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

Seismic Performance of Traditional Brick-Mortar and Interlocking Compressed Earth Brick Walls under Cyclic Loading

Junaid Shah Khan[i], Azam Khan[ii], and Tatheer Zahra[iii]

ABSTRACT

This study investigates the seismic performance of traditional mortar-bonded masonry and interlocking compressed earth brick (ICEB) masonry walls under lateral cyclic loading. An experimental program was developed to test full-scale specimens of both masonry types, assessing parameters such as initial stiffness, peak lateral resistance and lateral drift. The traditional mortar-bonded masonry wall constructed with first class bricks and 1:5 cement-sand mortar illustrated high initial stiffness but collapsed in a brittle manner. In contrast, the units of ICEB masonry wall made from a sustainable blend of sand, stone dust, and cement, with cavities grouted with 1:2:4 cement-sand-aggregate mixture demonstrated lower initial stiffness but significantly higher ductility and drift capacity, sustaining larger displacement without catastrophic failure.

KEYWORDS
brick-mortar walls, compressed earth blocks, ductility, lateral drift, seismic performance, structural resilience

[i] PhD Scholar, National University of Sciences & Technology, Islamabad, Pakistan, jkhan.phd19nice@student.nust.edu.pk
[ii] Professor, National University of Sciences & Technology, Islamabad, Pakistan, azam.khan@nice.nust.edu.pk
[iii] Senior Lecturer, Queensland University of Technology, Brisbane, Australia, t.zahra@qut.edu.au

INTRODUCTION

Masonry has been used in the construction of low and mid-rise buildings due to its cost efficiency, excellent insulation against noise and thermal transfer [1–3]. Traditional burnt brick mortar-bonded masonry which is widely adopted for residential and some commercial buildings for centuries, undeniably considered as structural system with highly brittle behavior and inadequate energy dissipation capabilities. These deficiencies and vulnerabilities under seismic impacts, have been highlighted by structural failures observed in the past earthquakes [4–6]. Such events have highlighted the masonry construction must be more resilient under seismic impacts, which has led researchers to explore more sustainable and earthquake resistant solutions.

Interlocking compressed earth bricks (ICEB's) masonry system has emerged as a significant development over the traditional mortar bonded masonry. Compared to traditional burnt brick masonry, which relies on mortar for bonding between bricks, ICEB's masonry system utilizes units that mechanically interlock, allowing for quick assembly and reducing the need for skilled labor [7-9]. The use of soil or other waste materials in these units not only reduces the carbon footprint but also offers a cost reduction over traditional bricks or concrete blocks [10-15].

The structural advantages of ICEB's in terms of energy dissipation and enhanced lateral deformability capabilities have been highlighted in the literature. Studies such as those by Strum et al. [18] have shown that even a simple interlocking key can significantly increase shear strength and help to facilitate energy dissipation during seismic events. Bland [27] and Qu et al. [28] have investigated the seismic behavior of various interlocking configurations and reinforcement techniques under cyclic loadings. Their studies highlighted significant performance under lateral loading regarding ductility and energy dissipation when reinforced. The studies also show that in comparison to traditional unreinforced masonry, interlocking masonry has the capabilities to withstand higher lateral loads and larger deformation without significant loss of structural integrity.

Although interlocking masonry shows advantages there is still a lack of comprehensive research evaluating how it performs in seismic conditions in comparison to conventional mortar-bonded masonry. The in-plane seismic response of conventional masonry walls has been evaluated in many studies [22–26], but there are very few studies that examine the cyclic performance of interlocking masonry, and those that exist are frequently limited to certain interlocking designs or configurations [27, 28]. Moreover, most of these studies are focused on the in-plane shear resistance of either interlocking masonry or traditional mortar-bonded masonry, with less attention given to the comparative assessment of these masonry systems.

The study aims to provide a detailed comparison of the mortarless grouted interlocking masonry walls against traditional mortar-bonded masonry wall under quasi-static lateral cyclic loading. The study investigates the overall structural behavior, damage mechanism, hysteresis response, and energy dissipation characteristics of both masonry systems.

Methodology

This study offers a comparison of two types of masonry walls: traditional burnt brick mortar-bonded masonry and mortarless grouted interlocking earth brick masonry shown in Fig. 1. The structural performance of these systems is evaluated under lateral cyclic loading tests, given the seismic vulnerability associated with traditional masonry.

