15th Canadian Masonry Symposium
Ottawa, Canada
June 2-5, 2025

Experimental Investigation on Unreinforced and Waste Fibre-Reinforced Masonry Under Impact Loading

Joel Junias[i], Nikhil Ranjan[ii], Sanket Nayak[iii], and Sreekanta Das[iv]

ABSTRACT

Most of the population in developing countries like India live in masonry houses. These structures are common because the materials are readily available and affordable. However, masonry houses located alongside roads or in hilly areas are vulnerable to natural calamities, such as rockfalls and debris flows due to landslides. While these structures perform well under gravity loads but are inadequate in withstanding lateral loads. Therefore, it is essential to mitigate these structures against lateral forces. In this study, an experimental investigation was conducted in which unreinforced and reinforced single brick walls measuring 1.5 m in length and 1.5 m in height were constructed. The coir fibre (agro waste) and nylon fibre (textile waste) were added to the mortar mix to test their effectiveness in strengthening unreinforced masonry walls (URM) against impact loading. A pendulum impact test setup was fabricated, consisting of a pendulum arm and external weight disks to introduce impact loads on the specimens. A 70 kg weight was attached to the pendulum arm, and the specimens were subjected to impact loading at the centre of the wall using a hemispherical-shaped impactor released at a 30^{o} angle. The reinforced masonry specimens exhibited significantly better performance than the URM in terms of impact resistance, load-carrying capacity, and energy absorption. This improvement may be attributed to the increase in tensile strength of the URM due to the addition of fibres, which initiates a fibre-bridging mechanism that restricts further crack propagation. This keeps the masonry intact and prevents the impactor from penetrating the wall, enabling the reinforced structures to endure more hits than the unreinforced specimen

KEYWORDS

Masonry, impact, pendulum, strengthening, fibre

[i] Research Scholar, Indian Institute of Technology (ISM), Dhanbad, India, 21dr0066@cve.iitism.ac.in
[ii] Assistant Professor, Gati Shakti Vishwavidyalaya, Vadodara, India, nikhil.ranjan@gsv.ac.in
[iii] Associate Professor, Indian Institute of Technology (ISM), Dhanbad, India, sanket@iitism.ac.in
[iv] Professor, University of Windsor, Canada, sdas@uwindsor.ca

INTRODUCTION

Masonry structures are widely used for housing across various regions, especially in developing countries where 70% of the population resides in these non-engineered dwellings [1]. Masonry structures are popular because of their sound insulation properties, thermal efficiency, and ease of construction, as the required constituents of masonry are readily available and affordable [2-5]. Typically, masonry walls serve as infill panels in reinforced concrete (RC) structures and can be classified into in-plane and out-of-plane walls based on their orientation to the direction of loading. In-plane walls are aligned parallel to the load direction, while out-of-plane walls are perpendicular [6]. While masonry structures generally perform well under gravity loads, they are vulnerable to lateral loads such as earthquakes and impact events, often resulting in significant damage and loss of life [7]. Unreinforced masonry (URM) walls are prone to lateral forces due to their inadequate tensile strength, weak bonding between bricks and mortar, and limited energy absorption capacity, often collapsing shortly after crack initiation [8-11]. To improve the lateral load resistance of masonry, researchers have explored various strengthening techniques, broadly categorized into external and internal methods. External reinforcement often involves mesh-type reinforcements or wrapping materials like polypropylene (PP) bands or geonets [12-13], while internal reinforcement typically uses fibres incorporated into the mortar mix to enhance its mechanical properties. Various fibres, including coconut, wool, nylon, and steel, have been used to reinforce concrete and mortar, preventing crack widening and enhancing the masonry's tensile capacity, as reported in previous studies [14-16].

Coir, a plant-based fibre extracted from coconuts, has shown enhanced mechanical properties of cementitious composites, reducing the self-weight of specimens by 5–12% and increased flexural strength by up to 12%. Furthermore, the toughness of coir-reinforced specimens improved ninefold, and ductility property was significantly enhanced [17]. Coir fibres strengthened the masonry against seismic loads and improved mortar tensile strength and crack control. Nylon, another material with significant waste disposal issues, is primarily derived from sources such as fishing nets, ropes, and carpets, with fishing nets contributing to 10% of marine pollution. Incorporating nylon fibres into the construction industry can help reduce landfill waste and mitigate environmental pollution [18]. Studies have demonstrated that nylon-reinforced cement mortar improved tensile strength by up to 35%, enhanced toughness by 13 times compared to URM, and improved flexural strength by 22%, resulting in better crack resistance [19]. Furthermore, when nylon fibres were mixed in varying proportions (0.10%, 0.20%, and 0.30% by weight), flexural strength improved by 28%, and the load-carrying capacity of the specimens increased by 106.3% in-plane and 161% out-of-plane compared to the unreinforced specimens [10].

