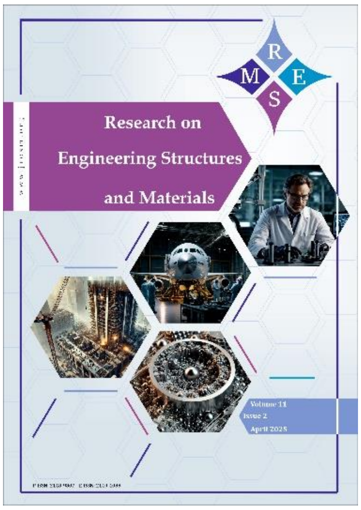
Research on Engineering Structures & Materials
www.jresm.org
Research Group


Research on Engineering Structures and Materials
Volume 11
Issue 2
April 2025

Performance of cement–clay interlocking hollow brick masonry walls with grout and vertical reinforcement

Lokanath Reddy Maddikera, Lingeshwaran N

Online Publication Date: 10 October 2025

URL: http://www.jresm.org/archive/resm2025-991ma0626rs.html
DOI: http://dx.doi.org/10.17515/resm2025-991ma0626rs

Journal Abbreviation: *Res. Eng. Struct. Mater.*

To cite this article
Maddikera L R, Lingeshwaran N. Performance of cement–clay interlocking hollow brick masonry walls with grout and vertical reinforcement. *Res. Eng. Struct. Mater.*, 2026; 12(3): 1519-1531.

Research on Engineering Structures & Materials
www.jresm.org
MIM Research Group

Research Article

Performance of cement–clay interlocking hollow brick masonry walls with grout and vertical reinforcement

Lokanath Reddy Maddikera [*,a], Lingeshwaran N [b]

Dept. of Civil Eng., Koneru Lakshmaiah Education Foundation (Deemed to be University), Guntur, Vaddeswaram, India

Article Info

Article History:

Received 26 June 2025
Accepted 05 Oct 2025

Keywords:

Cement–clay interlocking bricks;
Hollow masonry walls;
Diagonal compression;
Vertical reinforcement;
Grout infill

Abstract

This study investigates the diagonal compressive response of cement-clay interlocking hollow brick masonry walls under in-plane shear loading. The main objective was to measure the effect of grout infill and vertical steel reinforcement to the shear capacity, deformation behavior, energy dissipation and failure mechanism of these walls where seismic as well as wind resistant masonries are constructed. Four wall specimens (1000 x1000x125)mm were tested under diagonal compression in four wall systems. Grout was prepared in the ratio of 1:2 (cement: sand) with slump of 220 mm, vertical Fe 500 steel rebars were used where mentioned. The combination of grout and reinforcement (W4) has shown to give the best response, with 119 % greater peak shear stress, the greatest initial stiffness and excellent ductility than W1. Different observed failure modes that were found ranged between brittle diagonal shear cracking in W1 and a distributed cracking, with local crushing in W4, meaning a better load redistribution and damage tolerance. Experimental results demonstrate that cement-clay interlocking hollow bricks, when combined with grout infill and vertical reinforcement, significantly enhance the in-plane shear capacity of masonry walls. This system provides a robust, sustainable solution for improving structural resilience in seismic and high-wind regions.

1. Introduction

The strong growth rate of the world population in cities portrays the dire need of cost-efficient sustainable and resilient construction materials, especially in seismically affected areas. Interlocking hollow brick masonry has emerged as a viable solution, offering advantages in construction efficiency, material savings, and structural performance. Cement-clay interlocking hollow brick (CCIHB) products have a typical size of 250 mm x 125 mm x 100 mm with skills in engineering manufacture and interconnection capabilities to allow dry connection or limited mortar application, resulting in lightweight walls with better thermal properties [2]. But, in order to be structurally adopted (particularly where there is a seismic zone or high wind-regions), credible information regarding the in-plane shear (diagonal compressive) action of CCIHB masonry is imperative. The problem related to the distinctive lack of knowledge on the effect of the vertical reinforcement and core grouting on shear capacity, deformation capacity, and failure pattern of CCIHB walls in diagonal compression is being solved in the study.

Traditionally, hollow brick masonry has been avoided in load-bearing walls and in lateral-load-resisting walls; however, recent demands regarding the affordable and sustainable housing plans prompted it to be deployed in task-bearing structures and as a means of load [3,4]. The interlocking

---

[*] Corresponding author: maddikeralokanathreddy@gmail.com
[a] orcid.org/0009-0008-0222-5621; [b] orcid.org/0000-0003-2998-7315

DOI: http://dx.doi.org/10.17515/resm2025-991ma0626rs

geometries simplify the mortar joint thickness and the period of construction, but they disrupt the bond mechanics as compared with the traditional mortar bonded units [5]. There are voids between the bricks, and the interlocking bricks reduce self-weight and allow grouting or strengthening in cases when the increased strength is required. The CCIHB units can be described mechanically with great variations in compressive strength (typically 4-16 MPa), due to the variations in clays sources and manufacturing procedures [6]. As such, designers need experimental data of assemblage behavior to use CCIHB in a load-bearing or seismic design [2].

Shear resistance in-plane is critical to all wall structures undergoing seismic or wind actions because lateral forces cause each structure to develop diagonal tensile stresses that may trigger brittle failure before the shear capacity is reached [7]. Under monotonic loading condition, the standardized diagonal compression test [8] applies compressive force on one diagonal of a square masonry panel, causing shear on the orthogonal side; it measures the peak shear strength, initial stiffness, and post-peak softening of a panel, and allows seeing the crack initiation and propagation ASTM International, 2015 [9]. In the case of traditional clay-brick or concrete-block masonry, the diagonal compression experiments have been used to measure the relationship between the diagonal compression and the lateral drifting capacity in cyclic loading under which the code is based [3,10].

Particular to CCIHB masonry, experimental research indicates that grout-filling cores and with reinforcement enhance shear performance and change the falling patterns to more ductile behavior [1,2]. Similarly, diagnostic compression of 1000 mm x 1000 mm CCIHB panels by Joyklad and Hussain [1] found that grout-filled walls were found to reach higher peak loads and were found diagonally cracked as opposed to brittle failure ungrouted grout walls. The increased capacity and deformation capacity are further promoted by strengthening interventions, which are wire mesh overlays or CFRP jacketing [11]. But most investigations are combining vertical and horizontal reinforcement or external overlays therefore it is impossible to isolate just the effect of the vertical reinforcement in the cores. Besides, the majority of diagonal compression tests on CCIHB walls us monotonic; monotonic shear stress strain curves allow computing monotonic energy absorption (curve area to peak of shear stress) and monotonic ductility indices (post peak to peak strain ratio), but they do not reflect cyclic hysteretic behavior on which seismic response is assessed [7].

