DOI: https://doi.org/10.14256/JCE.3893.2023

Građevinar 7/2024

Primljen / Received: 28.10.2023.
Ispravljen / Corrected: 7.6.2024.
Prihvaćen / Accepted: 19.6.2024.
Dostupno online / Available online: 10.8.2024.

Experimental investigation on masonry structural joint repointing with cement-polymer mortar and polypropylene strips

Authors:

[1]Prof. **Sergey Churilov**
curilov@gf.ukim.edu.mk
Corresponding author

[1]Prof. **Elena Dumova-Jovanoska**
dumova@gf.ukim.edu.mk

[2]Prof. **Veronika Shendova**
veronika@iziis.ukim.edu.mk

[2]Prof. **Lidija Krstevska**
lidijakrstevska1@gmail.com

[3]**Bojan Damchevski**, MSc. CE
bojan@ading.com.mk

[3]**Dime Janchev**, MCE
jancev@ading.com.mk

[1] Ss. Cyril and Methodius University in Skopje
Faculty of Civil Engineering-Skopje
[2] Ss. Cyril and Methodius University in Skopje
Institute of Earthquake Engineering and Engineering Seismology - IZIIS
[3] ADING AD Skopje

Research Paper

Sergey Churilov, Elena Dumova-Jovanoska, Veronika Shendova, Lidija Krstevska, Bojan Damchevski, Dime Janchev

Experimental investigation on masonry structural joint repointing with cement-polymer mortar and polypropylene strips

Unreinforced masonry structures are prevalent in urban areas. Many of these structures are vulnerable to earthquakes, which are the primary causes of damage and failure. Therefore, conducting comprehensive studies to assess the structural capacity of these buildings is crucial for understanding their behaviour and vulnerability and for proposing effective strengthening measures. This integrated experimental and numerical study explored the effectiveness of joint repointing as a viable method for strengthening masonry structures. A review of recent research on various joint repointing techniques and materials is presented in the first part of this paper. The experimental investigations of unreinforced and strengthened masonry panels, utilising cement-polymer mortar and polypropylene strips in bed joints subjected to compressive and diagonal compressive strengths, are detailed. The experimental results demonstrate that structural joint repointing significantly improves the strength and has a minor effect on the ductility of the masonry, particularly when the original mortar has low-strength properties, as expected in existing buildings. The obtained results enable the calibration of nonlinear numerical models and modelling strategies used to study the elements in a more extensive manner, allowing for parametric studies and the application of the findings to existing buildings.

Key words:
masonry, strengthening, joint repointing, experimental investigation, structural stability

Prethodno priopćenje

Sergey Churilov, Elena Dumova-Jovanoska, Veronika Shendova, Lidija Krstevska, Bojan Damchevski, Dime Janchev

Eksperimentalno istraživanje konstrukcijskog reprofiliranja sljubnica cementno polimernim mortom i polipropilenskim trakama u zidu

U urbanim sredinama prevladavaju nearmirane zidane konstrukcije. Mnoge od tih konstrukcija su osjetljive na potrese, koji su glavni uzroci oštećenja i lomova. Stoga je provođenje opsežnih istraživanja za procjenu konstrukcijske nosivosti ovih zgrada ključno za razumijevanje njihovog ponašanja i izloženosti, kao i za predlaganje učinkovitih mjera pojačanja. To integrirano eksperimentalno i numeričko istraživanje bavi se učinkovitošću ponovnog fugiranja sljubnica kao održive metode za pojačavanje zidanih konstrukcija. U prvom dijelu rada dan je pregled suvremenih istraživanja različitih metoda i materijala za reprofiliranje sljubnica. Detaljno su prikazana eksperimentalna istraživanja nepojačanih i pojačanih zidanih panela upotrebom cementno polimernog morta i polipropilenskih traka u sljubnicama pod utjecajem tlačne i dijagonalne tlačne sile. Eksperimentalni rezultati pokazuju da fugiranje sljubnica značajno poboljšava nosivost i ima manji učinak na duktilnost zida, osobito kada izvorni mort ima nisku čvrstoću, kao što se i očekuje u postojećim zgradama. Dobiveni rezultati omogućuju kalibraciju nelinearnih numeričkih modela i strategija modeliranja koji služe za opsežnije proučavanje elemenata, pri tome omogućavajući parametarske studije i primjenu rezultata na postojeće zgrade.

Ključne riječi:
ziđe, pojačavanje, popravak sljubnica, eksperimentalno istraživanje, stabilnost konstrukcije

1. Introduction

Masonry structures are widely used in the construction industry due to their durability, strength, and aesthetic appeal. However, they are susceptible to damage from various natural and anthropogenic hazards, including earthquakes. Seismic events pose significant threats to masonry structures, often resulting in devastating damages that compromise their structural integrity and endanger lives. Beyond the commonly observed cracking, crushing, and splitting of masonry units, separation of units from each other, and mortar joints, seismic forces can induce many complex failure modes. For example, torsional and shear forces can lead to diagonal cracking and corner displacement, whereas differential settlement between interconnected elements can cause out-of-plane deformation and partial collapse. Recent studies have confirmed the severe damage and failure of masonry structures after strong ground motions. The 2023 Kahramanmaraș Mw 7.7 and Mw 7.6 sequences of earthquakes had devastating effects on masonry structures in the province of Adıyaman, where non-compliance with seismic design codes and the use of low-strength wall and joint building materials were the leading causes of damage [1]. The 2020 Elazığ-Sivrice Mw 6.8 earthquake led to 40 tragic losses of life and many collapsed or severely damaged buildings [2]. Structural failures of masonry structures have been attributed to various factors, including inadequate engineering services, non-compliance with construction standards, and the use of weakly bound materials such as lime mortar and adobe. Horizontal bonding beams, when used, are often not integrated within the wall, leading to partial collapse. The lack of rigid diaphragm arrangements at the roof and floor levels resulted in independent wall displacements and subsequent damage, as exemplified by cases of roof collapse and wall overturning. Similar structural behaviour, collapse, and damage patterns of masonry buildings were noted in the 2019 Mw 6.4 and Mw 5.6 Albania earthquakes [3], the 2020 Mw 5.3 Zagreb and Mw 6.4 Petrinja earthquakes in Croatia [4-6], and the 2017 Tehuantepec Mw 8.2 earthquake in Mexico [7].

The worldwide occurrence of earthquakes has highlighted the need to design and strengthen masonry structures to withstand seismic forces and prevent significant damage or collapse. Thus, the global significance of the seismic resilience of masonry structures cannot be overstated. With seismic activity occurring across diverse geographical regions—from the seismic hotspots of the Pacific Ring of Fire to intraplate zones—threats to the built environment are universal. In regions with historically low seismic activity, such as parts of Europe and Africa, the sudden occurrence of earthquakes can catch unprepared communities off guard, thereby amplifying the impact on masonry structures and posing formidable challenges to disaster response and recovery efforts. In light of these challenges, research aimed at enhancing the seismic resilience of masonry structures is imperative. By understanding the specific failure mechanisms and vulnerabilities inherent in masonry constructions, innovative retrofitting techniques and design approaches can be developed to mitigate the risks posed by seismic events, ultimately safeguarding lives and preserving invaluable cultural heritage worldwide.

1.1. Review of strengthening methods with composites and joint repointing

Various methods have been developed for strengthening masonry structures. Innovative materials such as externally bonded fibre-reinforced polymers (FRP) and near-surface-mounted bars have been used for repairing and strengthening masonry structures, providing additional tensile strength to masonry, increasing ductility capacity, and changing the failure mechanism [8-11]. Recently, fibre-reinforced cementitious matrix (FRCM) composites have been introduced [12-16]. The focus of FRCM applications is primarily on enhancing the structural performance and strength of masonry rather than altering its appearance [17].