RESEARCH SIGNIFICANCE

Vehicle collisions with roadside structures and landslide-related accidents are increasingly common in hilly regions, posing significant risks to both property and human lives. Such incidents generate high-impact forces in a short period, often leading to the failure of masonry structures, particularly in the flexural direction. The primary reason for the failure in flexural direction is due to the insufficient bond strength between bricks and mortar, which cannot withstand such extreme loads as illustrated in Fig. 1. To address these shortcomings, enhancing the impact resistance and flexural strength of masonry structures through appropriate strengthening measures is necessary. However, experimental research on the behavior of masonry under impact loading remains limited. This study investigates using agro-waste (coir fibres) and textile waste (nylon fibres) to reinforce mortar for strengthening masonry walls. The fibres, with lengths of 15 mm for coir and 18 mm for nylon, were incorporated into the mortar at 0.10% by weight. To assess the effectiveness of the fibre mixed in the reinforced walls against impact loading, a 70 kg load was applied to the centre of each wall using a pendulum impact test frame equipped with a load cell. Additionally, mortar cubes and prisms were cast to measure compressive and flexural strengths. Key parameters, including impact resistance, force-time history, displacement-time history, and energy absorption capacity, were analyzed and compared between unreinforced and reinforced walls.

Figure 1: Damage in the house due to vehicle impact.

EXPERIMENTAL PROGRAM

Experimental Design

A pendulum impact loading experiment was conducted on masonry walls consisting of an unreinforced wall (serving as the control wall) and fibre-reinforced walls. To assess the mechanical properties of the mortar, groups of mortar cubes and prisms were cast to measure compressive and flexural strengths, respectively. These specimens were tested at 7 and 28 days, with each group containing three specimens.

Material Characterization

Brick and Sand

Fly ash bricks were utilized in constructing the walls, with their physical and mechanical properties summarized in Table 1. The sand used as the fine aggregate in this study falls under Zone II (medium sand), and its properties are provided in Table 2. As per Indian standards, the sand is classified into four zones based on the percentage of sand passing through different sieve sizes.

Table 1. Physical and mechanical properties of bricks.

Property	**Value**
Density	1850 kg/m^3
Dimension (mm)	230 × 110 × 80
Compressive strength (MPa)	8.33 (CoV: 7.3, SD: 0.69) (IS 13757:1993) [20]
Water absorption (%)	14.86 (CoV: 5.9, SD: 0.89)
Tensile strength (MPa)	0.95 (CoV: 6.3, SD: 0.08)

Table 2. Physical properties of sand.

Property	Value
Grading zone	II
Fineness modulus	2.8
Specific gravity	2.7
Water absorption	1.05%
Free surface moisture contact	0.53%
Bulk density	1.51 kg/m^3
Bulking of sand	10.30%

Strengthening Techniques

Coir fibre

The coir fibres used in this study were untreated upon purchase. The fibres were thoroughly cleaned, washed with water, and dried at room temperature before use. Based on prior research [17], the coir fibres used in this study measure 15 mm in length and 0.20 mm in diameter. Their physical and mechanical properties are listed in Fig. 2.

Nylon fibre

Previous studies have shown that nylon fibres [19] have significantly improved load-carrying capacity and bond strength, making them an effective reinforcement material. In this study, recycled nylon fibres were sourced from discarded fishing nets, carpets, and waste plastic ropes. The physical and mechanical properties, as provided by the manufacturer, are detailed in Fig. 2.

Mortar

The mortar mix was prepared using a cement-to-sand ratio of 1:4. Initially, the cement and sand were thoroughly dry-mixed for about 3 minutes. Following this, the fibres were added to the dry mix and thoroughly mixed before water was added to achieve a consistent mixture.

Compressive and flexural strength tests were conducted on mortar cubes and prisms on 7 days and 28 days to evaluate the effectiveness of fibre-reinforced mortar. The mortar cubes, measuring 70.6 mm × 70.6 mm × 70.6 mm [21], and prisms, sized 500 mm × 100 mm × 100 mm [22], were cast following the standard guidelines for these tests.

Fibres were added at 0.10% by weight of the unreinforced mortar for coir fibre-reinforcement based on prior experimental findings that demonstrated improved flexural strength, displacement, and ductility properties with this concentration [23]. The reinforced cubes exhibited a decrease in compressive strength by 31.8% and 30.8% compared to unreinforced ones. However, the prisms showed notable improvements in flexural strength, increasing by 30.3% and 30.8% at 7 days and 28 days, respectively, as shown in Fig. 3.