In addition to diagonal compressions, grout flowability in interlocked bricks has been studied, where by care is taken in the mix design (e.g., aiming to achieve a slump of 200 mm when making cores of 60 mm thick) and they confirm complete consolidation of the core, but destructive tests (such as ultrasonics) to confirm a satisfactory level of consolidation are rarely reported [4]. Models based on empirical or analytical approaches to predict diagonal shear strength in CCIHB masonry are not well-developed: available regression methods on conventional hollow-brick masonry utilize unit strength, mortar strength, and reinforcement ratio, but those techniques should be modified to work on CCIHB systems by utilizing data on a systematic basis with a range of unit compressive strengths and reinforcement patterns [12]. The second reason is manufacturing variability in locally manufactured CCIHB units, which makes it more problematic to generalize, and controlled experimental schemes correlating unit characteristics with panel-level shear response are necessary [13].

Documentation of failure mode of CCIHB panels subjected to diagonal loads indicates that interlocking properties have the potential to affect crack propagation distribution and may affect frictional slip between units; grout confinement surrounding reinforcement causes splitting to be delayed, and facilitates distributed cracking [5]. However, there are limited systematic photographic and quantitative comparison of the un-reinforced and vertically reinforced CCIHB panels at monotonic diagonal compression. Conventional masonry has extensively undergone cyclic diagonal compression or lateral cyclic testing in order to record the hysteretic behavior and energy dissipation [16], whereas similar cyclic tests are rare on CCIHB walls.

Because of the already disparate property values of individual CCIHB units and the structural necessity to have an in-plane shear performance data that can be reliably used, it will certainly be desirable to determine and measure the vertical reinforcement effect within cores with and without grout-filling into the diagonal compressed behavior of a given masonry of a CCIHB. The study that exists has an issue with confusion of various reinforcement techniques or concentrating on external strengthening, so the unadulterated impact of the vertical bars has not been explored well. Moreover, despite the fact that monotonic diagonal compression tests can provide information on peak shear strength and monotonic energy absorption, the limitations to their use in seismic design (due to the insufficient hysteretic data), require specific comment, as well as future research guidelines. Lastly, methodology of ensuring that grout is flowable needs standardization and empirical modelling of shear strength in CCIHB masonry needs further development.

This paper is the result of an experimental examination of square CCIHB masonry panels (1000 mm 1000 mm 125 mm) subjected to diagonal compression in a monotonic manner and in four conditions of panel designed to isolate the two effects of vertical reinforcement (8 mm Fe 500 bars in cores) and grouting of the cores: (1) unreinforced, ungrouted; (2) unreinforced, grouted; (3) reinforced, ungrouted; and (4) reinforced Grouted

The following specific objectives are to be fulfilled:

- Determine peak shear strength and initial stiffness of each of the configurations to separate out the role of vertical reinforcement and grout on shear behavior of CCIHB walls.
- Determine deformation capability and monotonic energy absorbance, shear stress-shear strain curves and ductility coefficient of deformation.
- Record the failure modes and crack patterns in diagonal compression with the view of understanding mechanisms through which vertical reinforcement and grout can have any effect on shear response

2. Materials and Methods

In this research, uniformity in causing a consistent laboratory test was applied to examine the efficiency of cement-clay interlocking hollow bricks.

2.1. Materials

Ordinary Portland cement is used along with clay locally, sand, and water to prepare hollow bricks which interlock.

2.1.1 Cement–Clay Interlocking Hollow Bricks

The main masonry units considered in the current research are cement-clay interlocking hollow bricks. The units were 250 mm in length, 125 mm in width and 100 mm in height. Those bricks had two vertical cylindrical hollows (60 mm in diameter) to minimize the self-weight of the bricks, and allow, where possible, vertical grouting. Bricks had an average compressive strength of 6.7 M p, a value obtained by doing normal testing of compressive strength of individual brick units. The porosity of clay-based matrix was determined as 14.5% indicating the likelihood of the substance to affect the cementing with mortar and grout. Dimensional tolerances were kept at a range of zero to as much as 2mm so that constant bond patterns and load transfer were recorded when tested.

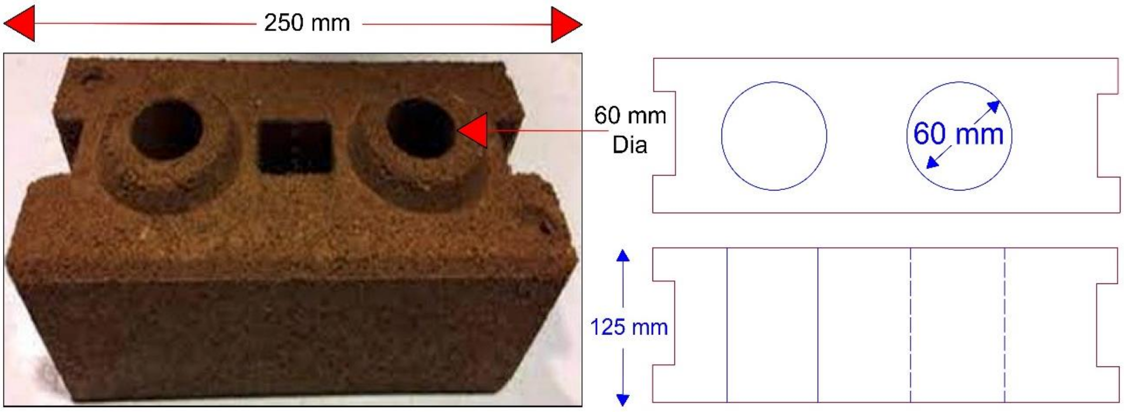


Fig. 1. Brick geometry

2.1.2 Mortar

To make mortar, the ratio used in bed and head joint was 1:4 (cement:sand by weight) of ordinary Portland cement (OPC) 43 grade with naturally sourced river sand, the fineness modulus of which was 2.70 and specific gravity of 2.65. The mortar mix had been prepared to ensure that the mortar has a slump between 220mm to enable the mortar to be sufficiently workable to facilitate uniform filling of joints and also good bond development. Mortar was checked after 28 days compression test using cube and concluded at 22.1 Mpa of compressive strength. The mortar was made in small quantities to ensure consistency of this ingredient during the assembly of masonry.

2.1.3 Grout

Where noted grout was added to the masonry to fill the voids in the vertical receptacles. The grout mix had the ratio of 1:2 (cement: sand by the weight), and the content was the same OPC and river sand as mortar. To get a slump of 220mm, the mix was modified so as to get the sufficient flowability to enable the entire filling of the vertical cores. The grout compressive strength of the grout after 28 days was found to be 28.5 MPa. The filling of grout was constantly checked during grout placement to ascertain the concrete appears on the surface of the cores and accompanied by minor taps on the sides of the panel to encourage compaction and dislodge the air holes.

