Proceedings of the 3rd Croatian Conference on Earthquake Engineering - 3CroCEE
19–22 March 2025, Split, Croatia

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.147

SEISMIC RETROFIT OF MASONRY WALLS USING REPOINTING WITH TRADITIONAL MORTAR AND POLYPROPYLENE STRIPS - TEST RESULTS

Festim ADEMI [(1)], Sergey CHURILOV [(2)], Enis JAKUPI [(3)], Elena DUMOVA - JOVANOSKA [(4)]

[(1)] *PhD student, Ss. Cyril and Methodius University in Skopje, Faculty of Civil Engineering, festim.ademi@unite.edu.mk*
[(2)] *Professor, Ss. Cyril and Methodius University in Skopje, Faculty of Civil Engineering Skopje, curilov@gf.ukim.edu.mk*
[(3)] *Professor, University of Tetovo, Faculty of Applied Sciences, enis.jakupi@unite.edu.mk*
[(4)] *Professor, Ss. Cyril and Methodius University in Skopje, Faculty of Civil Engineering Skopje, dumova@gf.ukim.edu.mk*

Abstract

Seismic strengthening of masonry structures through repointing is recognized as an effective and economical technique for increasing structural stability, especially in regions with high seismic activity. This paper presents results from a research program that includes laboratory tests of the mechanical properties of masonry and its components: bricks, mortar, and polypropylene strips. The aim of the research is to assess the effectiveness of repointing as a method for strengthening existing structures, ensuring greater resistance to compression and dynamic loads.

The results show that repointing, particularly when modern materials are used, significantly increases the compressive strength of masonry structures and their ability to withstand seismic forces. Additionally, this method contributes to preserving the integrity and long-term stability of important cultural and religious buildings, such as churches and mosques. These structures often carry immense historical, spiritual, and architectural significance, and repointing offers a practical solution for their seismic reinforcement, ensuring that they remain safe and enduring symbols of heritage.

Keywords: seismic strengthening, masonry structures, repointing, polypropylene strips, compressive strength, seismic resistance, cultural heritage conservation.

1. Introduction

Unreinforced masonry (URM) structures represent a significant portion of the global building stock, particularly in historic urban centres and cultural heritage sites [1, 2]. These structures, while demonstrating remarkable durability over centuries, exhibit characteristic vulnerabilities to seismic actions due to their low tensile and shear strengths, brittle behaviour, and poor ductility characteristics [2, 3]. The devastating consequences of recent earthquakes, such as the 2020 Zagreb earthquake and the 2023 Turkey-Syria earthquake, have highlighted the critical need for effective seismic strengthening solutions for URM buildings [4-6].

The seismic vulnerability of URM structures originates from several factors, such as the quality of construction materials, structural configuration, and connection details between structural elements [7-8]. During seismic events, these buildings typically exhibit in-plane and out-of-plane failure mechanisms, with damage patterns ranging from diagonal shear cracks to partial or complete collapse of wall elements [9-13]. The heterogeneous nature of masonry structures [14], combined with the degradation of material properties over time, further compounds these vulnerabilities [15-17].

Various strengthening techniques have been developed and implemented to enhance the seismic performance of URM structures. These methods can be broadly categorized into surface treatments, grout injections, external reinforcement, confining using RC ties [18, 19] and structural repointing techniques [19, 20]. Surface treatments, including fibre-reinforced polymer (FRP) applications and ferrocement overlays, primarily enhance the in-plane shear capacity [20-24] and out-of-plane bending resistance [25-26]. Grout injections improve the overall structural integrity by filling voids and cracks, thereby increasing compressive strength and homogeneity of the masonry assembly [18, 27-29]. Structural repointing, while less commonly employed, offers advantages in terms of minimal intervention and preservation of architectural authenticity [19, 20, 30-32]. Moreover, structural repointing of masonry enhances structural integrity, by improving compressive and shear strength, enhances ductility, increases weather resistance and durability, and offers cost-effective maintenance while maintaining the building's historical character. Several studies have highlighted the advantages of this method, particularly when combined with innovative materials such as Fiber Reinforced Polymers (FRP). FRP rebars embedded into mortar joints, a technique called FRP Structural Repointing, significantly improved the shear and flexural capacity of hollow clay brick wallets and beams [33-35]. Research on Textile Reinforced Mortar (TRM) strengthening systems, including joint repointing with Near Surface Mounted (NSM) helical rebars, has shown increased in-plane lateral strength and displacement capacity as well as out-of-plane strength of masonry buildings, which are crucial parameters for seismic assessment [36, 37].

Recent advances in strengthening techniques have predominantly focused on modern materials and sophisticated application methods. However, these solutions may not be suitable for all contexts, particularly in regions with limited access to specialized materials or in cases where preservation requirements restrict the use of contemporary materials due to compatibility issues [38, 39]. Additionally, the high cost and technical complexity of modern strengthening systems can present significant barriers to implementation, especially in developing regions or rural areas [40-42].

This research addresses a gap in the current state of practice by investigating the effectiveness of a hybrid strengthening approach that combines traditional lime mortar with polypropylene strips for structural repointing. This method offers several potential advantages: it utilizes readily available materials, maintains compatibility with historic masonry, and can be implemented with basic technical skills. The approach is particularly relevant for situations where modern strengthening solutions are impractical due to economic, technical, or conservation constraints.

The study aims to quantify the improvement in mechanical properties and seismic resistance achieved through structural repointing strengthening technique, focusing specifically on compressive strength, shear capacity, and deformation characteristics. Through comprehensive laboratory testing and analysis, this research seeks to establish the viability of this alternative strengthening method and provide practical guidelines for its implementation in various contexts.

2. Experimental programme for testing the effects of repointing

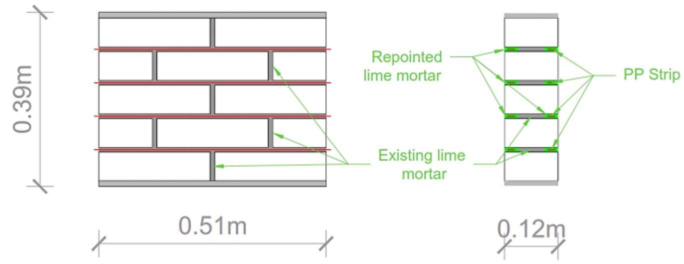
To evaluate the effects of repointing on the behaviour of bearing walls, an experimental program was designed and implemented. The program involved controlled laboratory testing of the bearing capacity of masonry structures with repointing applied in two distinct configurations. These configurations were selected to assess the influence of material properties and reinforcement orientation on structural performance. The repointing techniques tested included:

Strengthened masonry repointed with lime mortar and horizontally placed polypropylene strips: This configuration aims to enhance the tensile capacity of the masonry by introducing horizontal reinforcement to counteract lateral forces, Fig. 1a, Fig. 2a.