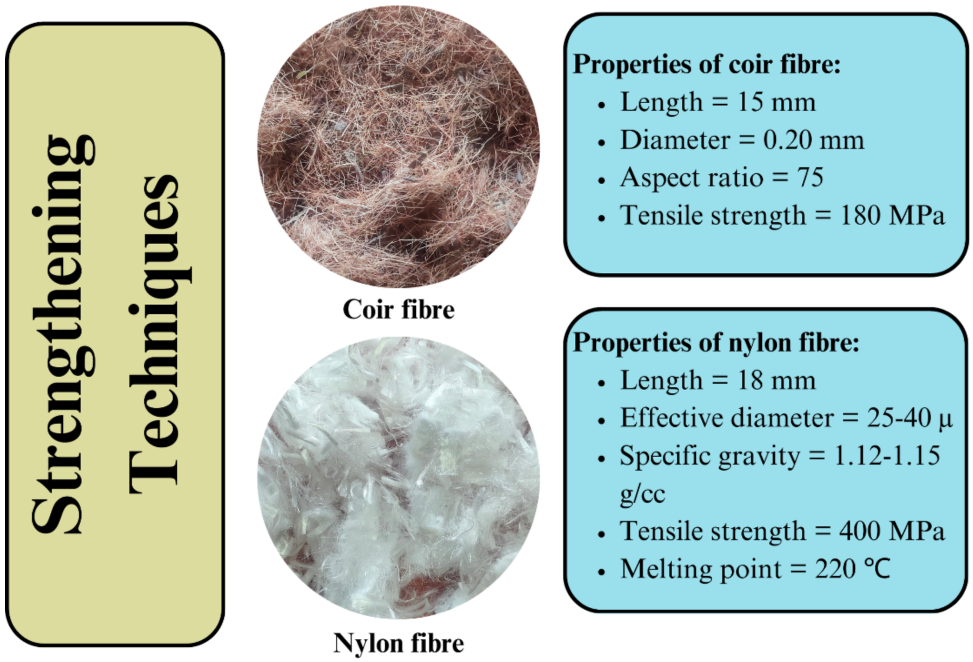
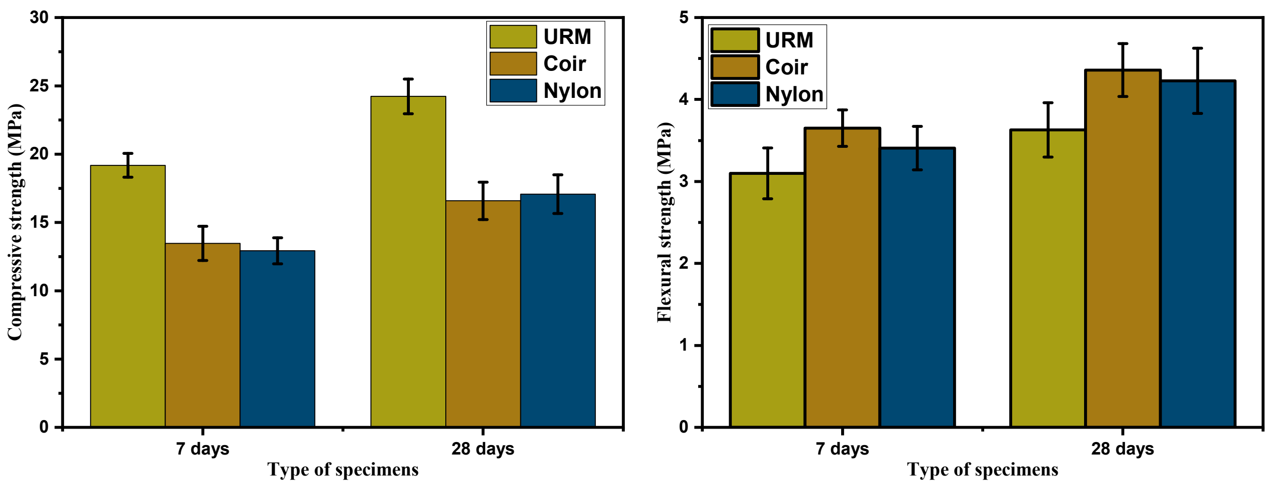


Figure 2: Physical and Mechanical Properties of Coir and Nylon Fibres.

Similarly, for nylon fibre reinforcement, 0.10% by weight of the control mortar was used, a concentration identified as optimal in previous studies [18]. The reinforced cubes showed a reduction in compressive strength by 34.6% and 35.3% after 7 and 28 days, respectively. In contrast, the flexural strength of the reinforced prisms increased by 30.47% and 33.45% at the same intervals, as illustrated in Fig. 3. The observed decrease in compressive strength of fibre-reinforced mortar cubes can be attributed to increased porosity caused by fibre addition and the corresponding reduction in cement content. However, this reduction does not significantly impact the structural integrity of masonry, as masonry structures are inherently good at enduring compressive loads. Notably, all fibre-reinforced specimens exhibited substantially enhanced flexural strength and lateral load-carrying capacity.



(a) (b)

Figure 3: (a) Variation in Compressive Strength for Unreinforced and Fibre-Reinforced Cubes; (b) Variation in Flexure Strength for Unreinforced and Fibre-Reinforced Prisms.