Joint repointing has emerged as a promising and effective technique for strengthening masonry, having a negligible effect on the aesthetic appearance of masonry structures [18-19, 30]. Masonry joint repointing involves the removal of deteriorated or old mortar from the joints and its replacement with a new mortar mix that matches the original colour, texture, and strength. This method has improved the structural stability, load-carrying capacity, and seismic performance of masonry structures [20-26]. The key factors for successful or unsuccessful repointing are the choice of mortar in terms of composition, colour, texture, joint profile, and the tools and techniques used to maintain and strengthen the masonry walls [27]. The application of bed joint reinforcement using carbon-fibre-reinforced polymer (CFRP) strips in compressed brick masonry walls embedded in pre-cut mortar joints, which were repointed using lime-based mortar, prevented the brittle loss of anchorage, and the debonding mechanism involved adhesion and friction [28]. By repointing FRP rods into masonry joints bonded with paste or epoxy, masonry walls subjected to out-of-plane loading under cyclic or static loads can be significantly enhanced in terms of shear and bending moment resistance [12]. Steel reinforcement bars embedded in masonry joints are considered alternatives to polymer bars. When applied to solid clay-brick masonry walls subjected to simulated seismic loads, the seismic resistance can be increased by a certain amount; however, the reinforcement may or may not increase the overall displacement capacity. Replacing a weak mortar with a stronger one can lead to a simultaneous significant decrease in the displacement capacity with or without horizontal joint reinforcement [29]. Experimental testing of joint repointing with twisted steel bars under quasi-static cyclic in-plane actions on a full-scale wall and four-point bending tests on masonry wallets showed that joint repointing efficiently reduced the crack width and length up to the serviceability limit state and increased the ductility (30-40 %) and displacement capacity (40-45 %) [30, 31].

The presence of joint reinforcements also resulted in different failure mechanisms. Joint reinforcement using joint-embedded high-strength steel cables fully embedded in mortar bed joints significantly increases the out-of-plane capacity of masonry brick panels, with minimal impact on the appearance of the wall [32, 33]. Smooth titanium rods embedded in solid clay-brick masonry panels using epoxy paste or cement mortar for the double-sided repair of unreinforced masonry panels demonstrated partial restoration of the original in-plane shear capacity of the damaged panels [34]. However, premature debonding of rods can occur in panels repaired with cement mortar.

The repointing depth significantly influences the effectiveness of the joint repointing method. For relatively level bed joints, poor mortar, and undamaged units, a depth of up to one-third of the wall thickness is recommended to ensure wall stability and improve masonry capacity [29, 35]. A joint repointing depth of 70-80 mm was found to be effective in enhancing the shear strength and stiffness of stone masonry walls with thicknesses ranging from 300 to 700 mm, where the resistance was up to three times higher than that before strengthening [36].

Polypropylene (PP)-based products have been successfully used to increase both the in-plane and out-of-plane strengths and displacement capacities of masonry materials. Short PP fibres and nets embedded in an inorganic matrix can enhance the lateral load-carrying capacity, failure mechanism, ductility, and energy dissipation capacity of unreinforced masonry wall panels tested under in-plane loads [37]. The inclusion of PP fibres in mortar joints, PP fibres in plaster, and their combination has demonstrated an increase in the compressive and flexural capacities of masonry [38]. Due to their low cost and ease of application, externally wrapped polypropylene bands have been extensively tested in recent years. Wrapping wall panels can halt crack development, reduce lateral capacity, alter the failure mechanism, and delay brittle collapse under seismic loading. Compared with unreinforced masonry (URM) walls, these methods can enhance maximum strength, strength at maximum displacement, deformation capacity, and, in some cases, masonry stiffness [39-45]. Geogrid reinforcement embedded in the bed and head joints has been applied to masonry panels, which increased the in-plane shear strength, lateral strength, and ductility [46]. In all the reviewed studies, joint repointing was performed using lime, cement, and epoxy mortar.

Several studies have indicated that for joint repointing, a mortar compatible with the original should be used [12-17, 27, 48]. This implies that the mortar's strength properties should be similar to those of the masonry unit. However, some studies have shown that masonry can benefit from joint repointing using high-strength cement mortar [21, 29, 34, 35, 46, 47]. The effects of joint repointing with polymer fibre-reinforced cement-based repair mortar and polypropylene strips were experimentally tested, showing that this combination significantly increased the diagonal tensile strength of the masonry but had a negative effect on the compressive strength [47]. It was also noted that traditional lime-based mortars can offer advantages over modern cement-based mortars, particularly in their flexibility and ability to accommodate thermal and moisture movements. To prevent the spalling of the units, the compressive strength of the repointing mortar should be lower than that of the existing masonry units and should be similar to or lower than that of the existing bedding mortar [48].

The field of masonry structural joint repointing has witnessed significant advancements in recent years, and various techniques and materials have been explored to improve the performance and durability of masonry structures. However, a notable research gap exists in the application of high-strength mortars and polypropylene strips. This study aims to address this gap by investigating the feasibility and effectiveness of incorporating high-strength, low-content cement-based, fibre-reinforced mortar and polypropylene strips in masonry joints. The motivation for this study is twofold. Firstly, the use of high-strength mortar enhances the overall strength and load-bearing capacity of masonry joints, thereby improving their structural integrity and resilience. Secondly, the incorporation of polypropylene strips can provide additional reinforcement and crack control, reducing the occurrence of cracks and increasing the longevity of the repointed joints.

1.2. Research motivation and objectives of the current study

The aim of this study is to experimentally investigate the effectiveness of a masonry joint repointing technique using cement-polymer mortar and polypropylene strips, building on prior research and insights from Damchevski et al. [47]. Previous studies have demonstrated a significant improvement in the seismic resistance of joint-repointed masonry compared with that of unreinforced masonry (URM). Specifically, the use of high-strength fibre-reinforced cement-based mortar, marketed as Reparatur Mortar F4 by ADING AD Skopje, resulted in a substantial increase of 137 % in the diagonal tensile strength of the repointed masonry compared to URM. However, certain key parameters, including compressive strength, shear modulus, and ductility capacity, exhibited inferior performance compared to URM specimens, with compressive strength and shear modulus registering approximately 18 % and 28 % lower values, respectively. Finally, the strengthened masonry specimens exhibited slightly lower ductility than the URM specimens.

Despite these limitations, the authors suggested that by optimising the compatibility of mortar with the existing masonry properties, its strength characteristics could be further enhanced. Therefore, the objectives of this research are to experimentally investigate a novel and improved polymer-cement mortar, Reparatur Mortar FS4, for joint repointing with agents that compensate for shrinkage and are reinforced with polypropylene fibres. Furthermore, this study aims to assess the overall enhancement in seismic resistance achievable through the incorporation of polypropylene (PP) strips into masonry bed joints as part of the structurally reinforced repointing process. The research goals also aim to:

- Design a tailored repointing material with a particular contribution to increasing the seismic resistance of the masonry.
- Evaluate the efficacy of the repointing method as a structural strengthening intervention for masonry structures.
- Assess the economic viability of the application, application duration, and procedural complexity.

The findings presented herein arise from the 'Masonry Strengthening by Joint Repointing (STREP)' research project, a collaborative effort between the Faculty of Civil Engineering-Skopje, Institute of Earthquake Engineering and Engineering Seismology Skopje, and ADING AD Skopje [49].