2.1.4 Reinforcement

In the case of the reinforced wall systems, the vertical reinforcement used was ribbed steel rebars of Fe 500 grade nominal diameter of 8 3/4mm. The yield strength of the rebars measured was 520 MPa and the elastic modulus bar was 200 GPa. The bars were positioned in the centre of the reserved hollow cores and cut up to the complete height of the panel. In this case, horizontal reinforcement was not given in order to domineer the role of vertical steel bars on diagonal compressive behavior. Table 1 summarizes the properties of the materials applied in the present study. These are the compressive and water absorption of cement-clay interlocking bricks, cement-clay mortar and cement-clay grout, fineness modulus along with the specific gravity of the fine aggregate, and also the mechanical characteristics of the reinforcement material which is of the steel Fe 500.

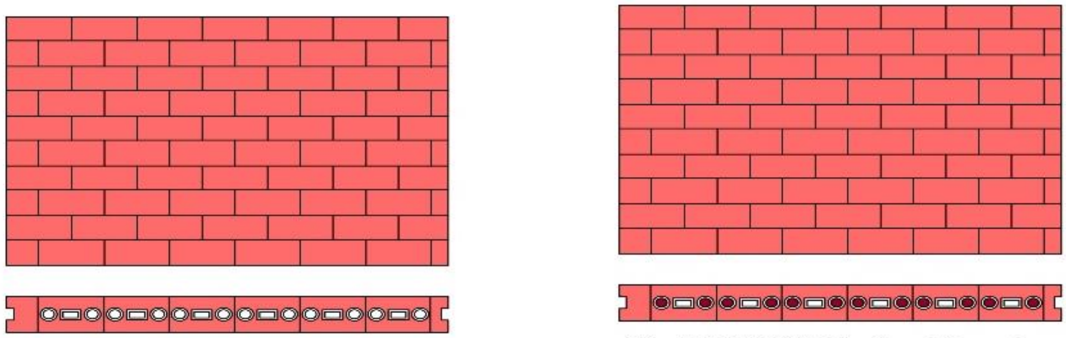
Table 1. Properties of the materials used in the construction of the cement–clay interlocking hollow brick masonry walls

Material	Description	Property	Value
Cement–clay interlocking brick	Hollow brick unit, 250 mm × 125 mm × 100 mm	Compressive strength	6.7 MPa
		Water absorption	14.5%
Mortar (1:4 cement: sand)	Bed and head joints	Compressive strength	22.1 MPa
Grout (1:2 cement: sand)	Vertical cell infill	Compressive strength	28.5 MPa
Fine aggregate	Naturally, sourced river sand	Fineness modulus	2.70
		Specific gravity	2.65
Reinforcement (Fe 500)	Vertical steel rebars, 8 mm diameter	Yield strength	520 MPa
		Modulus of elasticity	200 GPa

2.2 Specimen Details

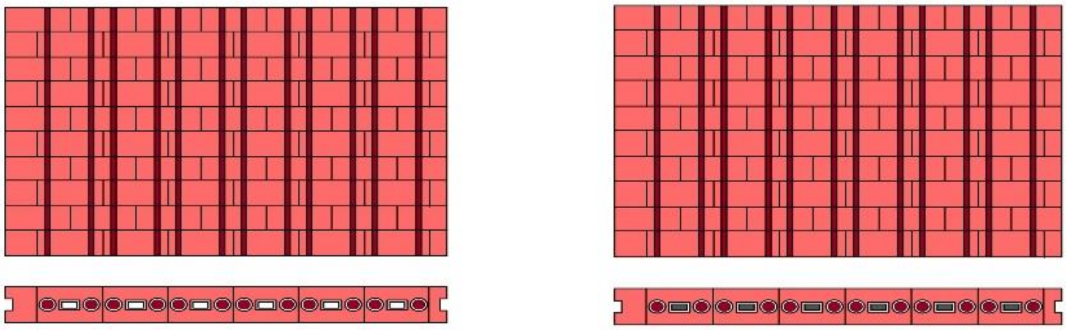
Nominal size of all the panels on the wall was 1000 mm x 1000 mm x 125 mm. The panels have been put together in running bond lay-up using mortar joint width of 10mm. In reinforced panels, the rebars were centered at the core of the hollow panels and kept vertical all through the construction. Grouted panels were filled with their core in a continuous work after laying of masonry was completed. Four wall types built and tested in this research as exhibited in Figure 2.

All the wall panels were designed with a nominal dimension of 1000 mm 1000mm 125mm. These panels were assembled using arrangements of a running bond, and a 10-mm joints of the mortar. In case of reinforced panels, the rebars were located at the center of the hollow cores and kept vertical during construction. After laying masonry, grouted panels were filled in one continuous process by pouring contents in their cores.



(a) W1 (URMW) - Unreinforced Masonry Wall with ungrouted hollow cores

(b) W2 (URMW-G) - Unreinforced Masonry wall with vertical cores Grouted



(c) W3 (RMW) - Reinforced Masonry wall with ungrouted cores, contain vertical 8mm dia Fe500 Bars

(d) W4 (RMW-G) - Reinforced Masonry wall with grouted vertical cores contain vertical 8mm dia Fe500 Bars

Fig. 2. Wall panel types (W1–W4)

The panels were also cured by covering with wet burlaps of 28 days to preserve a high-moisture environment that would promote the hydration process. After this time, the panels were air cured in the laboratory for an additional 7 days under ambient conditions to allow a moisture equilibrium before testing. Such an identical curing schedule was expected to reduce moisture gradients and allow specific material properties to be similar between all the specimens.

Table 2. Configuration of cement–clay interlocking hollow brick masonry wall specimens tested under diagonal compression

Specimen ID	Wall Type	Grouting	Reinforcement	Dimensions (mm)
W1	Unreinforced masonry	Ungrouted	None	1000 × 1000 × 125
W2	Unreinforced masonry	Grouted	None	1000 × 1000 × 125
W3	Reinforced masonry	Ungrouted	8 mm Fe 500 rebars (vertical)	1000 × 1000 × 125
W4	Reinforced masonry	Grouted	8 mm Fe 500 rebars (vertical)	1000 × 1000 × 125

2.3 Test Setup

It was done in accordance with the principles of ASTM E519 / E519M-15 diagonal compression tests. The panels were turned in 45 o to make one of the diagonals vertical. Load was added in this vertical diagonal with steel bearing shoes on the corners of the panel. The system used to apply loads was a hydraulic jack placed on top of a rigid steel loading frame on the rigid floor of the laboratory. The load was carried using a calibrated load cell mounted just over top bearing shoe which allowed the accurate determination of force applied. Each specimen was underpinned by a steel base plate, which was anchored to the floor, and the entire load, thereby applied, was directly transferred to the specimen, and no slip was possible at the support.