Construction Details

The walls, measuring 1.5 m × 1.5 m × 0.110 m (length × height × thickness), were constructed using fly ash bricks. Three groups of walls were built, each comprising 17 layers of bricks stacked one over the other. A uniform 10 mm thickness of mortar was used for plastering. The fibre-reinforced mortar was applied to the plaster and the joints (head and bed) for the reinforced wall. The walls were painted white to facilitate the observation of crack propagation and deformation during testing. After construction, the walls were cured by water spraying for 28 days to ensure proper strength development.

EXPERIMENTAL SETUP

Impact loading test

The experimental setup included a pendulum impact frame with dimensions of 4.5 m in height, 1.5 m in length, and 1.5 m in width. The pendulum arm, measuring 4 m in length, was hinged at the top of the frame, allowing it to swing freely. A 50-tonne load cell was mounted on a pin located 3.75 m from the top hinge, with a hemispherical impactor attached in front of it to ensure precise impact at the centre of the wall. The load cell measured the impact force, while a linear variable differential transducer (LVDT) with a sensitivity of ±100 mm recorded the wall displacement. The LVDT was positioned directly behind the wall at the point of impact.

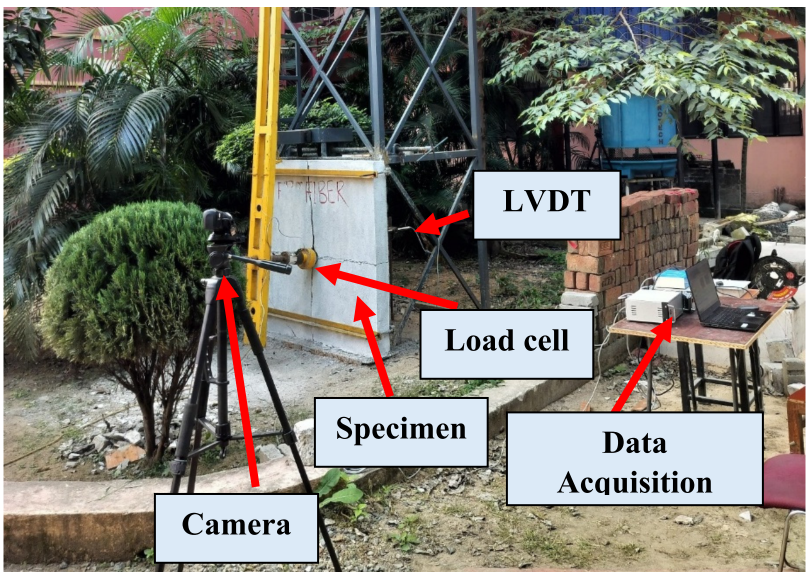


Figure 4: Impact Loading Test Setup and Instruments.

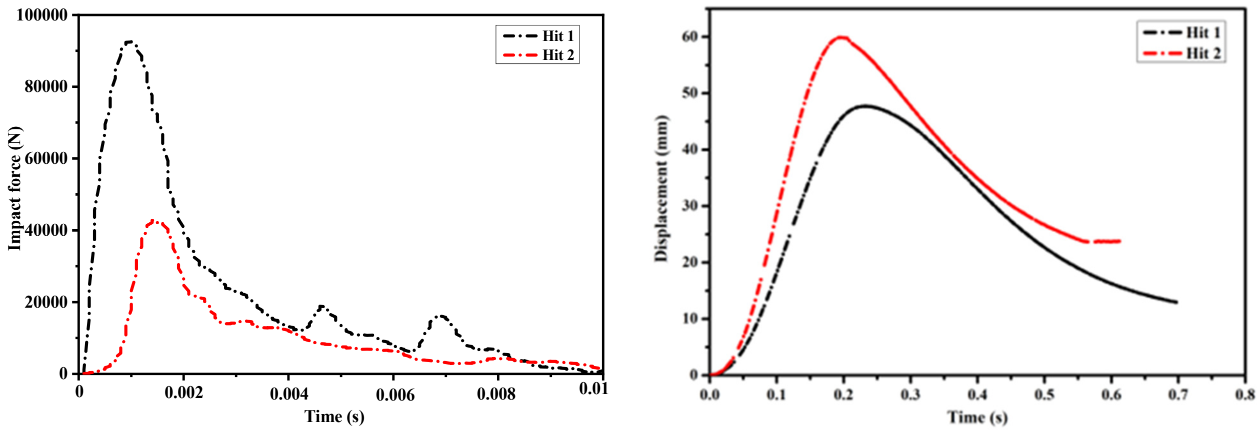
A total mass of 70 kg, including the pendulum arm, was used for the test. The pendulum arm was released from a 30-degree angle to generate the impact. Data recording was facilitated by an NI USB 16-channel data logger with a trigger system that captured data for 5 seconds, starting just before the impact and stopping automatically after the interval. The complete impact loading test setup is illustrated in Fig. 4.