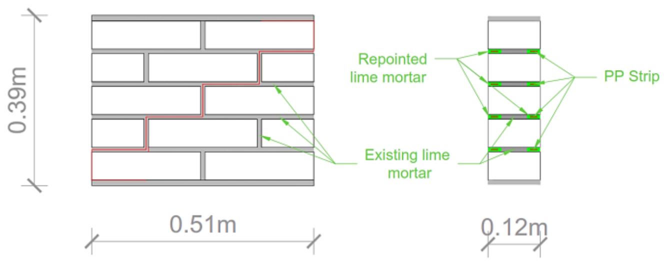
Strengthened masonry repointed with lime mortar and diagonally placed polypropylene strips: This arrangement provides multidirectional reinforcement, improving both shear resistance and the overall stability of the wall under dynamic and static loads, Fig. 1b, Fig. 2b.

Considering that masonry is a composite material, the experimental program was divided into three main phases: assessing the mechanical properties of its constituent materials (bricks and mortar), evaluating the compressive strength, and determining the shear strength of the masonry. To assess the effectiveness of the proposed repointing methods, the results from unreinforced masonry tests were used as baseline values. The following sections provide a concise overview of the tests conducted, the results obtained, and the corresponding conclusions drawn from the analysis.

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.147

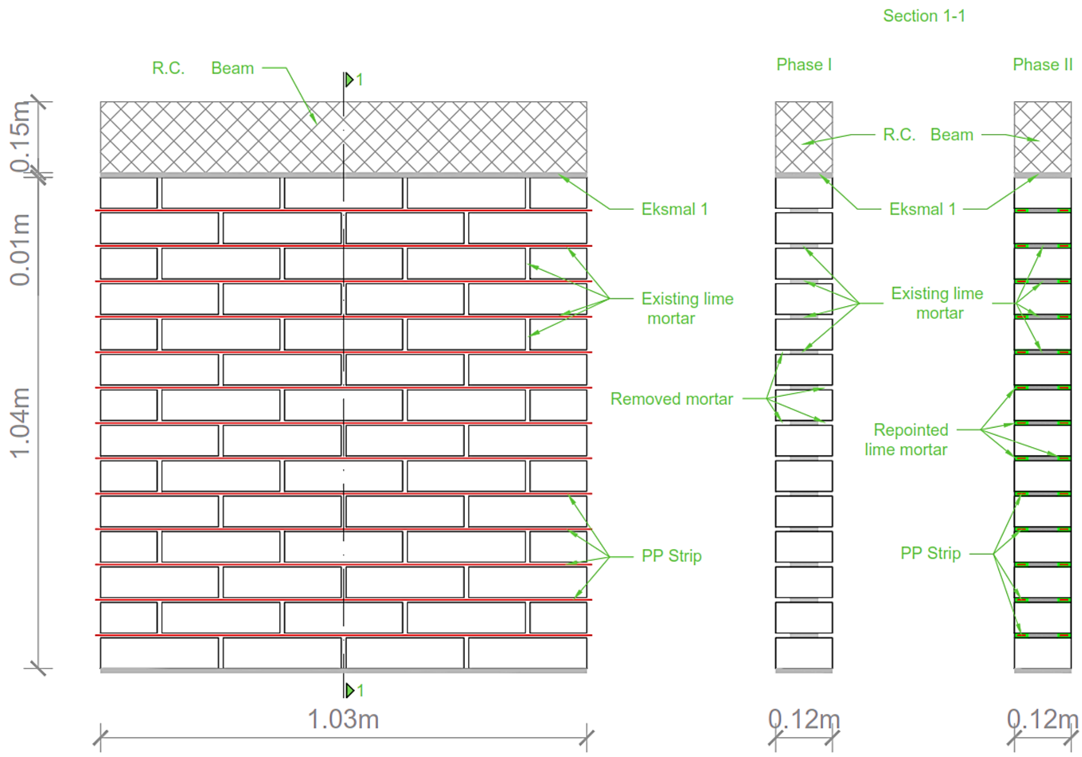


a) Horizontal PP strip and repointing (WS1_AP)



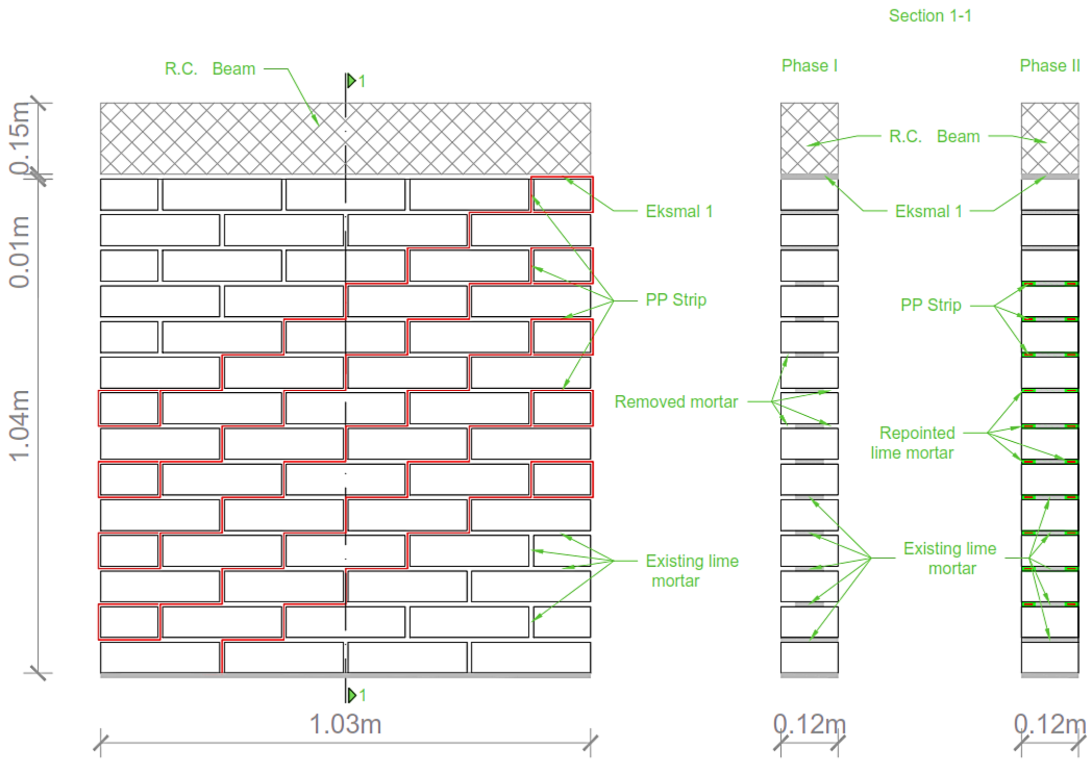
b) Diagonal PP strip and repointing (WS2_AP)