2. Experimental campaign

2.1. Introduction

Owing to various constraints, the experimental programme was structured and implemented in two distinct stages: (1) testing of the constitutive materials and (2) testing of the masonry panels under axial and diagonal compressions. This structured approach ensured a comprehensive analysis of each phase. Initially, the constitutive materials were rigorously tested to establish the baseline properties for the specific weight and compressive and tensile flexural strengths of the bricks and mortars. Subsequently, the masonry panels underwent in-plane compressive and diagonal compressive tests featuring solid clay masonry units and lime mortar to replicate the characteristics of masonry in old buildings. Additionally, the programme incorporated the evaluation of strengthened panels using structural joint repointing with cement-polymer mortar and polypropylene strips to assess the effectiveness of the strengthening method.

2.2. Constitutive materials

2.2.1. Bricks and lime mortar

To determine the physical properties of the units, solid clay bricks with dimensions of 250 × 120 × 60 mm^3 were tested according to EN 771-1:2011 [48] and MKS EN 772-1:2013 [51] to determine their compressive strengths, as shown in Figure 1. A series of tests were conducted on the masonry components, and the most critical parameters were reported. To recreate the actual conditions of old masonry buildings, lime mortar was used to join the bricks. Therefore, a mixture of sand, lime, and water was prepared, and test samples were collected from nine mortar prisms with dimensions of 160 × 40 × 40 mm^3, as depicted in Figure 1.

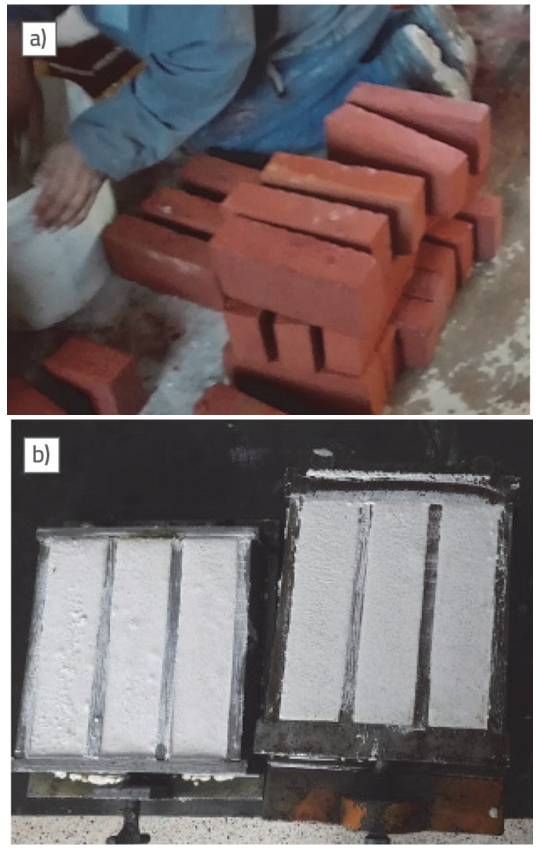

Figure 1. Constituent materials for masonry specimens: a) Solid clay brick; b) Lime mortar prisms

The mortar mixture was prepared by combining lime and sand in a 1:3 volume ratio. Natural river sand with two fractions ranging from 0 to 0.5 mm and 0.8 to 1.25 mm grain sizes was used. The proportions of both fractions were equal. The lime had controlled composition and chemical properties declared by the manufacturer in compliance with the EN 459 standard [52]. The flexural and compressive strengths of lime mortar were determined according to MKS EN 1015-11 [53]. Details of the tests can be found in Damchevski et al. [47], and Table 1 and 2 list the results obtained for the solid bricks and lime mortar prisms.

Table 1. Average material properties for solid clay bricks [47]

Material	Brick dimension [mm]			Water abs. [%]	Density [kg/m^3]	Compressive strength [N/mm^2]	Tensile flexural strength [N/mm^2]
	Length	Width	Height				
Solid clay brick	249.8	122.8	57.8	9.38	1977.0	10.64	3.04
CoV [%]	--	--	--	7.6	1.0	19.7	19.3

Table 2. Average material properties for lime mortar [47]

Material	Dimension of the test sample [mm]			Density [kg/m^3]	Compressive strength [N/mm^2]	Tensile flexural strength [N/mm^2]
	Length	Width	Height			
Lime mortar	159.4	40.0	39.8	1650.2	0.94	0.73
CoV [%]	--	--	--	1.9	5.4	9.3

Table 3. Average material properties for repointing mortar [47]

Material	Dimension of the test sample [mm]			Density [kg/m³]	Compressive strength [N/mm²]	Tensile flexural strength [N/mm²]
	Length	Width	Height			
Repointing mortar	159.6	39.9	39.8	2200.1	32.86	12.0
CoV [%]	--	--	--	2.3	4.5	7.8

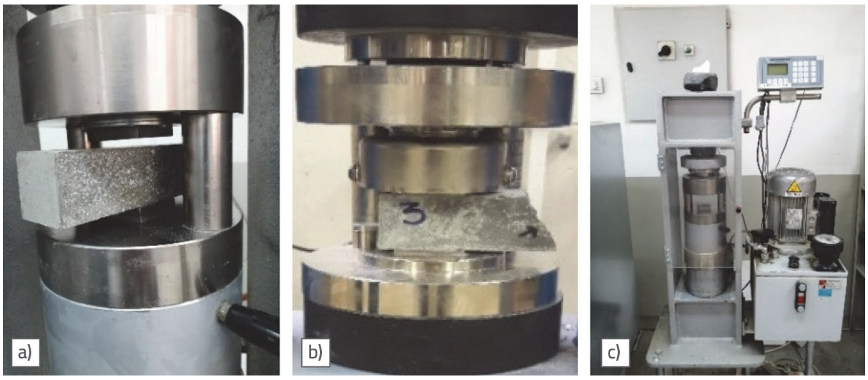

Figure 2. Repointing mortar tests: a) Tensile flexural strength test; b) Compressive strength test; c) Testing apparatus

2.2.2. Repointing mortar

The goal of this study was to develop a new repointing mortar with properties adjusted to match those of the units, considering the previous high-strength properties of the mortar used for joint repointing [46], which contributed to the high compressive and tensile strengths of the masonry. An investigation campaign was conducted to overcome the previously detected inconsistencies.

In addition, the mortar is formulated as a ready-mix, one-component, cement–polymer-based, microfiber-reinforced system that rapidly develops high compressive and flexural tensile strengths. It is also weatherproof, chloride-free, reinforced with polypropylene fibres with a length of 3 mm, and contains shrinkage compensation agents and microsilica (silica fumes). The new mortar mixes contain relatively low levels of cement and high levels of polymers. The sand aggregates prepared from a combination of river origins and quartz aggregates exhibited a maximum grain size of 4 mm. The tests were performed according to MKS EN 12190:2009 [54] and MKS EN 1504-3:2006 [55] on the mortar prisms, similar to those used to test the lime mortar properties. The water/mortar ratio was 0.12. The test and prism failures are shown in Figure 2.

Table 3 presents the test results for the newly repointed mortar. Compared with the originally used repointing mortar [47], a decrease in compressive strength of 44.8 % and an increase in tensile flexural strength of 182.3 % were obtained. The density of the mortar increased by 7.6.

2.2.3. Impregnation compound

To improve the adhesion of the repointing mortar to the masonry units, the repointing surfaces were impregnated with an impregnation component. This material consists of a single component and is a cement-based material without chlorides. This substance is used to enhance the adhesion and stabilise the old and new mortar surfaces.