RESULTS AND DISCUSSIONS

Unreinforced specimens

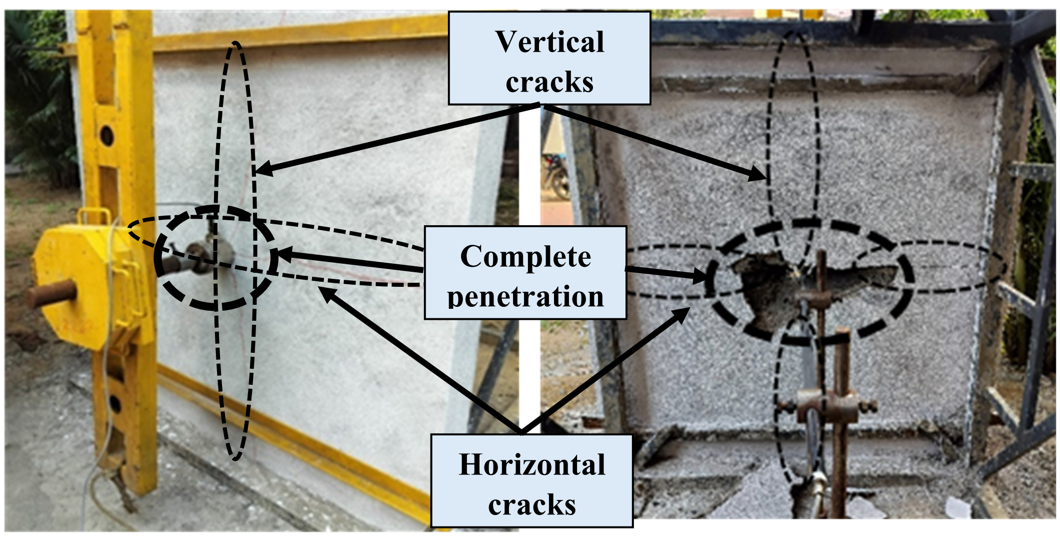
The unreinforced wall endured two impacts before collapsing entirely. During the first impact, a peak force of 91,565 N was recorded, with corresponding peak and residual displacements of 47 mm and 12.9 mm, respectively. In the second impact, the peak force dropped significantly to 42,771 N, nearly 53% lower than the first, as illustrated in Fig. 5.

The second impact resulted in peak and residual displacements of 59.95 mm and 23.67 mm, respectively. The wall absorbed 28.8 joules of energy during the first impact. The damage pattern of the URM wall in the last hit is shown in Fig. 6.



(a) (b)

Figure 5: Impact Loading History of URM Specimen: (a) Force-Time History; (b) Displacement-Time History.



(a) Front Side (b) Rear Side

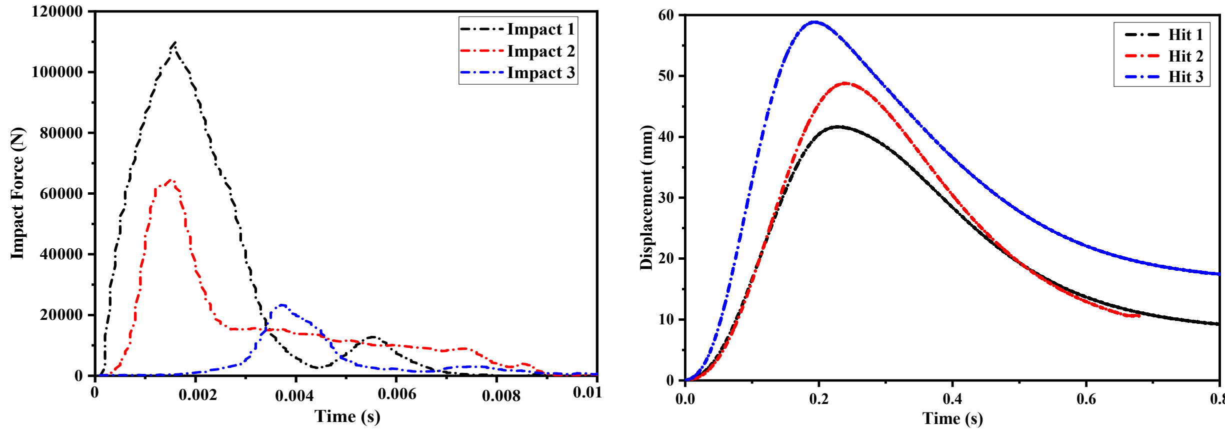
Figure 6: Damages In URM Wall In the Last Hit.