Figure 1. Specimens for compressive strength tests



a) Horizontal PP strip and repointing (WS1_SS)

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.147



b) Diagonal PP strip and repointing (WS2_SS)

Figure 2. Specimens for shear strength tests

2.1. Test of Constituent Materials

Tests on constituent materials are a crucial step in evaluating their durability and suitability for use in engineering structures. The mechanical and physical properties of the materials are determined through various tests, allowing for an analysis of their behaviour under different loads. The research presented involved testing solid clay bricks, mortars, and polypropylene strips to gather data on their strength, density, water absorption, and other characteristics essential for optimizing structural systems and enhancing the safety of structures. Table 1 presents the mechanical properties of the constituent materials obtained from these tests.

2.2. Tests on Masonry as Constituent Material

For the purposes of the investigation, two specialized setups were developed. These setups were designed to test the compressive strength and shear strength of masonry. They enabled precise and controlled analysis of various types of walls, including unreinforced and strengthened structures, to define their mechanical properties and behaviour under different loads. This provided a basis for comparing the results and optimizing strengthening methods in engineering practice.

Table 1. Mechanical characteristics of constituent materials.

Material	**Density** γ_d (kg/m^3)	**Compressive strength** $f_{m,comp}$ (MPa)	**Flexural tensile strength** $f_{m,flex}$ (MPa)
Clay brick	1750.5	9.54	2.05
Lime mortar		0.73	0.42

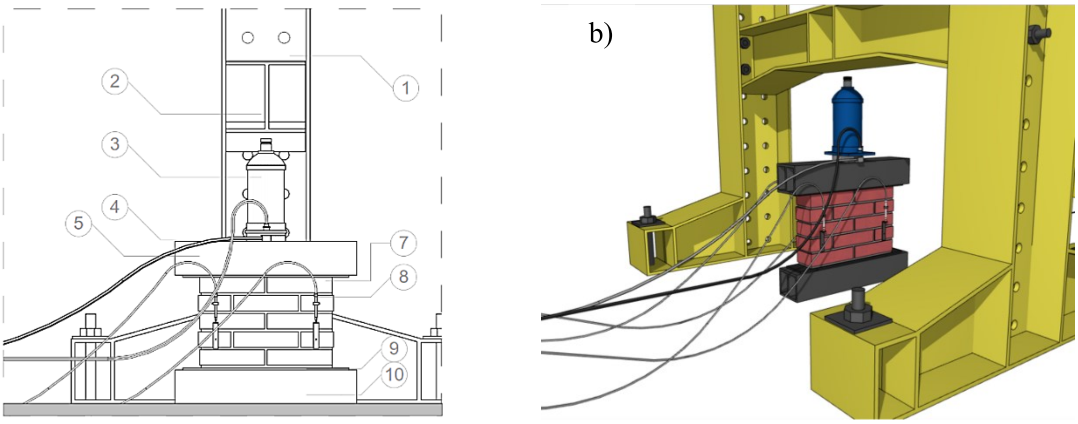
DOI: https://doi.org/10.5592/CO/3CroCEE.2025.147

2.2.1. Setup for testing compressive strength of masonry

The compressive strength test was conducted using a custom-built setup consisting of two steel columns firmly anchored to a reinforced concrete floor with steel bolts. These columns were interconnected at the top by a steel beam ("I 160"), providing structural stability and serving as a support frame for the hydraulic actuator, as shown in Fig. 3. The test wall was positioned between the steel columns under a second steel beam ("I 300"), separated by a 10 mm thick rubber layer to ensure uniform contact and force distribution. An additional rubber layer and a steel beam ("I 160") were placed on top of the wall to evenly distribute the applied load to the load cell connected to the hydraulic actuator.

It is important to note that the "I 300" and "I 160" beams, along with the steel columns, form a rigid frame, ensuring that these profiles are aligned and positioned above the test wall. This configuration functions as a stable support structure for the hydraulic actuator, enabling precise compressive strength measurements in a controlled laboratory environment.

a)



1: Steel column
2: Steel beam
3: Force hydraulic actuator
4: Load cell
5: Steel beam "I 160"
6: Rubber pad (10 mm)
7: URM Wall
8: Displacement transducer
9: Rubber pad (10 mm)
10: Steel beam "I 300"

Figure 3. a) Setup for compressive strength testing; b) 3D view of the test setup

This specialized setup enabled precise testing of masonry under compressive stress by minimizing external influences and ensuring controlled conditions for measuring compressive strength. The compressive strength tests conducted on various types of walls using this setup provided accurate and representative results under strictly controlled laboratory conditions. The configuration, which included fixed steel columns and beams along with rubber layers to improve contact and friction, effectively eliminated unwanted movements or deformations that could compromise the testing process.

The construction and positioning of the walls were meticulously executed to ensure their stability and central alignment, facilitating an even distribution of the applied load. The use of a hydraulic press and a load cell allowed for precise control of applied forces and displacements throughout the entire testing process. This setup proved to be an efficient method for testing walls. The introduction of various reinforcement techniques, such as polypropylene (PP) strips and different types of mortar, provided additional data for optimizing the mechanical properties of masonry.

2.2.2. Setup for testing shear strength of masonry

The experimental setup for shear strength testing comprised four steel columns securely anchored to a reinforced concrete floor, interconnected with steel beams to form a rigid frame. The test walls were positioned on a steel beam ("I 200") and stabilized by a reinforced concrete beam. Rubber layers, 10 mm in thickness, were placed at critical contact points to enhance load distribution and minimize localized stress concentrations. Horizontal force was applied using a hydraulic actuator, which transmitted the force to the walls through roller bearings, as depicted in Fig. 4.