High-quality solid burnt clay bricks refer as first-class brick, commonly used in Pakistan and measuring 220 mm × 105 mm × 73 mm, were used to construct the traditional mortar-bonded masonry specimen for this study. A brick laying method of English bond was employed and the joints were mortared with a 1:5

cement sand ratio, with an average joint thickness of 12.5 mm. This wall had dimensions of 2490 mm in height, 2134 mm in length, and a thickness of 220 mm. The RC band beam in the reinforcement configuration is situated 1524 mm above the base of the wall, had a depth of 152.4 mm, and contained two Grade-60 #3 bars. The beam acts as mid-height reinforcement, enhances the shear strength of the wall, contributing to improved seismic performance. To facilitate the lateral load application through the actuator, a loading beam was constructed at the top of both walls. The RC beam having a depth of 254 mm was reinforced with a total of six #4 bars as main reinforcement and #3 stirrups spaced at 76.2 mm near supports and 152.4 mm on center elsewhere.

(a) (b)

Fig. 1. Masonry typology (a) traditional masonry wall (b) ICEB masonry wall under construction

The ICEB specimen was constructed using a double leaf interlocking bonding pattern system. Each unit of ICEB had dimensions of 254 mm in length, 127 mm in width, and 81 mm in depth, comprising two cylindrical holes each of 58.7 mm diameter, strategically placed to allow for vertical grouting and reinforcement. The wall measurements were 2512 mm in height, 2159 mm in length, and a thickness of 254 mm. The ICEBs were arranged in a pattern that alternated headers and stretchers across successive rows. This layout was chosen specifically to lock the two leaves of the wall together, significantly enhancing the structural stability [18]. Vertical cavities were filled with a grouting mixture of 1:2:4 cement sand and coarse aggregates of size 12.7mm and smaller, enhancing the overall cohesion and load distribution capabilities of ICEB's wall. Additionally, RC band beam positioned at 1458 mm from the footing, with a depth of 152.4 mm and two Grade-60 #3 rebars were provided having steel ratio of 0.36%.

Locally sourced solid burnt bricks were employed for the construction mortar-bonded masonry wall. The bricks demonstrated an average compressive strength of 17.63 MPa. The ICEBs were manufactured using an optimize blend of 10% cement, 40% stone dust, and 50% sand to balance the load bearing structural requirement and environmental sustainability. The mixture was manually pressed under a 3-4 MPa load and cured through a combination of air and wet processes, achieving an average compressive strength of 3.18 MPa after 28 days.

For mortar-bonded masonry a mortar mixture of 1:5 cement sand was utilized which is typically used for local residential buildings. The average compressive strength of 6.81 MPa was obtained after 28 days. The grout mixture of 1:2:4 cement sand and coarse aggregates of size 12.7mm and smaller was used in ICEB masonry system to ensure easy placement within the cavities of bricks. The average compressive strength obtains for grout material as 10.87 MPa.

The in-plane lateral cyclic loading tests of traditional mortar-bonded and interlocking masonry walls were set up and carried out at the Structural Dynamics Laboratory, National University of Sciences and Technology, Islamabad. The specimens were constructed on 3048 mm × 915 mm × 254 mm footing which was connected to the strong floor using six bars of 25 mm diameter, which were post-tensioned to the maximum extent possible by hand tools, using additional levering for tightness, to ensure a secure attachment. The axial load of approximately 0.18 MPa was applied through two vertical hydraulic jacks equivalent to the dead load on the first story of two-to-three-story masonry buildings. To provide uniform distribution of axial load and avoid eccentric loading across the width of the walls, seven lubricated steel rollers were placed at equal distance and another steel girder was placed above through which the axial load was generated on the wall. The lateral load on the wall was applied at the top concrete beam using a servo-controlled hydraulic actuator. The actuator is capable of ±250 mm stroke range and 250kN loading capacity. The test setup and instrumentation are shown in Fig. 2 (a) and (b).