Reinforced specimens

Coir fibre

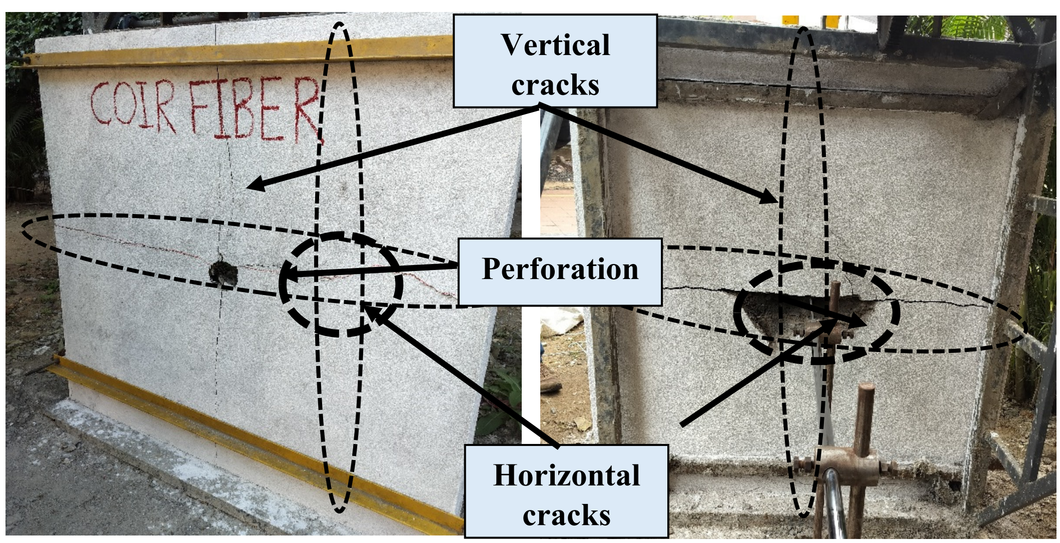
The coir fibre-reinforced wall demonstrated the ability to endure three impacts before the experiment was halted due to significant damage on the tension side during the third impact. The peak impact forces recorded for the three impacts were 109,804 N, 64510 and 23,083 N, respectively, which represented increases of 19.9% and 50.8% compared to the unreinforced masonry (URM) in the first and second impacts, as shown in Fig. 7. However, the wall's resistance to impact decreased by 41.2% after the first impact. Peak and residual displacements were recorded as 41.8 mm and 8.9 mm for the first impact and

48.7 mm and 10.8 mm for the second, with values lower than those observed in the unreinforced wall. The coir fibre strengthened the wall's damage pattern, as shown in Fig. 8.



(a) (b)

Figure 7: Impact Loading History of Coir Fibre-Strengthened Specimen: (a) Force-Time History; (b) Displacement-Time History.



(a) Front side (b) Rear side

Figure 8: Damages in Coir Fibre Strengthened Wall in the Last Hit.

The wall also showed improvement in energy absorption, with a calculated capacity of 40.6 J, representing a 40.9% increase over the URM specimen. The second impact resulted in perforation primarily on the back side, disrupting the stress distribution across the wall's surface. Despite this, the coir fibres prevented the wall from completely collapsing. Overall, the coir fibre-reinforced wall demonstrated superior performance compared to the unreinforced masonry in terms of impact resistance. This was evident through higher peak forces, reduced residual displacement, and enhanced energy absorption attributed to the fibre-bridging mechanism, as shown in Fig. 7.

Nylon fibre

The nylon fibre-reinforced wall demonstrated superior impact resistance compared to the unreinforced masonry (URM) counterpart, withstanding three hits before the experiment was terminated. In contrast, the URM wall could only endure two impacts. The peak forces for the three impacts were 107,560 N, 76,375 N, and 16,024 N, respectively, as shown in Fig. 9. The peak impact forces for hits 1 and 2 were 17.4% and 75.9% higher than those observed for the URM wall, respectively. However, resistance decreased significantly after each subsequent impact, with the peak impact force dropping by 28.9% after the first hit and 79.0% after the second, primarily due to the formation of cracks during the second hit and perforation during the third, which disrupted stress distribution across the wall's surface. The peak displacement and the residual displacements were recorded at 24.07 mm and 4.51 mm, respectively.