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.147

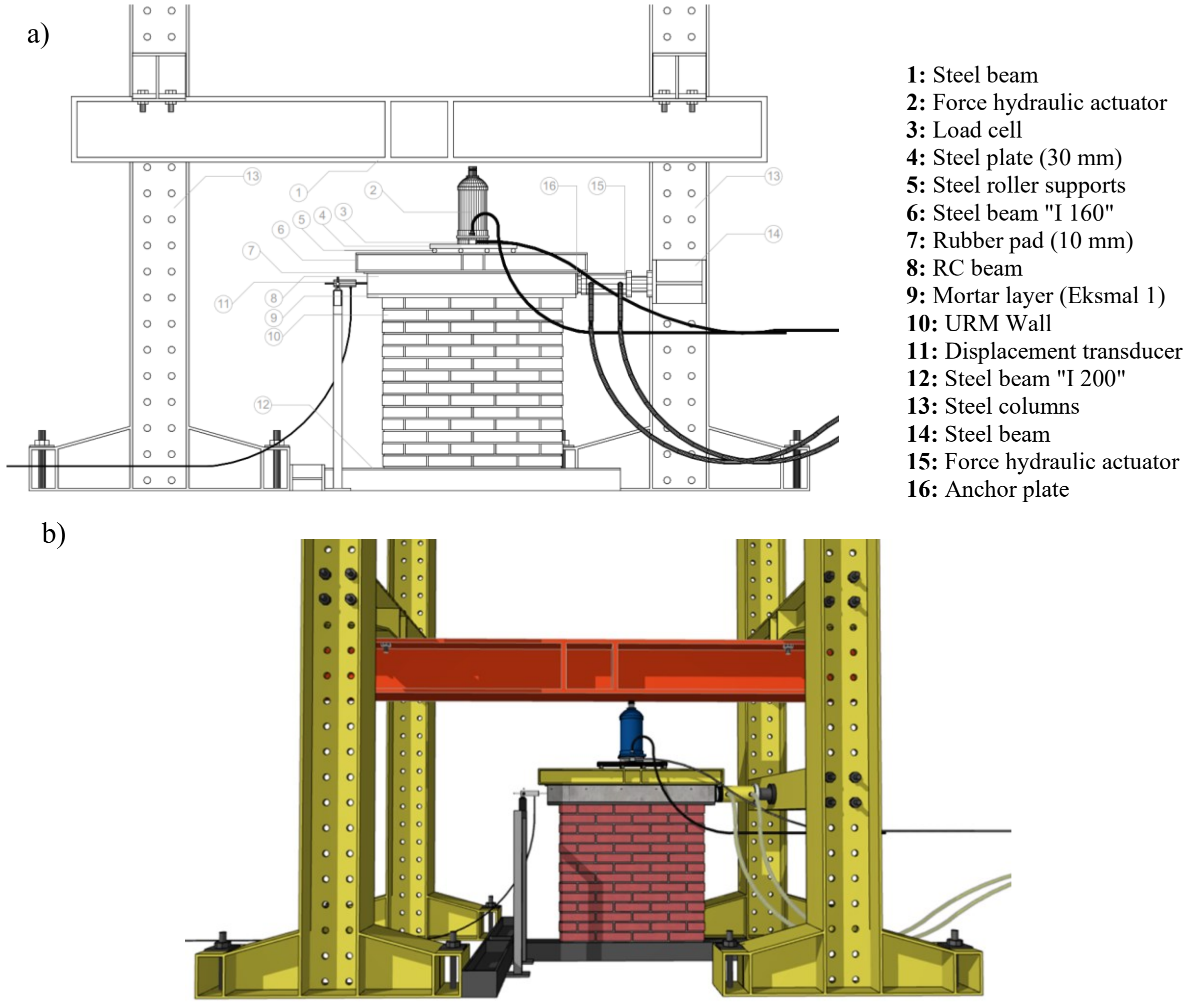


Figure 4. a) Setup for shear strength testing; b) 3D view of the test setup

To facilitate precise measurement of displacements induced by horizontal loading, a displacement transducer was installed. The wall was supported by the I 200 steel beam, ensuring it remained stationary during testing. The horizontal load was applied on the top RC beam. The horizontal force at the base of the specimen was not directly monitored, as the wall base was securely fixed to prevent any displacement. This configuration was specifically designed to accurately assess the transfer and distribution of horizontal forces through the upper portion of the wall, while maintaining stability and eliminating any unintended movement at the base. The testing platform designed for shear strength assessment enabled precise and controlled measurement of the performance of various types of walls. Accurate positioning of the walls, the use of roller supports for the transfer of horizontal forces, and the measurement of displacement with a displacement transducer ensured the reliability of the obtained results. This methodology facilitated the comparison between the shear strength of non-reinforced and reinforced walls, providing data that serves as a valuable contribution to the development of engineering practice. The results also support the optimization of construction materials and structural designs.

These two setups enabled precise and controlled assessment of the performance of different types of walls, including unreinforced and strengthened structures. The comprehensive data collected from these experiments provided valuable insights into the mechanical properties and behaviour of masonry under various loading conditions. This information is instrumental in developing advanced engineering solutions for retrofitting and strengthening existing structures, as well as optimizing the design of new masonry systems to enhance their durability, safety, and resilience against seismic and other dynamic forces.

Proceedings of the 3rd Croatian Conference on Earthquake Engineering - 3CroCEE
19–22 March 2025, Split, Croatia

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.147

2.3. Specimens for testing the compressive strength of masonry

As part of the investigation into the mechanical properties of masonry, several wall specimens were tested to determine their compressive strength, Fig. 5. The specimens consisted of 10 clay bricks and lime mortar, functioning as a composite material. The dimensions of the bricks were 250 x 120 x 60 mm, while the walls measured 510 x 390 x 120 mm. Six walls were tested in total, divided into three categories with two specimens in each category: unreinforced walls, walls strengthened with lime mortar and horizontally placed PP strips, and walls strengthened with lime mortar with diagonally placed PP strips.

a) b)

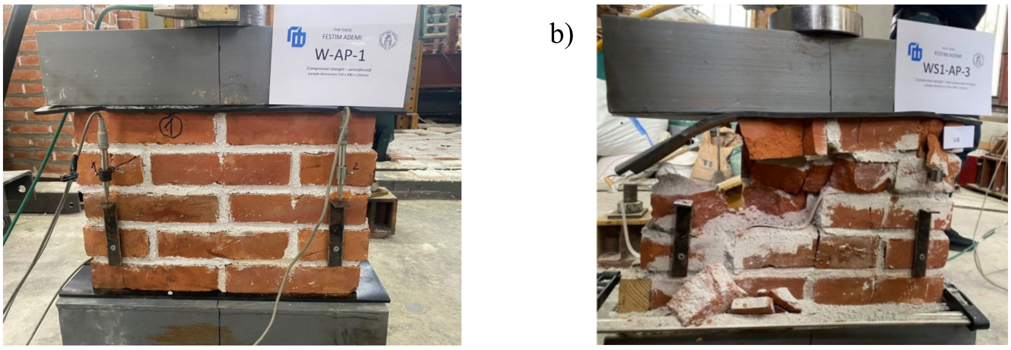


Figure 5. a) Testing the compressive strength of URM specimen; b) Failure mechanism of WS1_AP specimen