Each of the specimens also had two linear variable differential transformers (LVDTs) used to measure diagonal deformations. One LVDT was attached to the compressed diagonal (shortening), and another one attached to the tension diagonal (elongation). Measurements of these allowed computing the shear deformations and strains during testing. They were coupled to a digital recording data system with a frequency of 10 Hz to capture the peak behavior as well as post-peak behavior. The two signals were recorded simultaneously, the load cell readings and LVDT outputs. Observations of crack initiation and propagation as well as failure mode were recorded by visual means using high-resolution digital photography during the test. This study involved no strain gauges and other instrumentation.

All the tests were conducted in displacement control and the hydraulic jack was set to work at a rate of 0.5 mm/min. The loading rate was chosen in such a way that it will enable stable advancing of cracks as well as a reliable quantification of post-peak softening behavior. Loading was stopped when the shear stress had dropped to a much lower value than the peak stress, or until deformations were so large that it was not possible to add more load to panels. To be safe as well as complete, loading was carried to far beyond peak to define residual strength and the energy dissipation capacity.

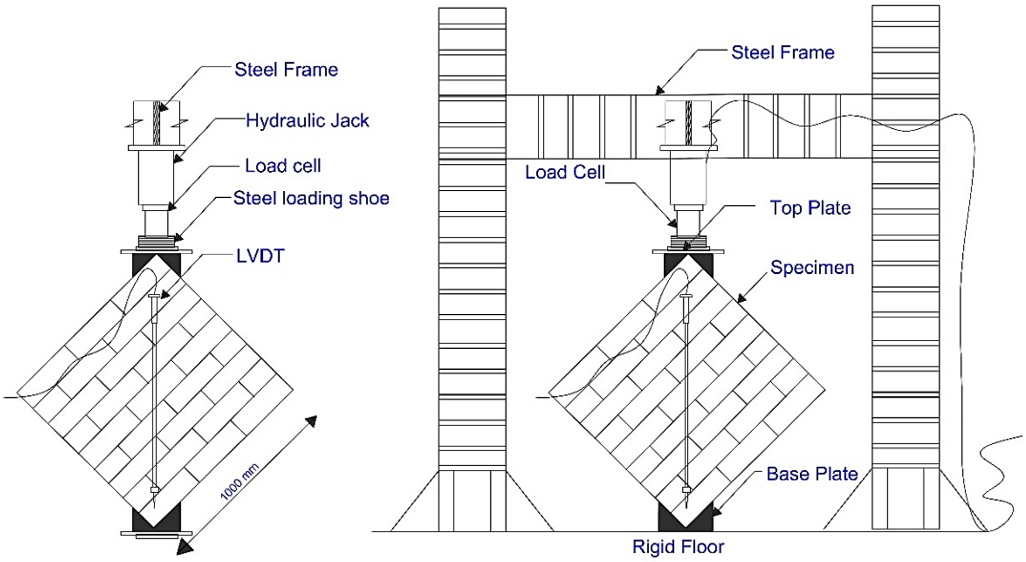


Fig. 3. Test setup and instrumentation

3. Results and Discussion

This part provides the mechanical behavior of the hollow brick masonry walls (W1 to W4), cement-clay interlocking with diagonal compression. They pay attention to their load-displacement response, shear stress-strain behaviour, energy dissipation, ductile behaviour, and failure mechanisms.

3.1 Diagonal Load–Displacement Response

All the tested wall specimen (W1 to W4) were subjected in-plane shear loading and a diagonal load displacement response. The response showed that the peak capacity, initial stiffness, and post-peak behaviour differed significantly because of the variations in reinforcement and grouting patterns. The four types of equipment walls, presented in Figure 5, gave the characteristic behaviour of masonry under diagonal compression loading: the first, linear elastic stage, followed by non-linear unloading response, including brick slippage, and resulting in the ultimate collapse governed by crack and crushing processes.

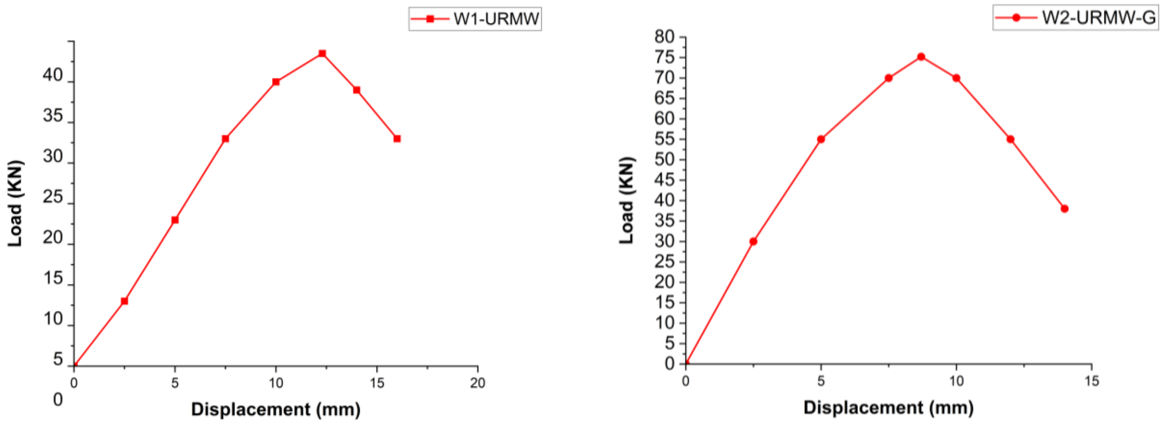
The highest peak load of 55.5 kN with a peak displacement of 20.1 mm was recorded by the reinforced ungrouted wall (W1) and the lowest comparatively was that of the unreinforced ungrouted wall (W1) which registered 38.5 kN and 12.3 mm peak displacement. This setup also showed the least initial stiffness (3.1 kN/mm) and brittle failure mode, since only one diagonal shear crack is formed. The reinforcement of the grout to the unreinforced specimen (W2) almost doubled the peak load as high as 75.2 kN and vastly improved the stiffness to 6.4 kNmm. Peak displacement was also decreased to 8.7 mm showing the influence of grout in confining the hollow brick units and restricting deformation. The failure at W2 had several diagonal cracks where the load redistribution and the increase in its shear resistance was good, where there was localized masonry crushing.