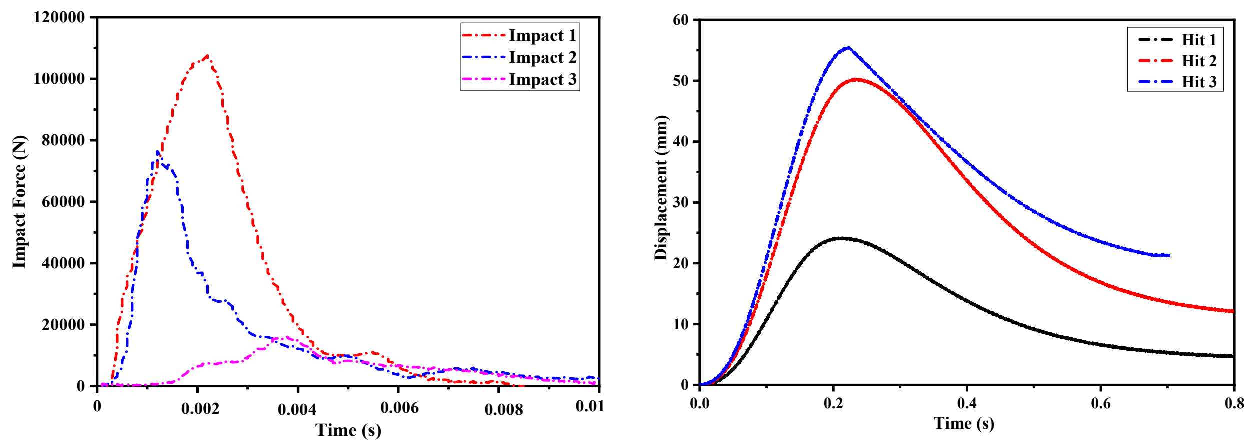
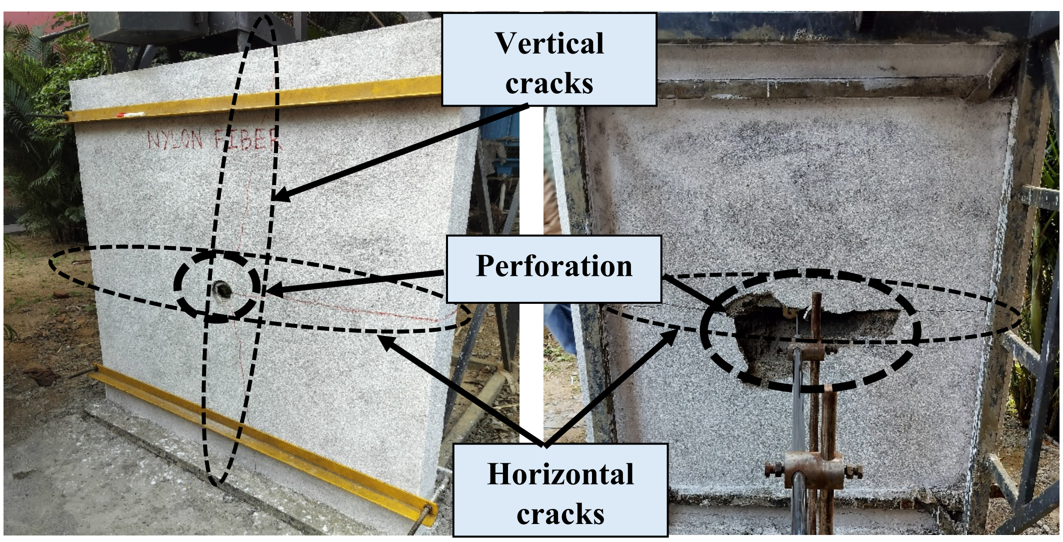


Figure 9: Impact Loading History of Nylon Fibre-Strengthened Specimen: (a) Force-Time History; (b) Displacement-Time History.



(a) Front side

(b) Rear side

Figure 10: Damages in Nylon Fibre-Strengthened Wall in the Last Hit.

The energy absorption capacity of the nylon fibre-reinforced wall was 46.5 J, a 61.4% improvement over the unreinforced wall. During the first impact, the wall sustained minimal damage, developing only a horizontal crack. The last impact was also well endured, owing to the fibre-bridging mechanism, which helped maintain the integrity of the wall by preventing sliding and collapse of the wall. The third impact caused a minor perforation on the tension side and resulted in a small piece of brick breaking off from the masonry, as shown in Fig. 10. Overall, the nylon fibre-reinforced wall performed better compared to the URM wall in terms of impact resistance, energy absorption, and delayed failure, showcasing its enhanced durability.

CONCLUSIONS

This study investigated the impact loading behavior of masonry walls constructed with fly ash bricks through an experimental program conducted in two phases. The first phase involved casting unreinforced and reinforced mortar cubes and prisms, while the second phase focused on constructing walls, including an unstrengthened control wall and walls reinforced with coir and nylon fibres. A comparative analysis was performed to assess the performance of these walls based on force-time history, displacement-time history, energy absorption capacity, and impact resistance. The key findings from this study are as follows:

1. The inclusion of coir and nylon fibres in mortar cubes led to a decrease in compressive strength by up to 34.6% and 35.3% at 7 and 28 days, respectively. However, the flexural strength of reinforced mortar prisms improved by 30.4% and 33.4% at the same intervals.
2. The coir and nylon-reinforced walls demonstrated higher impact resistance, withstanding three impacts compared to two impacts for the unstrengthened wall. Additionally, the unstrengthened wall suffered penetration upon the second impact, whereas the reinforced wall remained structurally intact.
3. The peak and residual displacements recorded in the strengthened wall were significantly lower than those in the unstrengthened wall. Specifically, the residual displacement was reduced by up to 65% after the first impact.
4. The reinforced wall exhibited a substantial increase in energy absorption capacity, improving by up to 61.45% compared to the unstrengthened wall.

Overall, the fibre-reinforced wall outperformed the unstrengthened wall in terms of impact resistance, displacement reduction, and energy absorption. Moreover, utilizing fibres derived from agro and textile waste not only enhanced the structural performance but also contributed to environmental sustainability.