The adhesion strength was determined by performing pull-out tests on nine samples according to MKS EN 1542:1999 [56]. The impregnation component was prepared by mixing the powder with water in a ratio of 10:3 and applying it to three-unit bricks in two steps at intervals of 30 minutes. Finally, the bricks were covered with a 10 mm thick layer of repointing mortar, which was cut with a metal ring with a diameter of 50 mm, as shown in Figure 3. In 90 % of the cases, the failure mechanisms after the pull-out tests occurred along the solid bricks. It can be concluded that the connection between the bricks and the repointing mortar was satisfactory. The mean adhesion strength is f_{adh} = 1.5 N/mm².

Figure 3. Pull-of tests on Reparatur mortar FS4

Figure 4. PP strip for bed joint reinforcement

Table 4. Average material properties for PP strips

Material	Dimensions of PP strip [mm]		Density [kg/m³]	Ultimate tensile force [N]	Tensile strength [N/mm²]	Elongation [%]
	Width	Thickness				
PP strip	16.0	0.7	719.64	2,124.9	189.7	18

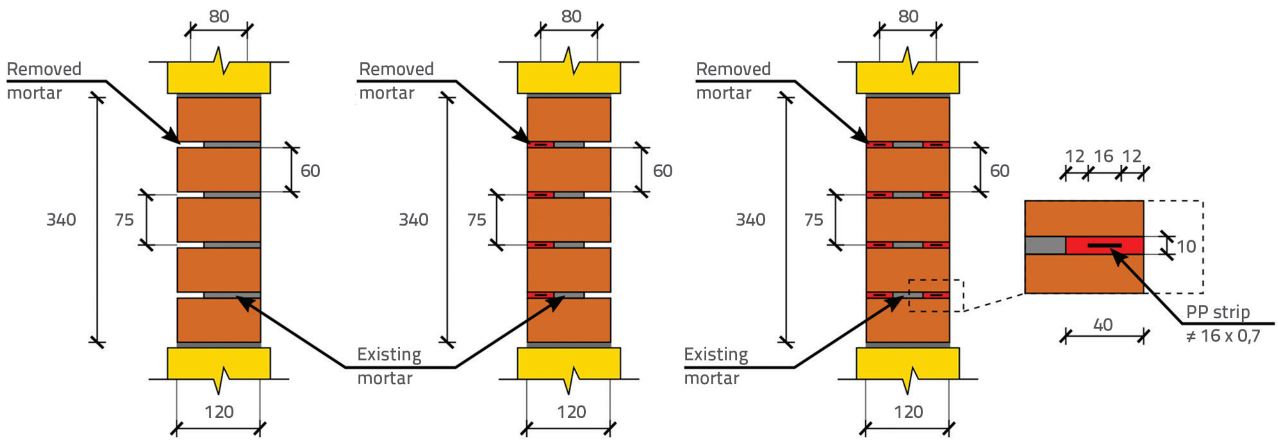

Figure 5. Joint repointing methodology of tested brick masonry panels

2.2.4. Polypropylene (PP) strip

PP strips were added to the repointed bed joints to improve the ductility of the repointed masonry, increase the tensile strength, and prevent brittle cracking. The strips had a rough texture on both sides, hus increasing the adhesion between the strip and the repointing mortar, as illustrated in Figure 4. The mechanical properties of the PP strips were not examined in this study; instead, the properties provided by the manufacturer were adopted. Table 4 lists the PP strip properties as tested according to the MKS EN ISO 9001:2015 standard [57].

2.3. Tests on masonry

The testing campaign was designed to determine the compressive and diagonal tensile strengths of two groups of test panels made from solid clay bricks and lime mortar: unreinforced masonry (URM) and strengthened joint-repointed (SM) masonry. A limited number of three panels per group were constructed and tested to obtain the necessary data for analysis.

2.3.1. Strengthening technique

Structural joint repointing and strengthening were performed on the previously grinded and impregnated mortar joints to a depth of approximately one-third of the wall thickness on both sides, following the methodology shown in Figure 5, to ensure the stability of the wall and to prevent buckling. This is typically performed using specialised hand tools, such as chisels and grinders, or electrical tools. In this case, a slow-oscillating drill bit was used to remove lime mortar from the joints. Subsequently, the joints were cleaned to ensure that they were free of debris and loose particles using a combination of compressed air and water.

As the impregnation compound was still fresh (sticky when touched), repointing mortar was applied over it to the joints. The joints were filled with repointing mortar in a single layer using a brick trowel and jointer. To improve ductility and energy dissipation capacity, PP strips were manually embedded in the horizontal joints at approximately the centre of each joint thickness.

2.3.2. Uniaxial compression tests

Unreinforced (W-AP) and strengthened masonry specimens (WS-AP-RPP) were constructed following standard provisions with fully filled head and bed joints, as shown in Figure 6.

Figure 6. Construction of test specimens

To prevent seasoning from influencing the results [59], the curing period for the URM panels was 212 days, whereas for the SM panels it was 244 days. The axial compression tests were conducted according to MKS EN 1052-1:1998 [58] at the laboratory premises of the Faculty of Civil Engineering-Skopje. The masonry compressive strength was tested on specimens with dimensions of 510 × 340 × 120 mm³, as illustrated in Figure 7. This modification was necessitated by the specific characteristics of our masonry units, the constraints of our testing apparatus, and the alignment with the dimensions used in the authors' previous tests [47]. Despite this deviation, several measures were taken to ensure the reliability of the results. The bricks were soaked in water prior to use. A rigid steel beam was positioned on top of each panel to allow uniform load distribution over the entire specimen area.

The vertical displacements were measured between two fixed points on both sides of the specimen. Kyowa digital linear variable displacement transducers (LVDTs), an 8-channel HBM Spider amplifier, and suitable connecting cables were used as the data acquisition systems. The load application was manual, using a vertical hydraulic actuator, and controlled with small load increments. For safety reasons, all the measurement equipment had to be removed before failure.

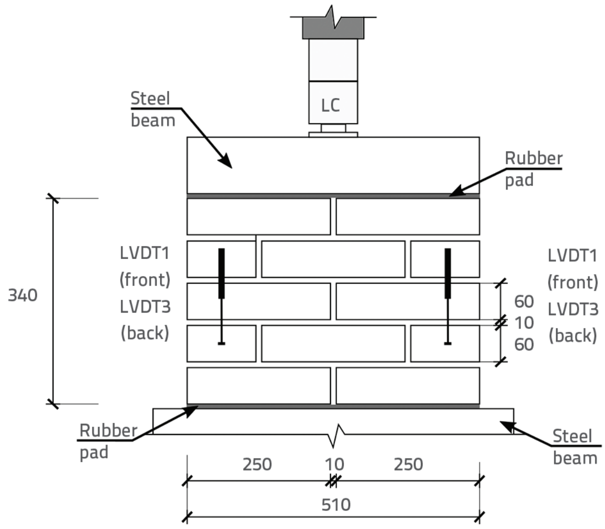

Figure 7. Test set-up for compressive strength of masonry

2.3.3. Diagonal compression tests

The diagonal tensile (shear) strength of the masonry was tested on three panels measuring 1040 × 1040 × 125 mm³. The tests were conducted in accordance with ASTM E 519-02 [60] at the Institute of Earthquake Engineering and the Engineering Seismology Testing Laboratory. This standard was specifically designed for the diagonal compression tests of masonry assemblies. It provides a detailed methodology for evaluating the shear strength of the masonry units, which is a critical parameter in our study. The unreinforced (W-DP) and strengthened masonry panels (WS-DP-RPP) were constructed from the same materials used for the compression tests. According to the standard, the test panel was rotated 45 degrees and loaded with a vertical compressive force along the diagonal panel. To prevent cracking or debonding of the constitutive materials when rotating and transferring the panels to the testing site, the rotated panels were constructed by supporting them in plywood formwork, as shown in Figure 8.a.