Table 3. Load–displacement performance of tested walls

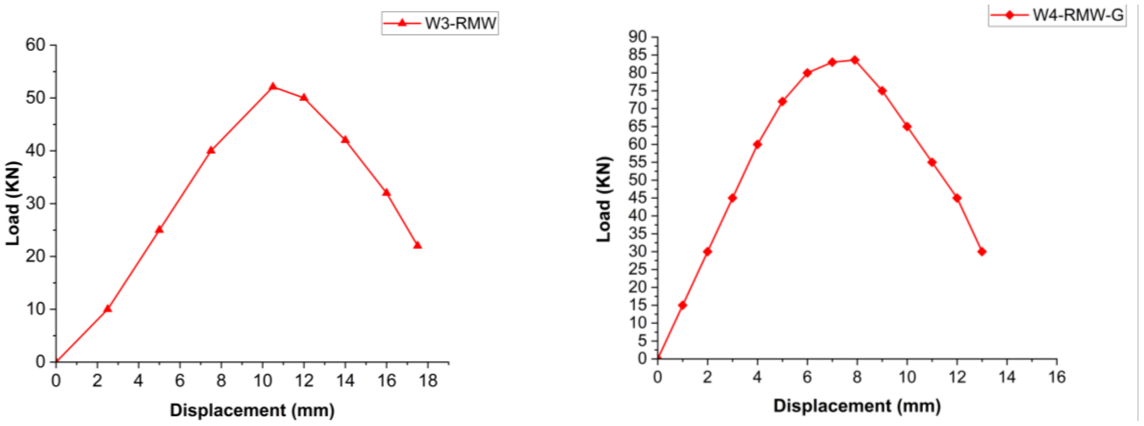
Specimen ID	Peak Load (kN)	Peak Displacement (mm)	Initial Stiffness (kN/mm)
W1	38.5	12.3	3.1
W2	75.2	8.7	6.4
W3	52.1	10.5	4.2
W4	83.6	7.9	7.1

Introducing the vertical reinforcement in the ungrouted wall (W3) led to the peak load of 52.1 kN and the peak displacement of 10.5 mm. A comparison of the load displacement curve of W3 and another showed a shallower decrease in load after the peak indicating a greater load carrying capacity in its reinforcement and a delay in its collapse. The first stiffness showed an increase to 4.2 kN/mm when compared to W1 showing that although reinforcement acted as a form of an increase in capacity, its effectiveness was not felt as much since they were not grouted to confer composite action with the masonry units. Best overall performance, the reinforced and grouted wall (W4) had the highest peak load (83.6 kN), and the minimum peak displacement of 7.9 mm. The initial rigidity was 7.1 kN/mm indicating that the synergistic effect of a combination of the use of grout and vertical reinforcement is exhibited. The W4 load-displacement response showed that it was a very strong structure that can support larger loads as it deformed less and showed greater ductility as it showed slower reduction in post peak loads than W1 and W2. Failure in W4 was of well distributed diagonal cracking with a few spitting along the cores of grouting in circles indicating good involvement of all the material components.

Quantitative comparisons are used to emphasize the fact that grouting alone gave a bigger boost of strength and stiffness over reinforcement alone. In particular, W 2 was superior to W 3 with respect to peak load (75.2 kN vs 52.1 kN), and stiffness (6.4 kN/mm vs 4.2 kN/mm). The reinforcement and grouting in W4 incorporated, however, presented the largest improvement as the peak load increased by 117 percent and the stiffness more than doubled compared to that of the baseline W1. Also, the peak-loading displacement was less severe as the number of grout and reinforcement was increased, which means that the structure is stiffer and more controlled. Such results emphasize that hollow brick masonry walls should be comprised of composite action, to resist in-plane shear forces.



(a) (b)



(c) (d)

Fig. 4. Load - Displacement curves for tested walls (a) W1 (URMW): Unreinforced masonry wall with ungrouted hollow cores, (b) W2 (URMW-G): Unreinforced masonry wall with vertical cores grouted, (c) W3 (RMW): Reinforced masonry wall with ungrouted hollow cores, containing vertical 8 mm Fe 500 rebars and (d) W4 (RMW-G): Reinforced masonry wall with grouted vertical cores containing vertical 8 mm Fe 500 rebars

Note: The x-axis and y-axis scales are individualized for each subplot to preserve graphical clarity and accurately represent the distinct load–displacement behavior of each wall configuration in Figure 4.

3.2 Energy Dissipation, Ductility and Stiffness Performance

The overall evaluation of energy dissipation, ductility as well as initial stiffness will give the overall knowledge of the in-plane shear behavior of masonry walls subjected to the diagonal compression. The combination of these parameters indicates the ability of the walls to resist lateral forces; inelastic deformation without violent failure; ability to restrict initial displacements underload. As summarized in Table 4 and plotted in Figure 6a and Figure 6b, it can be pointed out that the role of the grouting and reinforcement was significant on the structural response.

The low energy dissipation (185 kNmm), ductility index (2.8) and initial stiffness (3.1 kN/mm) of the unreinforced ungrouted wall (W1) were some of the specifications of the tested specimens. Strictly dealing with the brittle failure, the high prevalence of a single diagonal crack, the fast rate of post-peak load, and failure restricted the capacity of W1 to absorb energy, as well as a large deformation. The use of grout on W2 resulted in significant improvement as the energy dissipation was 390 kN-mm (111 percent greater than W1), the ductility index was 3.9 (compared to 2.9 in W1, 39 percent more), and the initial stiffness was 2 times larger, 6.4 kN/mm. This was achieved because the grout added internal confinement, which allowed distributed cracking, slow failure, and increased load redistribution capacity, thus fomenting both deformation control and toughness.

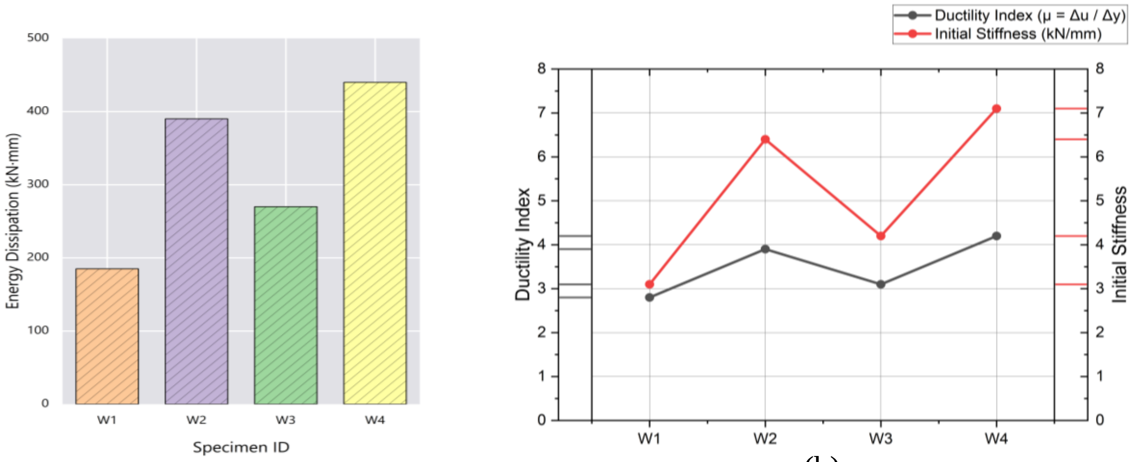
Vertical reinforcement in W3 has brought moderate gains on its own. Dissipation of energy improved to 270 kN.mm (46 percent improvement over W1), the ductility index improved in the slightest way to 3.1 and initial stiffness rose to 4.2 kN/mm. The steel rebars helped in bridging crack and post-cracking resistance of the loads but not as effective in restraining initial deformations and energy disappointment in the lack of grout to make the brick and mortar composite.