2.4. Specimens for testing the shear strength of masonry

As part of the investigation into the mechanical properties of masonry, shear strength tests were conducted in addition to compressive strength tests. Each wall was composed of 56 clay bricks and lime mortar, with brick dimensions 250 x 120 x 60 mm, while the test specimens measured 1030 x 1040 x 120 mm, Fig. 6. A total of six walls were tested, divided into three categories with two specimens in each: unreinforced walls, walls strengthened with lime mortar and horizontally placed PP strips, and walls strengthened with diagonally placed PP strips.

a) б)

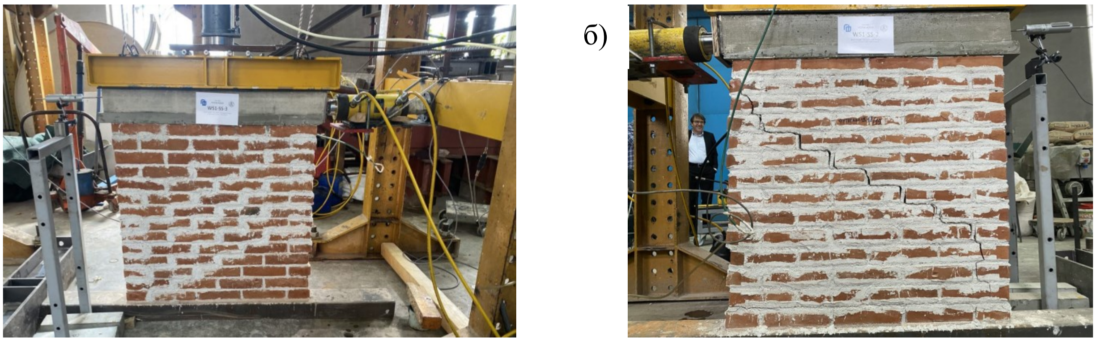


Figure 6. Testing of shear strength of masonry, a) Initial stage b) Failure mechanism

3. Results from experimental tests and discussion

The results from the compressive and shear strength tests of masonry structures provided a comprehensive understanding of the mechanical properties of various types of walls. The experimental findings revealed significant improvements in both compressive and shear strength when masonry walls were strengthened using repointing techniques with lime mortar and polypropylene (PP) strips. The effectiveness of these strengthening methods varied based on the orientation of the strips and the applied loading conditions. Applied force and displacement relationship shown the structural responses of the walls. These results provide valuable insights into the effectiveness of strengthening techniques and their contribution to enhancing the structural stability of masonry walls under both static and dynamic forces.

Proceedings of the 3rd Croatian Conference on Earthquake Engineering - 3CroCEE
19–22 March 2025, Split, Croatia

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.147

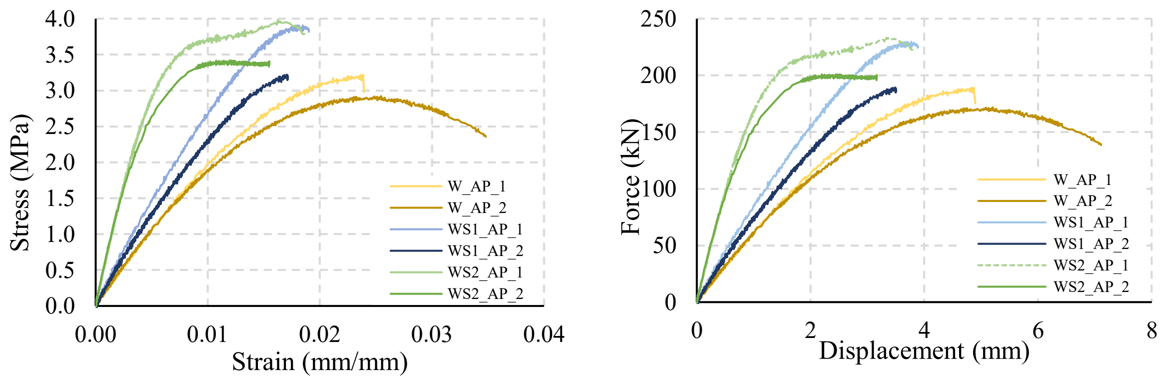
3.1. Compressive Strength of Masonry

The results of the compressive strength tests provide valuable insights into the behaviour of masonry under axial loads. These findings are presented through diagrams and tables, illustrating the force-displacement relationships, peak load capacities, and performance differences between unreinforced and strengthened walls, Fig. 7. The graphical and tabular data serve as a basis for analysing the effectiveness of the applied strengthening techniques and their impact on the structural stability of masonry walls.

For compressive strength, both strengthening configurations showed notable improvements, with diagonal PP strip placement (WS2_AP) yielding slightly better results than horizontal placement (WS1_AP). For WS1_AP, strengthening with lime mortar and PP strips in horizontal joints resulted in an increase in maximum strength by 16.1% and final strength by 31.9%, accompanied by a decrease in displacements of 27.6% and 38.5%. For WS2_AP, the diagonal placement of the PP strips led to an increase in maximum strength by 20.6% and final strength by 34.1, as presented in Table 2. This suggests that the strengthening technique effectively enhances not just peak strength but also post-peak behaviour and ductility. The tests revealed impressive results in reducing wall strain. Diagonal PP strips performed exceptionally well, cutting peak strain by 42.5% and ultimate strain by 41.9%. In comparison, horizontal strips achieved smaller but still significant reductions of 27.6% and 38.5%. These improvements mean the strengthened walls resist displacement much better under axial pressure.

3.2.Shear Strength of Masonry

The results of the shear strength tests offer detailed insights into the performance of masonry under lateral forces. These findings are presented in diagrams and tables, highlighting the force- displacement behaviour, peak shear capacities, and comparative effectiveness of the applied strengthening techniques, Fig. 8. The data provide a clear basis for evaluating the improvements in shear resistance and overall stability of masonry structures, especially under dynamic loading conditions.



