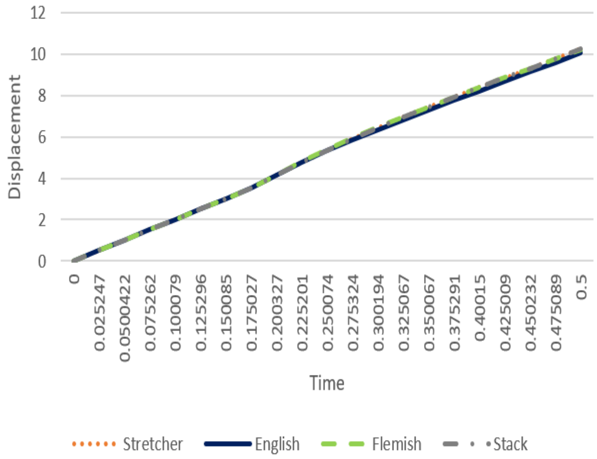


Figure 14: Displacement verses time graph

3.3 Damage Dissipation Energy

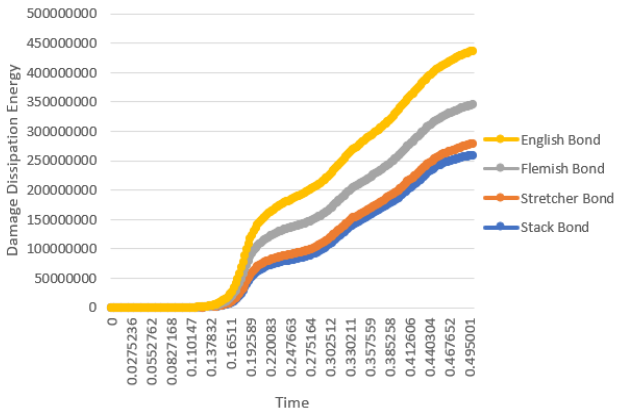


Figure 15: Damage Dissipation Energy verses Time graph

IV. Experimental Study

In the experimental setup, four types of bond arrangements of brick masonry walls were constructed of clay brick and mortar were assembled, and then the walls were subjected to tripod pendulum impact testing in order to investigate the bond behavior. All the experimental work was performed in the Workshop of the Civil Engineering Department at Mainpuri, RECM.

4.1 Materials:

We used first class clay brick and mortar with volumetric ratio is 1:4 used for 4.5inch wall and for 9inch wall is 1:6.

4.2 Assembly:

Four types of bond arrangements of brick masonry wall were constructed i.e. Stretcher Bond, Flemish Bond, Stack Bond and English Bond. After excavation of soft soil, different bond patterns brick wall is built upon each PCC. This arrangement is embedded in the soft soil, which provides support at the base.

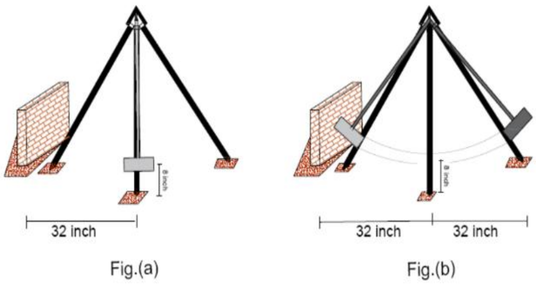


Figure 16: Pictorial representation of pendulum impact test using AutoCAD

4.3 Testing Mechanism:

A tripod stand is used to create a pendulum arrangement. A cylindrical weight of 25kg is used to produce impact effect on brick-masonry wall. Cylindrical Hammer is hanged on the tripod stand with the help of rope. The arrangement is made in such a way that brick masonry wall is placed at the distance of 32 inch from the normal condition of the cylinder hammer. Then the impacts are made from the distance of 32 inch away from normal condition. These distances can be changed as per requirements.

Figure 17: Experimental loading arrangement and masonry wall

4.4 Experimental Results:

Figure 18: Distortion of masonry wall under impact load

V. Conclusion

The dynamic response of different types of brick masonry walls under impact loading using a rigid hammer was studied. Different types of masonry walls were chosen. Maximum stresses versus time, load versus time and the comparison of failure the physical model and experimental behavior was studied. Based on this simulation investigation the following conclusions are drawn.

Using Abaqus to simulate the effects of impact loads on different types of brick masonry walls provides critical insights into their structural performance and failure mechanisms. This research aims to enhance understanding of masonry behavior under dynamic loading conditions and contribute to the development of safer, more resilient masonry structures.

Additionally, the numerical study can be used to identify the masonry structure's crack pattern.

- The finite element analysis using Abaqus revealed that brick masonry walls with an English bond effectively distribute impact-induced stresses, reducing localized concentrations and enhancing overall resilience. This bond pattern's interlocking geometry makes it a preferable choice for impact-prone constructions, validated by experimental data. English bond shows the least distortion and cracking when impact is applied on it when compared to Flemish bond and other brick bonds.
- The finite element analysis using Abaqus showed that brick masonry walls with a Flemish bond distribute stresses effectively under impact loads but are slightly less resilient than English bonds. Maximum stress concentrations typically occur at the brick-mortar interfaces. Despite this, the Flemish bond remains a strong, reliable choice for impact-resistant construction.
- The Abaqus analysis demonstrated that Stretcher bond brick masonry walls exhibit higher stress concentrations at brick-mortar interfaces under impact loads. While providing adequate resilience.
- The analysis using Abaqus highlighted that Stack bond brick masonry walls are prone to significant stress concentrations at brick-mortar interfaces during impact loads. Stack bond is the poorest brick bond arrangement, as it is the weakest among all and distort easily.

The English bond is found to be superior when finite element and experimental research are finished. This connection pattern outperforms other techniques in terms of strength and durability while improving structural integrity and load distribution. Its effectiveness is validated by both simulation and real-world testing, which makes it the best option for strong masonry building.

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