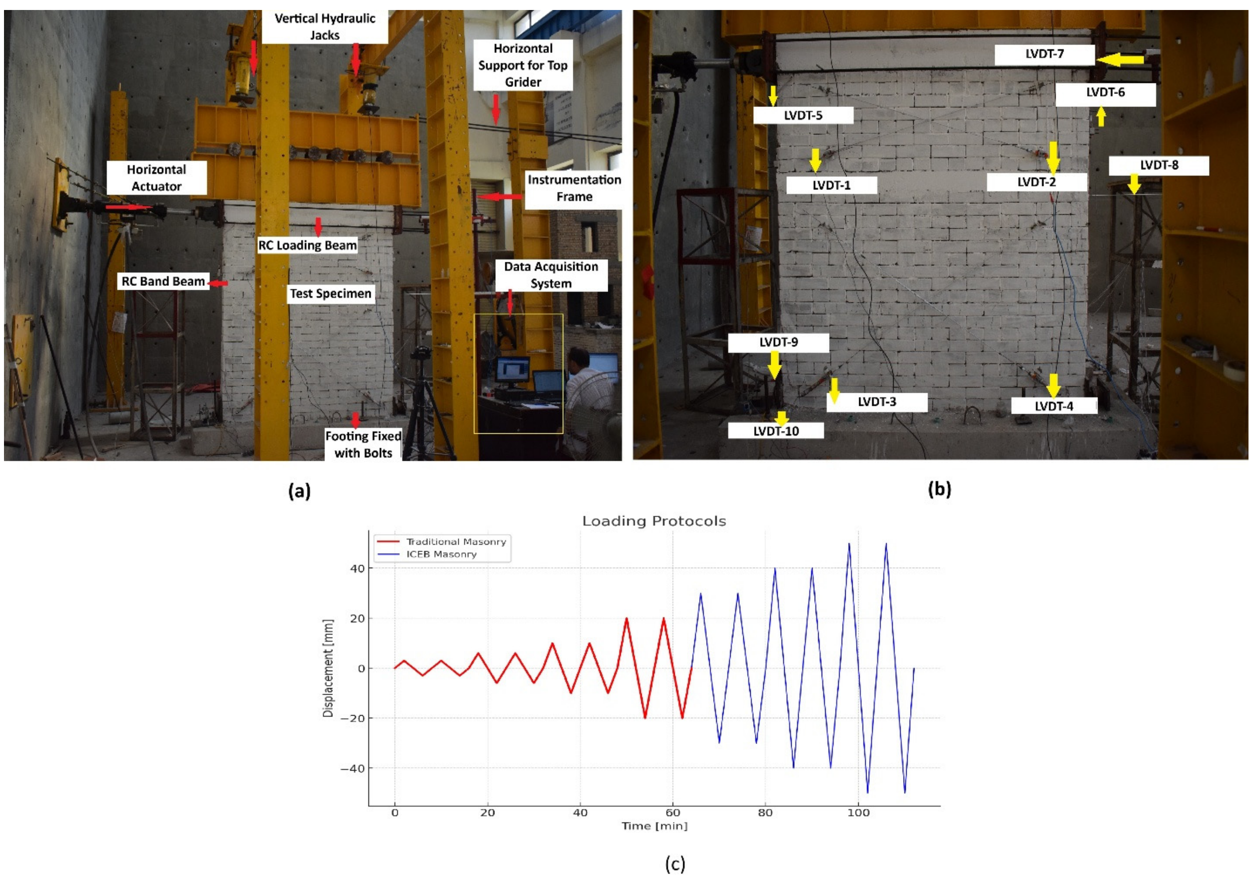


Fig. 2. (a) Detailed setup and (b) Instrumentation layout and (c) Loading protocols

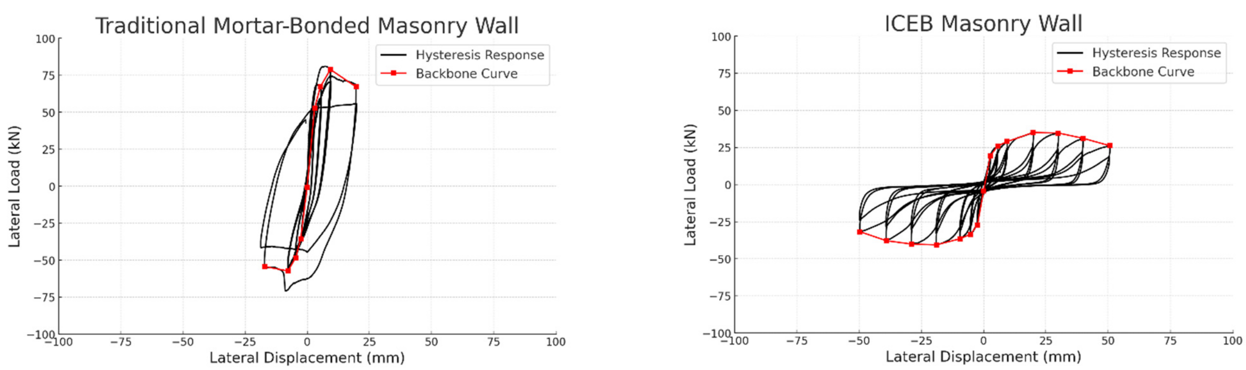
The servo-controlled hydraulic actuator is equipped with itself as a load-monitoring device. For axial load, two load cells were positioned at the location of the two vertical hydraulic jacks. A total of ten Linear Variable Differential Transformers (LVDTs) were placed on the samples. Four of them were placed diagonally to measure the combined effects of shear and axial force. Two LVDTs above and two below the band beam. Two LVDTs were placed on the sides to capture the vertical deformation along the wall.