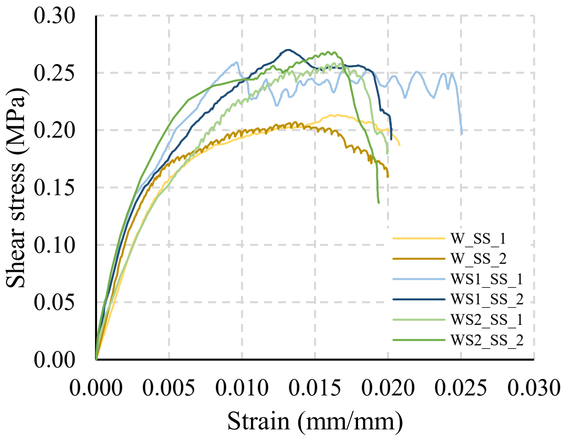
a) Shear stress - strain diagram

b) Force - displacement diagram

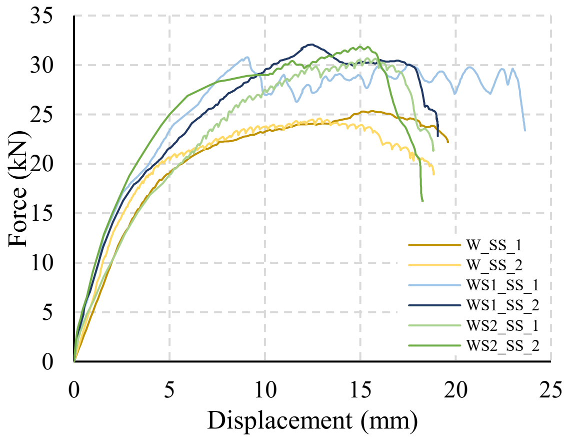
Figure 7. Compressive strength diagrams for URM (W_AP) and strengthened walls (WS1_AP and WS2_AP)

Table 2. Maximum stress and strain at compression for different types of walls

Mean Percentage difference	**Peak compressive stress, $f_{mas,test}$**	Peak stress increase (%)	**Ultimate compressive stress, $f_{mas,ult}$**	Ultimate stress increase (%)	**Peak strain, ε_{max}**	Peak strain decrease (%)	**Ultimate strain, ε_{ult}**	Ultimate strain decrease (%)
W_AP	3.07	0.0%	2.67	0.0%	0.0246	0.0%	0.0294	0.0%
WS1_AP	3.56	16.1%	3.52	31.9%	0.0178	-27.6%	0.0181	-38.5%
WS2_AP	3.70	20.6%	3.58	34.1%	0.0141	-42.5%	0.0171	-41.9%



a) Shear stress - strain diagram



b) Force - displacement diagram

Figure 8. Shear strength diagrams for URM (W_SS) and strengthened walls (WS1_SS and WS2_SS)

Table 3. Maximum stress and strain at shear for different types of walls

Mean Percentage difference	Peak shear stress, $f_{mas,test}$	Peak shear stress increase (%)	Peak shear strain, ε_{max}	Peak shear strain decrease (%)
W_SS	0.210	0.0%	0.0151	0.0%
WS1_SS	0.265	25.9%	0.0114	-24.5%
WS2_SS	0.263	25.3%	0.0161	6.3%

W_SS_1 and W_SS_2, the unreinforced walls, served as the baseline for comparison. In this case, both strip layouts worked similarly well. Horizontal strips increased the peak shear stress by 25.9%, just slightly better than diagonal strips at 25.3%. However, an interesting difference were noted in how the walls deformed. Horizontal strips reduced shear strain by 24.5%, while diagonal strips actually led to a small increase of the peak shear strain by 6.3%, Table 3. This suggests that horizontal strips may be more effective in controlling lateral deformations, even though both methods effectively strengthen the wall. The force-displacement relationships shown in Figure 8 indicates more stable post-peak behaviour in strengthened specimens compared to unreinforced walls, suggesting improved energy dissipation capacity. This is particularly important for earthquake resistance, as it shows the strengthened walls can better absorb and dissipate energy during repeated (cyclic) shaking.

It is important to emphasize that all graphical and tabular results pertaining to both compressive and shear strength tests are comprehensively presented within this chapter. These visual representations and data tables serve to convey crucial experimental findings, supporting a scientific evaluation of the performance enhancements achieved through the applied strengthening methods. The detailed analysis highlights not only the improvements in peak strength and post-peak response but also the impact on critical structural properties such as deformation capacity, ductility, and load transfer efficiency.

This holistic presentation of results contributes significantly to the scientific understanding of masonry behaviour under different load conditions, thereby offering valuable insights for optimizing structural reinforcement strategies in engineering practice.

4. Conclusions

The experimental investigations confirmed that the application of different techniques for strengthening with structural repointing significantly improved the mechanical characteristics of masonry, particularly in terms of its compressive and shear strength. The experiments were conducted at the Laboratory of the Faculty of Civil Engineering at Ss. Cyril and Methodius University in Skopje, North Macedonia, providing a controlled environment for reliable results. The unreinforced walls were used as a reference point for assessing the effectiveness of various strengthening techniques. The structural repointing strengthening technique using lime mortar and PP strips significantly enhances both compressive and shear strength of masonry walls. Compressive strength improvements reached up to 20.6% for maximum strength and 34.1% for ultimate strength, while shear strength increased by approximately 25% for both strengthening configurations. The orientation of PP strips influences the mechanical behaviour differently under various loading conditions. Diagonal placement proves more effective for compressive strength enhancement, while horizontal placement shows slightly better performance in shear strength improvement and displacement control, although in both tests the PP strips were effectively loop-tied in the neighbouring mortar joints. Both strengthening configurations greatly reduce displacements under compressive loading, with diagonal placement achieving up to 42.5% reduction in peak strain. This indicates significantly improved structural stiffness and stability. Moreover, The strengthening demonstrated particular effectiveness in enhancing post-peak behaviour and ductility, crucial characteristics for seismic performance. This is evidenced by the improved ultimate stress values and more stable force- displacement relationships in strengthened specimens.

These findings demonstrate the effectiveness of the applied strengthening methods in enhancing the structural stability of masonry walls. The outcomes of these experiments underline the importance of selecting and applying appropriate strengthening techniques to significantly enhance the bearing capacity, stability, and resistance of masonry structures, especially in seismically active regions. The use of horizontally placed PP strips was identified as a particularly effective solution, providing notable improvements in load-bearing capacity, deformation resistance, overall safety and cost-benefit efficiency. This methodology represents a significant contribution to engineering practice, with practical applications in the design and advancement of structures in high seismic risk zones and a validates a viable solution for improving the seismic resistance of masonry structures, particularly valuable for historical buildings where preservation of architectural authenticity is crucial. The use of traditional materials (lime mortar) combined with modern elements (PP strips) offers an effective compromise between structural enhancement and conservation requirements. Future research could focus on investigating the long-term durability of these strengthening techniques, their performance under cyclic loading conditions and to explore the contemporary applications and adaptations of established methodological frameworks within modern contexts.