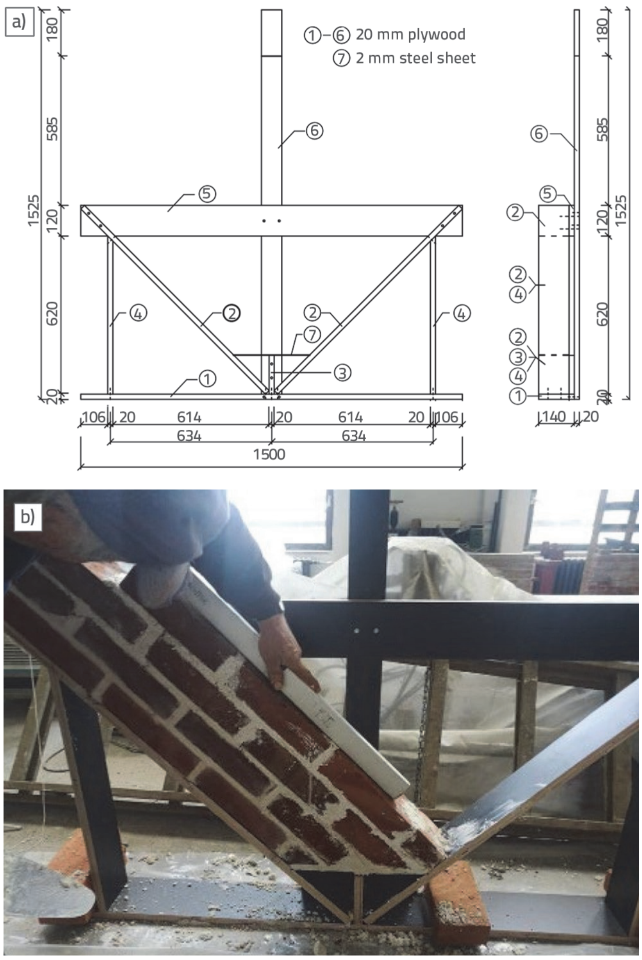

Figure 8. Plywood formwork and specimen construction for masonry diagonal tensile strength test: a) Drawing of the plywood formwork model; b) Construction of test panels

The URM panels were tested after curing for 202 days, and the SM panels were tested after curing for 356 days. The bed joint repointing and embedding of the PP strips into the SM walls were performed 100 days after construction. Loading shoes were not used because the wall panels were constructed with horizontal top and bottom edges in the supporting timber formwork, as depicted in Figure 8.b. A short rigid steel beam was positioned on top of each panel to allow for uniform load distribution over the entire panel area, as shown in Figure 9. The PP strips were embedded into each bed joint at approximately half of the joint thickness without any additional anchorage system.

The load application was automatic, using a vertical hydraulic actuator, and small load increments were controlled until failure. A National Instruments data-acquisition system and suitable connecting cables were used. A system of five LVDTs was positioned vertically and horizontally on the wall diagonals, as depicted in Figure 10. LVDT2 and LVDT4 were vertically oriented on the front- and back-wall surfaces, respectively, and were used to measure the vertical wall shortening. LVDT3 and LVDT5 were positioned horizontally on the front and back surfaces and were used to measure the horizontal wall lengthening. LVDT1 served as a reference and control transducer between the hydraulic actuator and load cell.

Figure 9. Test set-up for diagonal tensile strength test

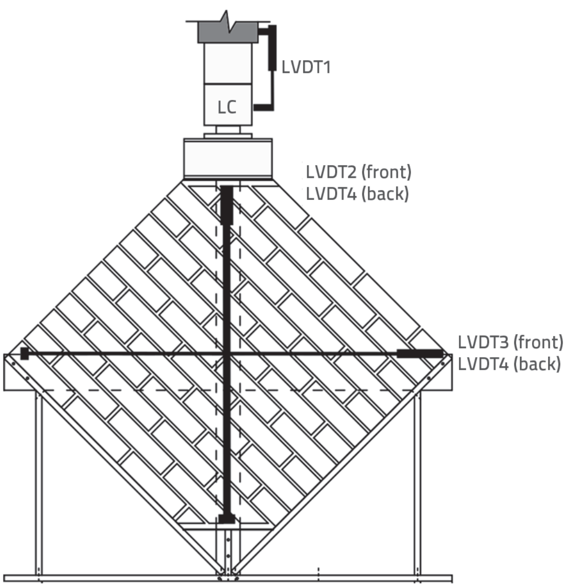

Figure 10. Test panel instrumentation with LVDTs position

3. Test results and discussion

3.1. Compressive strength

Figure 11 shows the typical failure mechanisms at the end of the compressive strength tests. The URM specimens developed visible continuous vertical cracking in the central part of the panel,as illustrated in Figure 11.a. Cracking was observed in the mortar joints, mortar-brick interfaces, and bricks. Small hairline cracks appeared during the tests until sudden brittle failure occurred, accompanied by a short loud breaking sound. Previous experiments have reported similar behaviours [61-63]. The SM specimens developed a brittle cracking pattern similar to that of the URM specimens, with additional vertical cracks throughout the specimens,as depicted in Figure 11.b. This crack pattern does not support the hypothesis that the insertion of PP strips in the horizontal joints can reduce the occurrence of cracks.
Table 5 presents the results of the compressive strength tests for both specimens. According to MKS EN 1052-1:1998 [58], compressive stress is calculated as the ratio of the applied force to the loaded cross-sectional area. Considering the mean value of the strains coming from both vertical transducers, Young's modulus was calculated as the secant modulus at one-third of the peak stresses and corresponding elastic strains. The peak strain was determined based on the peak stress of the specimen. In the post-peak branch of the curve, the ultimate strain was calculated as 80 % of the peak stress [64]. Stress-strain curves, derived from load and displacement measurements, are presented in Figure 12. All specimens exhibited a very similar section in the linear range up to one-third of the maximum strength achieved, with average strengths of 0.85 N/mm² for URM and 1.06 N/mm² for SM specimens, respectively.

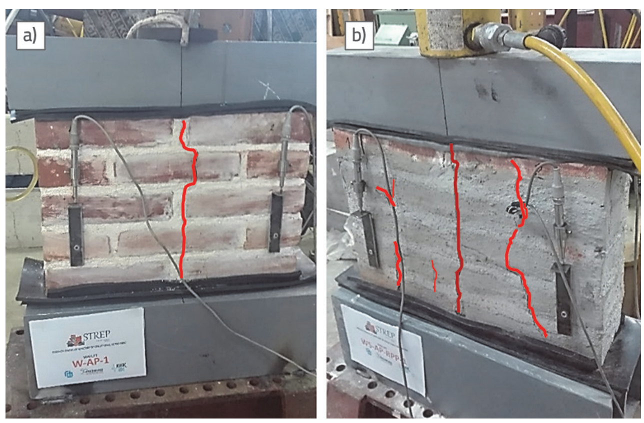

Figure 11. Typical failure mechanisms of masonry panel after compressive strength tests: a) URM panel (W-AP); b) SM panel (WS-AP-RPP)

The curves demonstrate that the material exhibits linear elastic behaviour up to a certain strain level, approximately 80-90 % of its strength [64]. Beyond this point, it becomes nonlinear as soon as the first cracks appear.