To measure the in-plane lateral displacement at the top, LVDT was placed at the top beam level. Additionally, one LVDT was installed at mid-height. The data was logged using the HBM data logger system. High-definition cameras were used to document the progressive damage to walls during tests.

The test procedure comprised two steps, axial pre-compression and lateral cyclic loading. The axial load was gradually applied equally through two vertical jacks placed above the wall. Displacement-controlled cyclic loading was applied, starting with 3 mm up to a maximum of 20 mm for traditional mortar-bonded masonry and 50 mm for interlocking mortarless and grouted masonry as shown in Fig. 2 (c). The loading speed was adjusted to maintain a constant cycle duration and each displacement cycle was repeated twice. The tests were terminated once the lateral load resistance dropped by more than 20% from its peak strength, in accordance with the acceptance criteria outlined in FEMA 356 and ASCE 41.

RESULTS AND DISCUSSION

The global hysteresis response in terms of lateral force and lateral displacement at top beam level of both the traditional mortar-bonded and ICEB's masonry walls are presented in Fig. 3. Initially at the 3 mm cycle, due to the elastic behaviour of both traditional and ICEB masonry walls demonstrated narrow hysteresis loops. The initial stiffness of traditional mortar-bonded masonry shows higher stiffness, measured at 16.2 kN/mm (push-direction) and 15.1 kN/mm (pull-direction), compared to ICEB masonry wall 7.1 kN/mm (push-direction) and 7.3 kN/mm (pull-direction). The high initial stiffness of mortar-bonded is primarily due to the cohesive bonding of bricks with mortar. In contrast, the lateral resistance in ICEB masonry is facilitated by the combination of bonding grout, mechanical shear keys and friction along bed and head joints. The presence of multiple friction contacts within the ICEB wall contributes to a more flexible and ductile system.



(a) (b)

Fig.3. Hysteresis loops of (a) traditional and (b) ICEB masonry walls

At 6 mm cycles, both walls began to show wide loops indicating structural damage in the walls. The traditional wall showed horizontal cracks at the bottom rows of the brick-mortar interface, typical of stress concentration and material failure under cyclic loading. Conversely, the ICEB masonry wall displayed vertical hairline cracks within the interlocking bricks at the location of interlocking key and grout lines below the band beam level laid in a stretcher pattern, indicating stress concentration due to material discontinuities. The cracks didn't follow a clear diagonal path as typically occurs in conventional mortar-bonded masonry. At 10 mm cycles, the traditional wall reached its peak 81 kN (push-direction), hysteresis loop became considerably wider, a clear indicator of structural damage. Diagonal cracks are initiated at the brick-mortar interface starting from the band beam corners to the base. However, the ICEB wall shows further crack initiation only in the stretcher-laid bricks and cracks growth in those from the previous cycle.

As the cycle amplitude increased to 20 mm, the lateral resistance in pull-direction reached to its peak 70.6 kN and hysteresis loop broadened significantly, diagonal cracks from the previous cycles turned into complete separation of wall and significant corner crushing. No cracks were observed in the wall above band beam due to restricted movement in the stiffer section of masonry above. The test was stopped for traditional mortar-bonded masonry at this stage. Notably, the ICEB wall at 20 mm cycles shows pinching within the loops with additional cracks in interlocking bricks at the location of interlocking keys, few headers laid interlocking bricks crack at this stage. The test was continued with an increase in displacement for the ICEB masonry wall, at 30 mm the ICEB showed the maximum lateral resistance of 35.1 kN (push-direction) and 40.6 kN (pull-direction), followed by an increase in crack severity and complexity, yet prominently diagonal with base corners crushing of the band beam. By 40mm and 50mm cycles, the lateral resistance dropped with a wider loop area indicating extensive damage, by experiencing more shear force complete separation of bricks and crushing at lower corners of the wall was observed. Test ended at 50 mm cycles; the lateral resistance eventually dropped more than 20% of peak lateral resistance. No visible damage was observed in the masonry above the band beam. The total energy dissipated by the traditional mortar-bonded masonry wall was computed as 7760 kN-mm over 8 loading cycles, compared to ICEB masonry wall which exhibited greater post-peak stability and residual strength, dissipated a total of 6290 kN-mm over 14 loading cycles, equivalent to approximately 81% of the energy dissipated by the traditional wall.