Table 4. Energy dissipation, ductility index, and initial stiffness of tested walls

Specimen ID	Energy Dissipation (kN·mm)	Ductility Index (μ = Δu / Δy)	Initial Stiffness (kN/mm)
W1	185	2.8	3.1
W2	390	3.9	6.4
W3	270	3.1	4.2
W4	440	4.2	7.1

The wall with the reinforced grouted (W4) had the most desirable performance by all the measures. It earned the best energy dissipation (440 kN.mm), increased the best ductility index (4.2 or 50 percent more than W1) and the best initial stiffness (7.1 kN/mm which is 129 percent more than W1). Such combination of grout and reinforcement allowed W4 to restrict initial shear deformations, carry high loads with these deformations being developed in a controlled manner, and inelastic deformed before failure. The load displacement curves showed more gradual post peak soft paths with a better energy absorption and deformation capacity than the other obvious configurations.

Based on the relative trends, there was no doubt that grouting used alone had a greater beneficial effect on the performance of the structure as compared to the reinforcement used alone. Yet, the combination of grout and vertical steels in W4 was the best combination of strength, stiffness, ductility, and energy dissipation needed by masonry systems that is built to withstand lateral forces.



(a)

(b)

Fig. 5. Performance of W1–W4 wall specimens(a) Bar Graph for Energy Dissipation and (b) Curves Indicating Ductility Index and Initial stiffness

3.3 Failure Modes and Cracking Patterns

The cracking pattern and the failure mode of the masonry wall specimens of which were tested present very important details about the mechanisms of shear resistance and deformation behavior of the load masonry walls under through-thick diagonal compression. The nature of failures of the reported four configurations namely unreinforced ungrouted (W1), unreinforced grouted (W2), reinforced ungrouted (W3) and reinforced grouted (W4) was captured in Table 5 and shown in figure 7.

In all specimens, development of diagonal tension cracks in transverse directions along diagonal lines of maximum principal tensile stress indicated the onset of failure as it would be expected in masonry exposed to racking shear forces. The occurrence, distribution and the post-cracking behavior was however found to vary highly depending on whether there was use of grout and reinforcement.

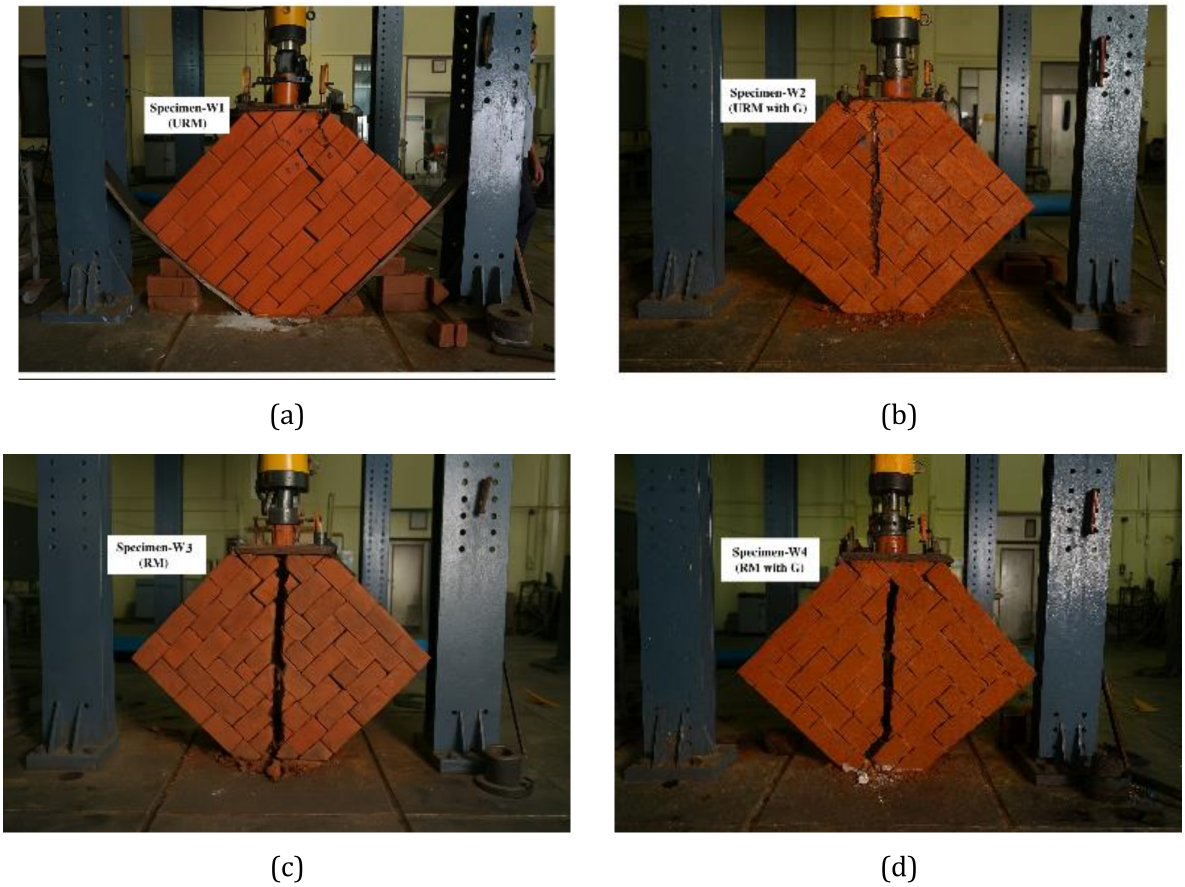
The wall of ungrouted and unreinforced construction (W1) exhibited brittle failures, with only a single and well-defined diagonal crack taking the load through one corner that was load-free to the far constrained corner. When the peak load was attained the crack propagated very quickly and the loss of load-carrying capacity was abrupt. The results that were found showed minimal crushing of the brick units meaning that tensile failure of the masonry led the response.

Conversely, the grouted wall was unreinforced (W2) and it displayed several diagonal and stepped cracks which were evenly spread throughout the panel. Internal restraint given by the grout cores slowed down coalescence of cracks and the formation of a single dominant plane of failure. A more ductile failure mode was achieved and post-peak energy dissipation was enhanced due to localised crushing of masonry in areas of maximum compressive stress that tend to be found around grouted zones. The increase in the crack distribution in W2 was also an additional factor leading to the increase in load-bearing capacity over W1.