Acknowledgements

The authors would like to express their sincere gratitude to several individuals who played crucial roles in the successful completion of this research. First, we want to thank Mr. Borce Jovik, our lab's backbone. His expertise made our experimental tests possible, and his guidance kept us on track throughout the process. We are also deeply grateful to Prof. Toni Arangjelovski who significantly enhanced the quality of our research methodology and analysis. Special appreciation goes to assist. MSc Dejan Janev for helping with the measurements and data collection. A special shoutout goes to the students Marko Gjorgjioski and Petar Janev, for their tireless assistance and valuable input during the experimental phase of the study.

References

[1] Tomaževič, M. (2000): Seismic Rehabilitation of Existing Masonry Buildings. *GRAĐEVINAR*, **52** (11), 683-693, http://www.casopis-gradjevinar.hr/assets/Uploads/JCE-52-2000-11-06.pdf.

[2] D'Ayala, D., Speranza, E. (2003): Definition of Collapse Mechanisms and Seismic Vulnerability of Historic Masonry Buildings. *Earthquake Spectra*, **19** (3), 479-509. doi: https://doi.org/10.1193/1.1599896.

[3] Lourenço, P. B., Mendes, N., Ramos, L. F., Oliveira, D. V. (2011): Analysis of Masonry Structures Without Box Behavior. *International Journal of Architectural Heritage*, **5** (4–5), 369–382. doi: https://doi.org/10.1080/15583058.2010.528824.

[4] Markušić, S., Stanko, D., Penava, D., Ivančić I., Bjelotomić Oršulić, O., Korbar, T., Sarhosis, V. (2021): Destructive M6.2 Petrinja Earthquake (Croatia) in 2020 - Preliminary Multidisciplinary Research. *Remote Sensing*, **13** (5), 1095, doi: https://doi.org/10.3390/rs13061095.

[5] Radnić, J., Grgić, N., Buzov, A., Banović, I., Smilović Zulim, M., Baloević, G., Sunara, M. (2021): Mw 6.4 Petrinja earthquake in Croatia: Main earthquake parameters, impact on buildings and recommendation for their structural strengthening. *GRAĐEVINAR*, **73** (11), 1109-1128, doi: https://doi.org/10.14256/JCE.3243.2021.

[6] Işık, E., Avcil, F., Büyüksaraç, A., İzol, R., Arslan, M.H., Aksoylu, S., Harirchian, E., Eyisüren, O., Arkan, E., Güngür, M.Ş., Günay, M., Ulutaş, H. (2023): Structural damages in masonry buildings in Adıyaman during the Kahramanmaraş (Turkiye) earthquakes (Mw 7.7 and Mw 7.6) on 06 February 2023. *Engineering Failure Analysis*, 151, doi: https://doi.org/10.1016/j.engfailanal.2023.107405.

[7] Sansoni, C. (2021): *Seismic Vulnerability Assessment of Existing URM Structures through a Simplified Analytical Method*. PhD thesis, Sapienza University of Rome, Department of Geotechnical and Structural Engineering.

[8] Koc, A. B., Erberik, M. A., Askan, A., & Karimzadeh, S. (2023): The Sensitivity of Global Structural Parameters for Unreinforced Masonry Buildings Subjected to Simulated Ground Motions. *Buildings*, **13** (8), 2060, doi: https://doi.org/10.3390/buildings13082060.

[9] Gonçalves, M., Ponte, M., & Bento, R. (2024): Seismic Assessment of Existing Masonry Buildings Using Damage Mechanics. *Buildings*, ***14*** (8), 2395, doi: https://doi.org/10.3390/buildings14082395.

[10] Deneko, E., Bilgin, H. (2024): Observed failure modes in existing URM buildings after November 26, 2019 earthquake in Albania. *Research on Engineering Structures & Materials*, **10** (3), 1085-1107, doi: http://dx.doi.org/10.17515/resm2024.106ea1202rs.

[11] Patel, K.P., Dubey, R.N. (2024): Effect of in-plane damage on the out-of-plane strength of masonry walls with openings. *Structures*, **65**, 106708, doi: https://doi.org/10.1016/j.istruc.2024.106708.

[12] Menon, A., Magenes, G. (2008): Out-of-Plane Seismic Response of Unreinforced Masonry. *Research Report No. ROSE-2008/04*, ROSE School, EUCENTRE, Pavia, Italy.

[13] Barbieri, G., Biolzi, L., Bocciarelli, M., Fregonese, L., and Frigeri, A. (2013): Assessing the seismic vulnerability of a historical building. *Engineering Structures*, 57, 523–535, doi: https://doi.org/10.1016/j.engstruct.2013.09.045.

[14] Scamardo, M., Zucca, M., Crespi, P., Longarini, N., Cattaneo, S. (2022): Seismic Vulnerability Evaluation of a Historical Masonry Tower: Comparison between Different Approaches. *Applied Sciences*, **12**, 11254, doi: https://doi.org/10.3390/app122111254.

[15] Binda, L., Saisi, A., Tiraboschi, C. (2000): Investigation procedures for the diagnosis of historic masonries. *Construction and Building Materials*, **14** (4), 199-233, doi: https://doi.org/10.1016/S0950-0618(00)00018-0.

[16] Miedziałowski, C., Walendziuk, A. (2023): Description of Material Properties of Degraded and Damaged Segments of Multi-Leaf Masonry in Analyses of Large Three-Dimensional Structures. *Materials*, ***16*** (11), 4076, https://doi.org/10.3390/ma16114076.

[17] Ceroni, F., Pecce, M., Sica, S., & Garofano, A. (2012): Assessment of Seismic Vulnerability of a Historical Masonry Building. *Buildings*, ***2*** (3), 332-358, doi: https://doi.org/10.3390/buildings2030332.

[18] ElGawady, M., Lestuzzi, P., Badoux, M. (2004): A Review of Conventional Seismic Retrofitting Techniques for URM, *13th International Brick and Block Masonry Conference*, July 4-7, Amsterdam, Nederlands.

[19] Tomaževič, M. (1999): *Earthquake-resistant design of masonry buildings*. Series on Innovation in Structures and Construction: Volume 1, Imperial College press, doi: https://doi.org/10.1142/p055.