Table 5. Results of the compressive tests on URM (W-AP) and SM (WS-AP-RPP) specimens

Panel	Peak load [kN]	Compressive stress, f_k [N/mm²]	Young's modulus, E [N/mm²]	Ratio E/f_k [-]	Peak strain [-]	Ultimate strain [-]
W-AP-1	170.15	2.78	1211.0	436	0.0111	0.0114
W-AP-2	155.81	2.55	980.0	385	0.0159	0.0157
W-AP-3	144.19	2.36	986.0	418	0.0118	0.0118
Mean	**156.72**	**2.56**	**1059.0**	**413**	**0.0129**	**0.0130**
CoV [%]	8.3	8.2	12.4	6.2	20.0	18.3
WS-AP-RPP-1	183.73	3.00	1217.0	405	0.0086	0.0206
WS-AP-RPP-2	197.76	3.23	924.0	286	0.0153	0.0595
WS-AP-RPP-3	201.48	3.29	1295.0	393	0.0093	0.0529
Mean	**194.32**	**3.17**	**1145.3**	**362**	**0.0111**	**0.0443**
CoV (%)	4.8	4.8	17.1	18.2	33.3	47.0

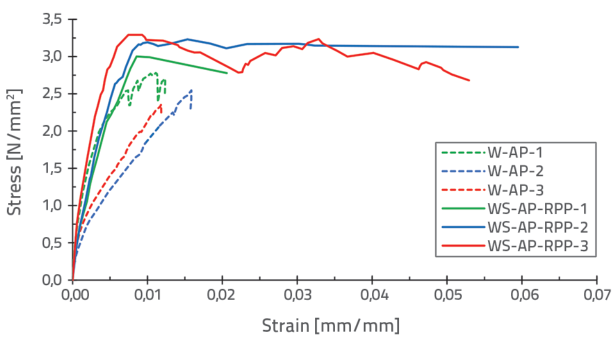

Figure 12. Comparison of compressive stress-strain diagrams

The average compressive strength, f_k, of the URM specimens was 2.56 N/mm², and the calculated average Young's modulus of elasticity, E, was 1211.0 N/mm². The average ratio of E to f_k, was 413. The obtained value is in the lower range of values suggested by Tomaževič [35], 200 $f_k \leq E \leq 2000\ f_k$, but much lower than the values proposed for new masonry in Eurocode 6 [65] and the Italian building code, NTC 2018 [66], which suggest E = 1000 f_k, FEMA 306 [67] suggests E = 550 f_k, TMS 2016 [68] suggests E = 700–900 f_k, IBC 2003 [69] and MSJC 2002 [70] suggest E = 700 f_k, and the Canadian masonry code [71] suggests E = 850 f_k.

The average compressive strength of the SM specimens was 3.17 N/mm², and the calculated average Young's modulus of elasticity was 1145.3 N/mm². The average ratio of E to f_k, was 362, which is slightly smaller than the value calculated for the URM specimens. Although only a small number of specimens were tested, this study indicates that the relationship between the compressive strength and modulus of elasticity of the URM and SM specimens can be considered similar. This suggests that the addition of a strengthening material does not significantly alter the relationship between the compressive strength and modulus of elasticity. However, further research is required to fully understand the effects of strengthening materials on masonry and to confirm this hypothesis.

The SM specimens increased the average compressive strength of the masonry by approximately 24 %. By contrast, the average Young's modulus of the SM specimens increased by only 8 %. This implies that the strengthening method increased the compressive strength and stiffness of the masonry due to the improved mortar properties. Although the behaviour of the PP strips has not been measured, it is believed that their contribution to these tests is relatively small, primarily because of the lack of anchorage at the ends of the specimens. The horizontal strain values at the end of the first linear section confirmed that the repointing mortar and the PP strip reinforcement initially improved the masonry. The coefficient of variation of the Young's modulus of elasticity for both specimens indicates that a reliable conclusion cannot be drawn from a small number of tested specimens. From the peak and ultimate strain values, the SM specimens showed a higher deformation capacity than the URM specimens. This suggests that the applied method not only increased the strength but also enhanced the material's ability to absorb energy, which is crucial for structures that must withstand forces without cracking or failing. The increased deformability may have been influenced by more efficient load redistribution within the masonry walls, allowing the stress distribution to become more uniform and reducing stress concentrations and localised failures.

It is worth noting that the URM specimen W-AP-1 exhibited better stiffness properties than the other two specimens. This discrepancy can be explained by possible variations in brick and mortar materials or the bond between them. Although the same masons constructed all the test specimens, certain construction variations such as the alignment of the masonry units or compaction during construction could contribute to variations in stiffness.

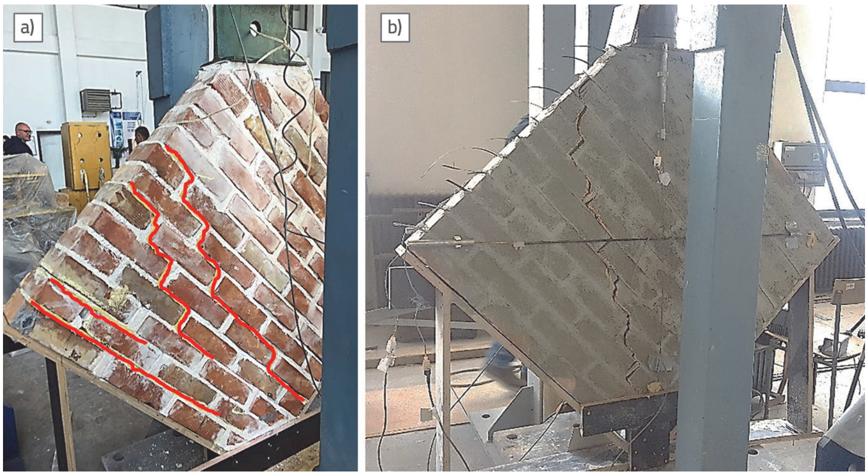

Figure 13. Typical failure mechanisms of masonry walls after diagonal tensile strength tests: a) URM panel (W-DP); b) SM panel (WS-DP-RPP)

3.2. Diagonal tensile strength

Figure 13 shows the typical failure mechanisms of the masonry panels at the end of the diagonal tensile strength tests. At the ultimate load limit, the URM panels developed diagonal and horizontal sliding-shear failures. The failure mechanisms were characterised by visible diagonal staircase cracking in the lower parts of the panels, which exceeded the tensile strength of the masonry, as depicted in Figure 13.a. Additionally, the lowest two bed joints experienced cracks along the joints, exhibiting typical in-plane shear sliding along the brick courses. Cracking was also observed in the mortar joints and the mortar-brick interface. The SM panels exhibited in-plane diagonal cracking, which resulted in unit failure. The main crack is vertical and located at approximately one-third of the main diagonal, as shown in Figure 13.b. The failure of all the panels was sudden, accompanied by a short, loud sound, indicating brittle behaviour. Figure 14 presents the load-displacement diagrams for all test panels. Elongation was considered positive, and shortening was considered negative. The mechanical properties were calculated according to ASTM E 519-02 [60]. Masonry behaviour in diagonal shear does not exhibit a typical yielding point; therefore, the modulus of rigidity can be determined using the slope of a secant line on the shear stress-shear strain diagram.

To calculate the secant modulus of rigidity, three levels of shear stress were used with consistent shear strains: $0.05S_s$, $0.3S_s$, and $0.7S_s$, corresponding to 5 % (crack-damage limit state), 30 % (evident changes in stiffness), and 70 % (severe degradation of resistance) of the maximum shear stress S_s, respectively [29, 37]. The URM panels failed at an average of 18.24 kN, corresponding to an average shear stress of 0.1012 N/mm² and an ultimate drift of 0.308 %, indicating ductile behaviour. The SM panels failed at an average of 55.75 kN, corresponding to an average shear stress of 0.316 N/mm² and ultimate drift of 0.252 %.