Table 5. Summary of observed failure modes in tested walls

Specimen ID	Dominant Crack Pattern	Crushing Zones	Post-Peak Behaviour
W1	Single diagonal crack	Minimal	Brittle, rapid collapse
W2	Multiple diagonal/stepped cracks	Near grouted cores	Gradual, ductile failure
W3	Diagonal + stepped mortar joint cracks	Limited	Moderate softening, crack bridging
W4	Distributed diagonal + splitting cracks	Compression strut, grouted core zones	Most ductile, controlled failure

Reinforced ungrouted wall (W3) developed cracks in the diagonal pattern that resembled W1, with the cracks being stepped in the order, followed partially in the mortar joints. The onset presence of the vertical steel reinforced increased the load carrying capacity after a crack and as the reinforcement crossed the cracks the rebars provided dowel action. This meant more moderate appliance of an appliance after peak and better crack control than using W1. Nonetheless, without grout, the reinforcement could not play its roles in limiting the opening of the cracks and sharing the stresses to the fullest capacity.



(a) (b)

(c) (d)

Fig. 6. Representative cracking patterns and failure modes of W1–W4 specimens (a) W1 – URMW, (b) W2 - URMW – G (c) W3 - RMW and (d) W4 - RMW - G

Reinforced grouted wall (W4) exhibited the best crack pattern and mode of failure of the specimens. A network of diagonal cracks was well distributed over the panel besides splitting cracks around the grouted cores which reveal that there was effective transfer of load among the grout, reinforcement, and units' masonry. The crushing of the brick work was observable near the load corners as well as the zone of compression struts indicating a possible equal proportion of tensile cracking and compression crushing to cause failure. The comprehensive effect of grout reinforcement improved the shear strength and energy-dissipation ability of the wall besides shrinking large crack gaps and sudden collapse.

3.3 Combined Shear Stress–Strain Behavior

Shear stress strain behavior of the interlocking hollow brick cement clay masonry walls under test gives a very important indication of the ability of these walls to carry in-plane lateral actions whilst exhibiting controlled deformations. The stress-strain curves constructed based on the test data show an understandable difference between the four versions of the walls, the influence of the grouting and reinforcement showed itself not only in the peak capacities but also in the post-peak behavior. As seen in Table 6 and as explained in Diaphragm Tests, the increase in peak shear caused by the combined effects of grout and rebars placed vertically was 119% with the highest value 0.68 MPa in reinforced grouted specimen (W4) and the lowest value 0.31 MPa in unreinforced ungrouted specimen (W1). In the same manner, the peak shear strain rose to 0.52% in W4 compared to 0.37% in W1 and was proof of better deformation capacity and energy absorption.

The linear sections of the stress-strain curves show how the increasing stiffness resulted, as grout and reinforcement were added. Well, W1 had the most accommodating reaction which steelously climbed to peak stress before collapsing immediately after it was achieved, because of a single and overriding diagonal crack, whereas W2 had a much steeper initial slope and peak shear stress. The existence of grout improved the mechanism of transferring loads, constrained the masonry units as well as distributed stresses more evenly, allowing the wall to carry loads of better magnitudes and bigger deformations before collapse. In W3, vertical reinforcement gave the crack-bridging capacity, and constrained the width of the cracks, with the net result that there were slight improvements in peak stress and strain compared with W1. Nevertheless, it could have accomplished little without the grout since the distribution of the load was minimal.

Table 6. Summary of shear stress–strain response of tested walls

Specimen ID	Peak Shear Stress (MPa)	Shear Strain at Peak (%)
W1	0.31	0.37
W2	0.61	0.48
W3	0.42	0.41
W4	0.68	0.52

The reinforced grouted wall (W4) gave the most desirable behavior in terms of stress-strain behavior, which was provided by the steepest initial stiffness, maximum stress, and softening that occurring in post peak with the least gradual slope. This behavior was an expression of the synergistic effect of the combination of masonry, grout and reinforcing which enabled the transfer of cracks throughout the structure and hence the delayed occurrence of major damage and the capability to maintain prolonged shear strength after large amounts of inelastic deformation were produced. W4 stress strain envelope showed not only stronger, stiffer plate, but an especially high level of ductility and energy absorption, which are key factors in masonry systems that must be placed in a seismic/high wind environment. The hierarchy of the performance which is clearly evident when comparing the comparative curves (Figure 8) shows that the maximum performance of the W4 configuration was better overall in comparison with the other configurations in both the shear strength and deformation capacity, followed by W2, W3 and W1.

In comparison with previous works by Joyklad et al., the present study isolates the influence of vertical reinforcement in cement–clay interlocking hollow brick (CCIHB) walls, a factor not explicitly addressed in earlier investigations. Joyklad et al. [1] reported that unreinforced interlocking masonry walls exhibited brittle diagonal cracking under diagonal compression, with limited ductility. Their subsequent work on CFRP and cement–sand mortar strengthening [2] improved shear strength but required externally bonded retrofitting techniques that are relatively costly and less feasible for large-scale application in low-income housing. By contrast, the present study demonstrates that combining grout infill with vertical reinforcement provides an integrated solution, improving shear strength by 119% while enhancing ductility and energy dissipation. Unlike externally applied CFRP systems, the proposed approach uses conventional materials and simple construction practices, making it highly scalable. Moreover, unlike predictive modeling studies [3], this work provides experimental validation of reinforcement effects, offering practical insights for design and code development in seismic and wind-prone regions.

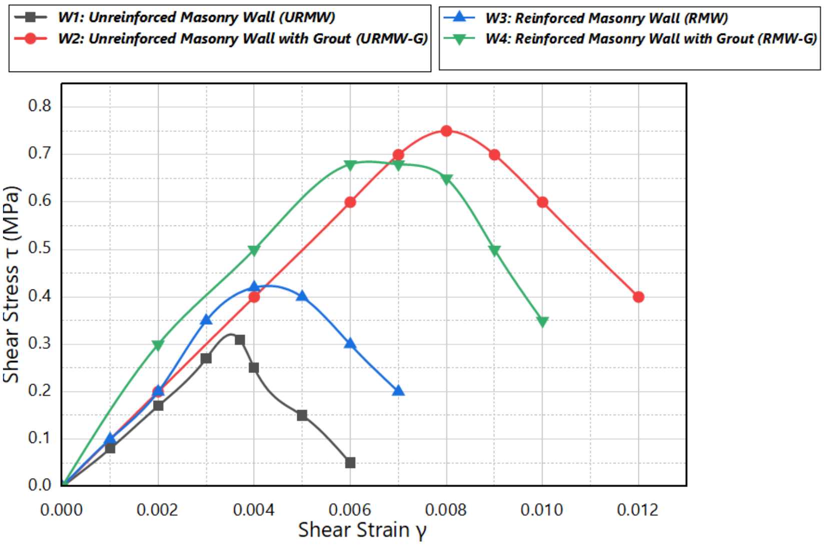


Fig. 7. Shear stress–strain curves for W1–W4 specimens

Table 7. Comparison of present study with previous works by Joyklad et al.