REFERENCES

[1] Banerjee, S., Nayak, S. and Das, S. (2020). "Shear and flexural behaviour of unreinforced masonry wallets with steel wire mesh." J. Build. Eng., 30, 101254.

[2] McNary, W. S. and Abrams, D. P. (1985). "Mechanics of masonry in compression." J. Struct. Eng., 111(4), 857-870.

[3] Gumaste, K. S., Nanjunda Rao, K. S., Venkatarama Reddy, B. V. and Jagadish, K. S. (2007). "Strength and elasticity of brick masonry prisms and wallettes under compression." Mater. Struct., 40, 241-253.

[4] Costigan, A. and Pavía, S. (2009). "Compressive, flexural and bond strength of brick/lime mortar masonry." Proc., PROHITEC, 9(1), 1609-1615.

[5] Banerjee, S., Nayak, S. and Das, S. (2021). "Seismic performance enhancement of masonry building models strengthened with the cost-effective materials under bi-directional excitation." Eng. Struct., 242, 112516.

[6] Banerjee, S., Nayak, S. and Das, S. (2020). "Improving the in-plane behavior of brick masonry wallet using PP band and steel wire mesh." J. Mater. Civ. Eng., 32(6), 04020132.

[7] Naraine, K. and Sinha, S. (1992). "Stress-strain curves for brick masonry in biaxial compression." J. Struct. Eng., 118(6), 1451-1461.
[8] Palanisamy, M. and Premalatha, J. (2012). "Experimental study on masonry infill material properties." Int. J. Sci. Eng. Res., 3(7).
[9] Ravi, S., Viswanathan, S., Nagarajan, T., Srinivas, V. and Narayanan, P. (2014). "Experimental and numerical investigations on material behaviour of brick masonry." 2nd Int. Conf. Res. Sci. Eng. Technol. Dubai, UAE.
[10] Ranjan, N., Banerjee, S., Nayak, S. and Das, S. (2023). "Exploring applicability of recycled nylon fiber reinforced mortar in joints and plaster to enhance the bond strength, in-plane and out-of-plane capacity of masonry structures." J. Build. Eng., 72, 106744.
[11] Moon, F. L., Yi, T., Leon, R. T. and Kahn, L. F. (2006). "Recommendations for seismic evaluation and retrofit of low-rise URM structures." J. Struct. Eng., 132(5), 663-672.
[12] Padalu, P. K. V. R., Singh, Y. and Das, S. (2018). "Experimental investigation of out-of-plane behaviour of URM wallettes strengthened using welded wire mesh." Constr. Build. Mater., 190, 1133-1153.
[13] Banerjee, S., Nayak, S. and Das, S. (2019). "Enhancing the flexural behaviour of masonry wallet using PP band and steel wire mesh." Constr. Build. Mater., 194, 179-191.
[14] Bischoff, P. H. and Perry, S. H. (1991). "Compressive behaviour of concrete at high strain rates." Mater. Struct. Constr., 24, 425-450.
[15] Wang, J., Tomor, A. K., Melbourne, C. and Yousif, S. (2013). "Critical review of research on high-cycle fatigue behaviour of brick masonry." Constr. Build. Mater., 38, 602-609.
[16] Pereira, E. L., de Oliveira Junior, A. L. and Fineza, A. G. (2017). "Optimization of mechanical properties in concrete reinforced with fibers from solid urban wastes (PET bottles) for the production of ecological concrete." Constr. Build. Mater., 149, 837-848.
[17] Ranjan, N., Banerjee, S., Nayak, S., and Das, S. (2023). "Agro-waste fiber reinforced mortar for augmenting the performance of masonry structures." Constr. Build. Mater., 363:129848.
[18] Ranjan, N., Banerjee, S., Nayak, S. and Das, S. (2024). "Seismic safety evaluation of coir and nylon fiber-reinforced masonry building models subjected to bi-axial shaking table test." J. Build. Eng., 85, 108767.
[19] Spadea, S., Farina, I., Carrafiello, A. and Fraternali, F. (2015). "Recycled nylon fibers as cement mortar reinforcement." Constr. Build. Mater., 80, 200-209.
[20] BIS (Bureau of Indian Standards) 13757. 1993. Indian standard code of practice for burnt clay fly-ash building bricks-specification (reaffirmed 2007). New Delhi, India: BIS.
[21] BIS (Bureau of Indian Standards) 4031 (Part 6). Indian standard methods of physical tests for hydraulic cement part 6 determination of compressive strength of hydraulic cement other than masonry cement. New Delhi, India: BIS.
[22] BIS (Bureau of Indian Standards) 4031 (Part 8). Indian standard methods of physical tests for hydraulic cement part 8 determination of transverse and compressive strength of plastic mortar using prism. New Delhi, India: BIS.
[23] Li, Z., Wang, L. and Wang, X. (2006). "Flexural characteristics of coir fiber reinforced cementitious composites." Fibers Polym., 7, 286-294.