[20] Churilov, S., Dumova-Jovanoska, E., Shendova, V., Krstevska, L., Damchevski, B., Janchev, D. (2024): Experimental investigation on masonry structural joint repointing with cement-polymer mortar and polypropylene strips, *GRAĐEVINAR,* **76** (7), 607-620, doi: https://doi.org/10.14256/JCE.3893.2023.

[21] Kałuża, M. (2022): Experimental Analysis of Surface Application of Fiber-Reinforced Polymer Composite on Shear Behavior of Masonry Walls Made of Autoclaved Concrete Blocks. *Buildings*, **12**, 2208, doi: https://doi.org/10.3390/buildings12122208.

[22] Di Tommaso, A., Focacci, F., Micelli, F. (2017): Strengthening Historical Masonry with FRP or FRCM: Trends in Design Approach. *Key Engineering Materials*, **747**, 166–173, doi: https://doi.org/10.4028/www.scientific.net/KEM.747.166.

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.147

[23] Incerti, A., Ferretti, F., Mazzoti, C. (2019): FRCM strengthening systems efficiency on the shear behavior of pre-damaged masonry panels: An experimental study. *Journal of Building Pathology and Rehabilitation*, **4** (14), doi: https://doi.org/10.1007/s41024-019-0053-9.

[24] Hung, C.C, Dai, Y.X., Yen, C.H., Mosalam, K.M. (2024): Comparative studies on in-plane shear behavior of masonry wallettes retrofitted with mortar, UHPC, and ECC ferrocement: Shotcrete and prefabricated panels. *Case Studies in Construction Materials*, **21**, e03801, doi: https://doi.org/10.1016/j.cscm.2024.e03801.

[25] Chen, S. P. (2010): Out-of-Plane Behavior of Masonry Walls Strengthened with Ferrocement. *Advanced Materials Research*, **163–167**, 3545–3550, doi: https://doi.org/10.4028/www.scientific.net/amr.163-167.3545.

[26] Joyklad, P., Ali, N., Verre, S., Magbool, H.M., Elnemr, A., Qureshi, M.I., Hussain, Q., Chaiyasarn, K. (2021): Experimental Study on the Out-of-Plane Behavior of Brick Masonry Walls Strengthened with Mortar and Wire Mesh: A Pioneer Study. *Infrastructures*, 6 (11), 165, doi: https://doi.org/10.3390/infrastructures6110165.

[27] Harvey Jr., D.W., Schuller, M.P., Ruth, W.T. (2012): Internal Strengthening of Historic Clay Brick Masonry Pump Houses in New Orleans, *8th International Conference on Structural Analsyis of Historical Constructions-SAHC 2012*, October 15-17, Wroclaw, Poland.

[28] Oliveira, D.V., Silva, R.A., Garbin, E., Lourenço, P.B. (2012): Strengthening of three-leaf stone masonry walls: an experimental research. *Materials and Structures*, 45 (8), 1259–76. doi: https://doi.org/10.1617/s11527-012-9832-3.

[29] Luso, E., Lourenço, P. B. (2016): Experimental characterization of commercial lime based grouts for stone masonry consolidation. *Construction and Building Materials*, 102 (1), 216-225, doi: https://doi.org/10.1016/j.conbuildmat.2015.10.096.

[30] Damchevski, B., Churilov, S., Dumova-Jovanoska, E. (2018): Mechanical characterisation of polymer fibre-reinforced cement-based mortar for masonry joint repointing, *16th European Conference on Earthquake Engineering*, Thessaloniki, Greece.

[31] Saad, Z.A., Bataineh, M. (2021): Preventive preservation approach for the preservation of unique early neolithic architectural remains of the archaeological site of Beidha-Jordan. *International Journal of Conservation Science*, **12** (2), 493-506, ISSN: 2067-533X.

[32] Kocić, N., Krasić, S., Tomić, J., & Mitrović, I. (2024): Assessment of protective structures for architectural heritage: Case study of Pompeii, Lepenski Vir and Gobekli Tepe. *Journal of the Faculty of Civil Engineering and Architecture*, **39**, doi: https://doi.org/10.62683/ZRGAF39.91-102.

[33] Tinazzi, D., Modena C., Nanni A. (2000): FRP-Structural Repointing of Masonry Assemblages, *3rd International Conference on Advanced Composite Materials in Bridges and Structures*, Ottawa, Canada.

[34] Tumialan, J.G., Micelli, F., Nanni, A. (2001): Strengthening of Masonry Structures with FRP Composites. *Structures 2001: A Structural Engineering Odyssey*, 1-8, doi: https://doi.org/10.1061/40558(2001)130.

[35] Tumialan, J.G., Nanni, A. (2002): Strengthening of Masonry Walls with FRP Bars. *Composites Fabricator Magazine*, Arlington, VA.

[36] Ramonda, L.G. (2020): *Seismic retrofit of masonry with innovative materials for strengthening and repair*. PhD thesis, Universitat Politècnica de Catalunya, Barcelona Tech.

[37] Boem, I. (2022): Masonry Elements Strengthened with TRM: A Review of Experimental, Design and Numerical Methods. *Buildings*, **12**, 1307, doi: https://doi.org/10.3390/buildings12091307.

[38] Binda, L., Penazzi, D., Valluzi, M.R., Cardani, G., Baronio, G., Modena, C. (2000): Behaviour of historic masonry buildings in seismic areas: Lessons learned from the Umbria-Marche earthquake, *12th International Brick/Block Masonry Conference*, Madrid, Spain.

[39] Penazzi, D., Valluzi, M.R., Saisi, A., Binda, L., Modena, C. (2001): Repair and strengthening of historic masonry buildings in seismic areas. International Congress, more than Two Thousand Years in the History of Architecture Safeguarding the Structure of Our Architectural Heritage, Bethlehem, Palestine 10-12 December, Paris: International Council on Monuments and Sites. Vol. 2, Section V, 1-7.

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.147

[40] Shrestha, H., Pradhan, S., Guragain, R. (2012): Experiences on Retrofitting of Low Strength Masonry Buildings by Different Retrofitting Techniques in Nepal, *15th World Conference on Earthquake Engineering*, Lisbon, Portugal.

[41] Ali, A., Mandal, P., Swailes, T. (2016): Strengthening Masonry for Seismic Actions in Developing Communities, *MACE PGR Conference*, University of Manchester, UK.

[42] Tsiavos, A., Sextos, A., Stavridis, A., Dietz, M., Dihoru, L., Di Michele, F., Alexander, N.A. (2021): Low-cost hybrid design of masonry structures for developing countries: Shaking table tests. *Soil Dynamics and Earthquake Engineering*, **146**, 106675, doi: https://doi.org/10.1016/j.soildyn.2021.106675.