Figure 15 illustrates a comparison of the diagonal tensile stress-strain diagrams of the URM and SM panels. An obvious increase in the diagonal shear strength of the SM panels compared with that of the URM panels was observed. The calculated average increase in shear strength was 3.12 times. However, there was a small decrease in the average ductility of the SM panels compared with that of the URM panels. The diagrams for both the URM and SM wall panels show initial linear elastic branches up to the first peak and different post-

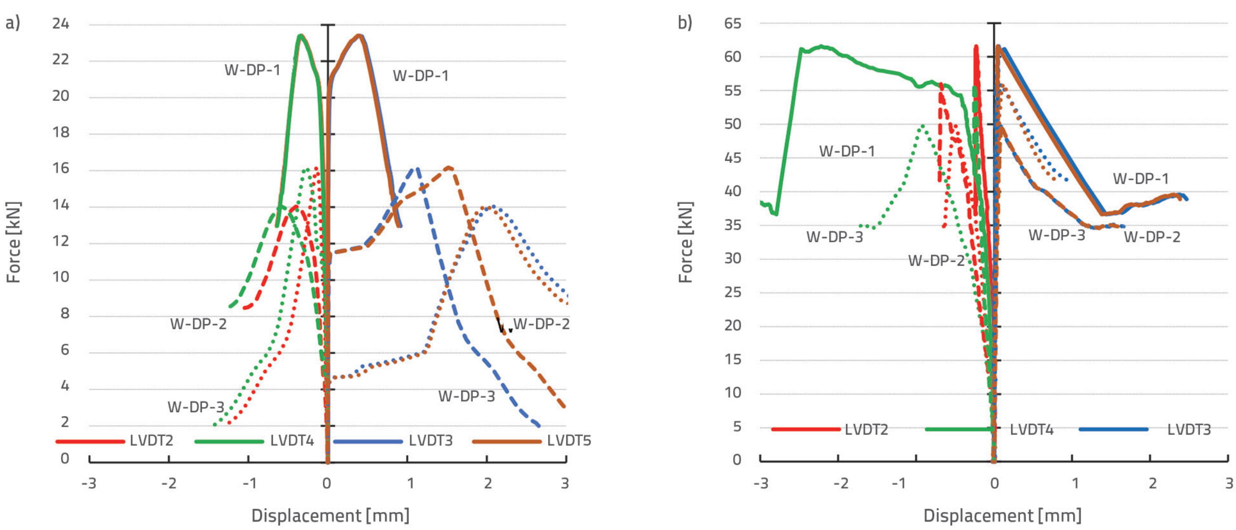

Figure 14. Force-displacement diagrams from diagonal tensile strength tests (LVDT2 and LVDT4-vertical displacement, LCDT3 and LVDT5-horizontal displacement): a) URM panels (W-DP); b) SM panels (WS-DP-RPP)

Table 6. Results of the diagonal tensile strength tests on URM and SM panels

Panel	Maximum load [kN]	Shear stress τ_0 (S_s) [N/mm²]	Modulus of rigidity, G at 0.05 τ_0 [N/mm²]	Modulus of rigidity, G at 0.3 τ_0 [N/mm²]	Modulus of rigidity, G at 0.7 τ_0 [N/mm²]
W-DP-1	23.71	0.1326	1319.48	1717.54	1310.18
W-DP-2	14.47	0.0795	1306.79	1604.95	234.20
W-DP-3	16.53	0.0916	4345.69	1888.18	660.57
Mean	**18.24**	**0.101**	**2323.99**	**1736.89**	**734.98**
CoV [%]	26.6	27.5	75.3	8.2	73.7
WS-DP-RPP-1	61.57	0.3488	3268.48	2813.66	1160.45
WS-DP-RPP-2	49.72	0.2817	3594.73	874.55	534.56
WS-DP-RPP-3	55.95	0.3170	8464.24	908.99	771.94
Mean	**55.75**	**0.316**	**5109.15**	**1532.40**	**822.32**
CoV (%)	10.6	10.6	57.0	72.4	38.4

peak behaviours. Most URM panels exhibited exponential softening, while almost all SM wall panels exhibited a rapid stress drop and linear softening after reaching the yield shear stress. Two URM and one SM wall exhibited post-peak hardening, followed by a subsequent decrease in shear stress until the ultimate displacement when the cracks were fully developed. As expected, the softening branches describe a gradual decrease in mechanical resistance under a

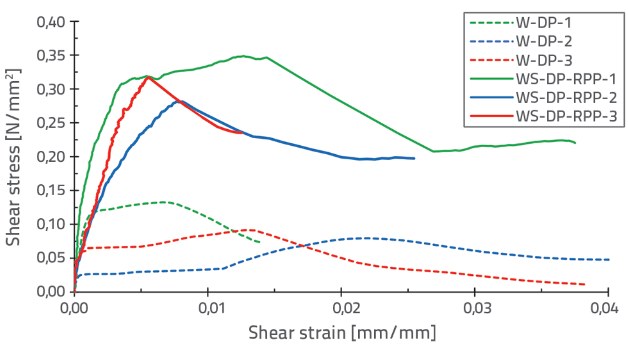

Figure 15. Comparison of diagonal tensile stress-strain diagrams

continuous increase in deformation. Finally, the values of the modulus of rigidity in the initial elastic phase of the SM panels were almost twice of those of the URM panel. However, for shear stress levels of 30 % and 70 % of the maximum shear stress, the values of the modulus of rigidity for both panels were relatively similar, with percentage differences ranging from 12.5 % to 20.4 %. It can be concluded that bed joint repointing effectively increases the diagonal tensile capacity by a factor of up to three. However, the deformation capacity does not increase; instead, a decrease was observed.

Although bed joint repointing improves the tensile strength of masonry joints, it also leads to a stiffer and less deformable system. The repointing mortar exhibited higher stiffness than the original mortar. This stiffness restricts the overall deformation capacity of the masonry panels, resulting in decreased deformation. Joint repointing reduces crack propagation and widening during loading, which contributes to the increased diagonal tensile capacity. However, this may also limit the overall deformation capacity because cracks tend to dissipate energy and allow for larger deformations. Careful consideration of the conclusions should be made due to the limitations of this study, as only a few test panels were examined. Nevertheless, there was a clear trend towards increasing the diagonal shear capacity using the selected strengthening technique.

4. Conclusions

In this study, joint repointing is examined as a method for strengthening masonry structures. An experimental investigation was conducted using a newly developed cement-based repointing mortar with high-strength fibre-reinforced polypropylene strips embedded in masonry joints. The results indicated that joint repointing using high-strength mortar and PP strips can significantly improve the strength and deformation capacity of unreinforced masonry as a structural material. A comparison of the experimental results for unreinforced and reinforced masonry under compressive loading showed that the joint-repointed panels exhibited a 20 % increase in compressive strength.

The applied strengthening method also had a positive effect on ductility, as observed in the specimens examined. An average increase of approximately 75 % was observed. By comparing the behaviours of the unreinforced and strengthened masonry under diagonal tensile loading, the average increase in diagonal tensile strength was approximately 65 %. In terms of ductility, the applied strengthening method did not have a significant effect, as observed for the three strengthened panels. At lower shear stress levels, cracks developed gradually. However, after a certain level of generated stress, the cracks opened suddenly. Under real earthquake conditions, the damage was expected to be more ductile considering that only the self-weight of the wall was considered during the tests.