(a) (b)

Fig. 4. Damage pattern after test (a) traditional masonry and (b) ICEB masonry

CONCLUSIONS

The seismic behaviour of conventional mortar-bonded and ICEB masonry walls has been thoroughly investigated in this study using hysteresis response and damage pattern observation under lateral cyclic loadings. The findings of this study are crucial for understanding distinct mechanical behaviour of both systems. Following are the main findings from this study:

- ICEB wall demonstrated lower initial stiffness, yet higher ductility compared to traditional mortar-bonded masonry wall. The lower initial stiffness of ICEB masonry wall, which typically leads to a larger yield drift, contributes to almost 60% increase in drift capacity over traditional masonry wall.

- Due to limited drift capacity, traditional wall was more prone to brittle failure under higher displacement demand while ICEB demonstrated greater ductility, it can sustain larger displacement without catastrophic failure.
- Damage in traditional masonry is characterized by diagonal cracks that rapidly led to significant degradation in structural integrity. However, damage in ICEB is more distributed across the wall leading to not compromise the overall stability.
- Although the ICEB masonry wall exhibited 81% of the total energy dissipation of the traditional mortar-bonded masonry wall, its enhanced post-peak stability and residual strength underline its outstanding seismic performance in terms of structural integrity.

While this research provides valuable insights into the structural behavior of masonry walls, yet it also highlights areas needing further exploration. Future research should focus on optimizing the composition of both bricks and grout materials to enhance their performance characteristics. Additionally, the integration of vertical rebars with varied reinforcement ratios. Such studies could determine the most effective rebar configurations for maximizing seismic resilience while remaining cost-effective. Comparative studies with the findings presented here will further clarify the role of reinforcement in improving structural response during lateral cyclic loading.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support of the Higher Education Commission (HEC) of Pakistan, provided under the National Research Program for Universities NRPU project number 15177. We also extend our sincere appreciation to the Military College of Engineering MCE, Risalpur for the provision of laboratory facilities that enabled the experimental work. This support has been instrumental in the advancement of our research objectives.

REFERENCES

[1] D'Amato, M., Laterza, M., & Diaz, F. D. (2020). Simplified Seismic Analyses of Ancient Churches. International Journal of Architectural Heritage, 14, 119–138.

[2] Fuentes, D. D., Laterza, M., & D'Amato, M. (2019). Seismic Vulnerability and Risk Assessment of Historic Constructions: The Case of Masonry and Adobe Churches in Italy and Chile. In R. Aguilar, D. Torrealva, S. Moreira, M. A. Pando, & L. F. Ramos (Eds.), Structural Analysis of Historical Constructions (pp. 1127–1137). Cham: Springer International Publishing.

[3] Ramírez, E., Lourenço, P. B., & D'Amato, M. (2019). Seismic Assessment of the Matera Cathedral. In R. Aguilar, D. Torrealva, S. Moreira, M. A. Pando, & L. F. Ramos (Eds.), Structural Analysis of Historical Constructions (pp. 1346–1354). Cham: Springer International Publishing.

[4] Fallahi, A. (2007). Lessons Learned from the Housing Reconstruction Following the Bam Earthquake in Iran. Australian Journal of Emergency Management, 22, 26–35.

[5] Oyguc, R., & Oyguc, E. (2017). 2011 Van Earthquakes: Lessons from Damaged Masonry Structures. Journal of Performance of Constructed Facilities, 31(3), 04017062.

[6] Sun, B., Yan, P., Hu, C., & Zhang, M. (2008). Overview on seismic damage to different structures in Yingxiu Town during Wenchuan Earthquake. Journal of Earthquake Engineering and Engineering Vibration, 28, 1–9.

[7] Wang, G., Li, Y., Zheng, N., & Ingham, J. M. (2017). Testing and modelling the in-plane seismic response of clay brick masonry walls with boundary columns made of precast concrete interlocking blocks. Engineering Structures, 131, 513–529.

[8] Ramamurthy, K., & Kunhanandan Nambiar, E. K. (2004). Accelerated masonry construction: Review and future prospects. Progress in Structural Engineering and Materials, 6, 1–9.