Study	Strengthening Method	Peak Shear Strength Improvement	Ductility Behavior	Failure Mode	Practical Implications
Joyklad et al. (Diagonal Compression)	Unreinforced CCIHB	–	Limited, brittle response	Sudden diagonal cracking	Demonstrated baseline weakness of CCIHB
Joyklad et al. (CFRP/Mortar Strength.)	CFRP laminates + cement mortar	~80–100%	Improved ductility, but external FRP	Debonding + cracking	Effective but costly; limited scalability
Joyklad et al. (Predictive Modeling)	Empirical models for CCIHB	N/A	Modeled stiffness/strength trends	N/A	Provided predictive framework
Present Study (2025)	Grout (1:2) + vertical Fe 500 rebars	119%	Significant improvement; controlled cracking	Distributed cracking + localized crushing	Economical, scalable, sustainable solution

4. Conclusion

This study has investigated the in-plane shear behavior of cement–clay interlocking hollow brick masonry (CCIHB) walls subjected to diagonal compression, with a focus on the effects of grout infill and vertical reinforcement. Experimental results demonstrate that grout infill significantly increases the peak shear strength and initial stiffness of masonry walls, while vertical reinforcement enhances ductility and delays brittle diagonal cracking. The combination of grout and reinforcement produced the most favorable performance, with a 119% improvement in peak shear stress compared to the unreinforced control wall. These results confirm the potential of CCIHB masonry as a sustainable and resilient system for structural applications.

Beyond laboratory performance, the findings have broader implications for sustainable construction in seismic and wind-prone regions. The integration of grout and reinforcement provides a cost-effective means of strengthening masonry without resorting to expensive external retrofitting methods, such as CFRP laminates. This makes the system particularly attractive for low- to middle-income communities, where affordability and constructability are critical. Furthermore, the use of locally available clay and cement-based materials supports resource efficiency and reduces reliance on energy-intensive alternatives.

Practical recommendations from this study include the adoption of grout mixes with a 1:2 cement-to-sand ratio and slump values around 220 mm, which proved effective in enhancing bond and filling interstices. Vertical reinforcement using Fe 500 rebars provided additional crack control and energy dissipation, suggesting that modest reinforcement detailing can yield significant performance benefits. Policymakers and engineers are encouraged to consider these findings in revising design codes and standards for masonry construction in seismic regions, where current provisions for interlocking systems remain limited.

In summary, the study demonstrates that CCIHB masonry with grout and vertical reinforcement offers a viable pathway toward sustainable, durable, and disaster-resilient construction. By combining material efficiency, ease of implementation, and structural reliability, this system represents a practical solution for improving housing resilience in vulnerable regions.

References

[1] Joyklad P, Hussain Q. Axial compressive response of grouted cement–clay interlocking hollow brick walls. Asian J Civ Eng. 2019;20(5):733–44. https://doi.org/10.1007/s42107-019-00140-2

[2] Joyklad P, Ali N, Rashid MU, Hussain Q, Magbool HM, Elnemr A, Chaiyasarn K. Strength enhancement of interlocking hollow brick masonry walls with low-cost mortar and wire mesh. Infrastructures. 2021;6(12):166. https://doi.org/10.3390/infrastructures6120166

[3] Wilding BV, Dolatshahi KM, Beyer K. Shear-compression tests of URM walls: Various setups and their influence on experimental results. Eng Struct. 2018;156:472–9. https://doi.org/10.1016/j.engstruct.2017.11.057

[4] Garcia-Ramonda L, Pelà L, Roca P, Camata G. In-plane shear behaviour by diagonal compression testing of brick masonry walls strengthened with basalt and steel textile reinforced mortars. Constr Build Mater. 2020;240:117905. https://doi.org/10.1016/j.conbuildmat.2019.117905

[5] Casapulla C, Mousavian E, Argiento L, Ceraldi C. Torsion–shear behaviour at the interfaces of rigid interlocking blocks in masonry assemblages: Experimental investigation and analytical approaches. Mater Struct. 2021;54:43. https://doi.org/10.1617/s11527-021-01721-x

[6] Joyklad P, Hussain Q. Experimental study on axial and diagonal compressive behavior of brick masonry walls. Kasem Bundit Eng J. 2018;8(2). Available from: https://ph01.tci-thaijo.org/index.php/kbej/article/view/133170

[7] Sandoval C, Calderón S, Almazán JL. Experimental cyclic response assessment of partially grouted reinforced clay brick masonry walls. Bull Earthq Eng. 2018;16(8):3127–52. https://doi.org/10.1007/s10518-018-0308-x

[8] ASTM International. Standard Test Method for Diagonal Tension (Shear) in Masonry Assemblages (ASTM E519/E519M-15). West Conshohocken (PA): ASTM International; 2015.

[9] Di Maggio E, Milani G, Lourenço PB. Experimental and numerical insights on the diagonal compression test for the shear characterisation of masonry. Constr Build Mater. 2021;289:124789. https://doi.org/10.1016/j.conbuildmat.2021.124789

[10] Yin L, Wang Y, Li X. Numerical investigation on masonry panel under diagonal compression. Discov Concr Cement. 2023;1:5. https://doi.org/10.1007/s44416-025-00007-7

[11] Joyklad P, Waqas HA, Hafeez A, Ali N, Ejaz A, Hussain Q, Khan K, Sangthongtong A, Saingam P. Experimental investigations of cement–clay interlocking brick masonry structures strengthened with CFRP and cement-sand mortar. Infrastructures. 2023;8(3):59. https://doi.org/10.3390/infrastructures8030059

[12] Pulatsu B, Gonen S, Lourenço PB, Lemos JV. Computational investigations on the combined shear–torsion–bending behavior of dry-joint masonry using DEM. Comput Part Mech. 2022. https://doi.org/10.1007/s40571-022-00493-7

[13] Morinière F, Lourenço PB. Recommended properties for advanced numerical analysis of masonry: Interface and material parameters. In: Finite Element Analysis for Building Assessment. London: Routledge; 2022. p. 209–320. https://doi.org/10.1201/9780429341564-4

[14] Priestley MJN, Elder DM. Cyclic loading tests of slender concrete masonry shear walls. Bull N Z Soc Earthq Eng. 2015;48(1):3–21. https://doi.org/10.5459/bnzsee.15.1.3-21