[9] Peirs, G. (1998). Masonry in the third millennium. In H. W. H. West & S. British Masonry (Eds.), Masonry (8) (pp. 6–8). British Masonry Society.
[10] [Yong, H. T. D. (2011). Utilisation of topologically-interlocking osteomorphic blocks for multi-purpose civil construction. Perth, Western Australia: The University of Western Australia.
[11] Ali, M., Gultom, R. J., & Chouw, N. (2012). Capacity of innovative interlocking blocks under monotonic loading. Construction and Building Materials, 37, 812–821.
[12] Gul, A., Alam, B., & Shahzada, K. (2022). Seismic performance evaluation of unconfined dry stacked block masonry structure. Engineering Structures, 265, 114529.
[13] Fay, L., Cooper, P., & Morais, H. F. (2014). Innovative interlocked soil–cement block for the construction of masonry to eliminate the settling mortar. Construction and Building Materials, 52, 391–395.
[14] Ben Ayed, H., Limam, O., Aidi, M., & Jelidi, A. (2016). Experimental and numerical study of Interlocking Stabilized Earth Blocks mechanical behavior. Journal of Building Engineering, 7, 207–216.
[15] Uzoegbo, H. C. (2001). Lateral Loading Tests on Dry-Stack Interlocking Block Walls. In Structural Engineering: Mechanics and Computation (pp. 427–436).
[16] Thomas, J. (2019). Technical Details. Bellevue, WA: Tetraloc Pty Ltd.
[17] Dolatshahi, K. M., Nikoukalam, M. T., & Beyer, K. (2018). Numerical study on factors that influence the in-plane drift capacity of unreinforced masonry walls. Earthquake Engineering and Structural Dynamics, 47, 1440–1459.
[18] Sturm, T., Ramos, L. F., & Lourenço, P. B. (2015). Characterization of dry-stack interlocking compressed earth blocks. Materials and Structures, 48, 3059–3074.
[19] Liu, H., Liu, P., Lin, K., & Zhao, S. (2016). Cyclic Behavior of Mortarless Brick Joints with Different Interlocking Shapes. Materials (Basel, Switzerland), 9.
[20] Lin, K., Liu, H. J., & Totoev, Y. Z. (2013). Lateral bearing capacity and simplified equations of dry-stack in-filled reinforcement concrete frame structure. Journal of Civil Architectural Environmental Engineering, 35, 21–27.
[21] Lin, K., Liu, H. J., & Totoev, Y. Z. (2012). Quasi-static experimental research on dry-stack masonry infill panel frame. Journal of Building Structure, 33, 119–127.
[22] Ahmed, A., Afreen, A., & Moin, K. (2017). State of Art Review: Behaviour of Masonry Structures under Gravity and Seismic Loads. International Journal of Emerging Technology and Advanced Engineering, 7, 202–214.
[23] Ferretti, E., & Pascale, G. (2019). Some of the Latest Active Strengthening Techniques for Masonry Buildings: A Critical Analysis. Materials (Basel, Switzerland), 12.
[24] [24] Ferreira, T. M., Costa, A. A., & Costa, A. (2015). Analysis of the Out-Of-Plane Seismic Behavior of Unreinforced Masonry: A Literature Review. International Journal of Architectural Heritage, 9, 949–972.
[25] Gupta, P., & Sankhla, S. S. (2018). A Review Study on Performance of Stone Masonry Building Under Earthquake. International Journal of Advance Engineering and Research Development, 5, 45–50.
[26] Magenes, G., & Penna, A. (2011). Seismic design and assessment of masonry buildings in Europe: recent research and code development issues. In J. M. Ingham, M. Dhanasekar, & M. Masia (Eds.), Proceedings of the 9th Australasian Masonry Conference. Auckland, N.Z.: Australasian Masonry Conference.
[27] Bland, D. W. (2011). In-Plane Cyclic Shear Performance of Interlocking Compressed Earth Block Walls. San Luis Obispo, California: California Polytechnic State University.

[28] Qu, B., Stirling, B. J., Jansen, D. C., Bland, D. W., & Laursen, P. T. (2015). Testing of flexure-dominated interlocking compressed earth block walls. Construction and Building Materials, 83, 34–43.

[29] Ashraf, M., Ali, Q., Khan, A. N., Alam, B., & Naseer, A. (2010). Experimental study on the performance of brick masonry piers before and after retrofitting with reinforced plaster. In 9th US national and 10th Canadian conference on earthquake engineering (pp. 2024-33).