Acknowledgements

This study is based on the results of the Strengthening Masonry with Joint Repointing (STREP) project. The project was realised with the cooperation of three partner institutions: the Faculty of Civil Engineering, Skopje, the Chair of Theory of Structures and Computational Analysis, and the Institute of Earthquake Engineering and Engineering Seismology, both parts of Ss. Cyril and Methodius University in Skopje conducted the experimental tests and numerical simulations. The company ADING A.D. from Skopje was responsible for the production of the specially modified joint repointing material and its application in the test models. We thank the laboratory staff for their technical assistance during this project.

REFERENCES

[1] Işık, E., Avcil, F., Büyüksaraç, A., İzol, R., Arslan, M.H., Aksoylu, S., Harirchian, E., Eyisüren, O., Arkan, E., Güngür, M.Ş., Günay, M., Ulutaș, H.: Structural damages in masonry buildings in Adıyaman during the Kahramanmaraș (Turkiye) earthquakes (Mw 7.7 and Mw 7.6) on 06 February 2023, Engineering Failure Analysis, 151 (2023).

[2] Caglar, N., Vural, I., Kiretl, O., Saribiyik, A., Sumer, Y.: Structural damages observed in buildings after the January 24, 2020. Elazığ-Sivrice earthquake in Türkiye, Case Studies in Construction Materials, 18 (2023).

[3] Marinković, M., Brzev, S., Baballëku, M., Isufi, B., Blagojević, N., Milićević, I., Žugić, Ž., Bursać, P.: Out-of-plane behaviour of loadbearing and non-structural masonry walls during recent earthquakes, Proceedings of 1st Croatian Conference on Earthquake Engineering, Zagreb, Croatia, 2021.

[4] Markušić, S., Stanko, D., Penava, D., Ivančić I., Bjelotomić Oršulić, O., Korbar, T., Sarhosis, V.: Destructive M6.2 Petrinja Earthquake (Croatia) in 2020 - Preliminary Multidisciplinary Research, Remote Sensing, 13 (2021) 6, p. 1095

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

[6] Uroš, M., Šavor Novak, M., Atalić, J., Sigmund, Z., Baniček, M., Demšić, M., Hak, S.: Post-earthquake damage assessment of buildings – procedure for conducting building inspections, GRAĐEVINAR, 72 (2020) 12, pp. 1089-1115, https://doi.org/10.14256/JCE.2969.2020.

[7] Pozos-Estrada, A., Chávez, M.M., Jaimes, M.A., Arnau, O., Guerrero, H.: Damages observed in locations of Oaxaca due to the Tehuantepec Mw8.2 earthquake, Mexico, Natural Hazards, 97 (2019) 2, pp. 623–641

[8] Rashadul, I.: Inventory of FRP strengthening methods in masonry structures, Master thesis, Technical University of Catalonia, Barcelona, 2008.

[9] Valluzi, M.R., Tinazzi, D., Modena, C.: Shear behavior of masonry panels strengthened by FRP laminates, Construction and Building Materials, 16 (2002) 7, pp. 409–416

[10] Foraboschi, P.: Effectiveness of novel methods to increase the FRP-masonry bond capacity Composites, Part B: Engineering, 107 (2016), pp. 214–232

[11] Vaculik, J., Visintin, P., Burton, N.G., Griffith, M.C., Seracino, R.: State-of-the-art review and future research directions for FRP-to-masonry bond research: test methods and techniques for extraction of bond-slip behavior, Construction and Building Materials, 183 (2018), pp. 325–345

[12] Babatunde, S.A.: Review of strengthening techniques for masonry using fiber reinforced polymers, Composite Structures, 161 (2017), pp. 246-255

[13] Di Tommaso, A., Focacci, F., Micelli, F.: Strengthening Historical Masonry with FRP or FRCM: Trends in Design Approach, Key Engineering Materials, 747 (2017), pp. 166–173

[14] Incerti, A., Ferretti, F., Mazzoti, C.: FRCM strengthening systems efficiency on the shear behavior of pre-damaged masonry panels: An experimental study, Journal of Building Pathology and Rehabilitation, 4 (2019).

[15] Angiolilli, M., Gregori, A., Pathirage, M., Cusatis, G.: Fiber Reinforced Cementitious Matrix (FRCM) for strengthening historical stone masonry structures: Experiments and computations, Engineering Structures, 224 (2020), p. 111102

[16] Ferretti, F., Khatiwada, S., Incerti, A., Giacomin, G., Tomaro, F., De Martino, V., Mazzotti, C.: Structural strengthening of masonry elements by reinforced repointing combined with FRCM and CRM, Procedia Structural Integrity, 44 (2023), pp. 2254-2261

[17] Cassacci, S., Gentilini, C., Di Tommaso, A., Oliveira, D.V.: Shear strengthening of masonry wallettes resorting to structural repointing and FRCM composites, Construction and Building Materials, 206 (2019), pp. 19-34

[18] Valluzzi, M.R., Tinazzi, D., Modena, C.: Strengthening of masonry structures under compressive loads by FRP strips: Local-Global Mechanical Behaviour, Science and Engineering of Composite Materials, 12 (2005) 3, pp. 203-218

[19] Cruz, A.I., Perez, O. Gavilan, J.J.: Seismic performance of confined masonry walls with joint reinforcement and aspect ratio: An experimental study, Engineering Structures, 242 (2021), p. 112484

[20] Sandoval, C., Serpell, R., Araya-Letelier, G., Calderón S.: Shear behavior of single- and triple-thickness masonry panels strengthened by bed-joint structural repointing, Construction and Building Materials, 286 (2021), p. 122925

[21] Zhao, W., Zhou, Q., Min, Q., Yang, L., Sun, B., Song, G.: Experimental study on the seismic performance of masonry wall reinforced by cement mortar and polypropylene band, Earthquake engineering and engineering vibration, 22 (2023), pp. 469–479

[22] De Santis, S., AlShawa, O., de Felice, G., Gobbin, F., Roselli, I., Sangirardi, M., Sorrentino, L., Liberatore, D.: Low-impact techniques for seismic strengthening fair faced masonry walls, Construction and Building Materials, 307 (2021) 1, p.124962

[23] Parisi, F., Menna, C., Prota, A.: 10 - Fabric-reinforced cementitious matrix (FRCM) composites: Mechanical behavior and application to masonry walls, Failure Analysis in Biocomposites, Fibre-Reinforced Composites and Hybrid Composites, 2019., pp. 199-227

[24] Umair, S.M., Numada, M. Amin, M.N., Meguro, K.: Fiber reinforced polymer and polypropylene composite retrofitting technique for masonry structures, Polymers, 7 (2015) 5, pp. 963-984

[25] Viswanathan, K.E., Ramasamy, J.V.: Flexural strengthening of brick masonry walls using fiber and polypropylene grid, Proceedings of the National Symposium for Post-Graduate Students in Civil Engineering, 2011.

[26] Jarc Simonič, M., Gostič, S., Bosiljkov, V., Žarnić, R.: Testing and analysis of walls strengthened with FRP, GRAĐEVINAR, 66 (2014) 6, pp. 533-548, https://doi.org/10.14256/JCE.960.2013.

[27] Jeffs, P.: Repointing Masonry Walls - Matching the Techniques for Success or Failure, PJ Materials Consultants Limited, www.guelph.ca, [19.3.2023].

[28] Valluzzi, M.R., Binda, L., Modena, C.: Mechanical behaviour of historic masonry structures strengthened by bed joints structural repointing, Construction and Building Materials, 19 (2005), pp. 63-73

[29] Gams, M., Tomaževič, M., Kwiecien, A.: Strengthening brick masonry by repointing – An experimental study, Key Engineering Materials, 624 (2014), pp. 444–452

[30] Drougkas, A., Licciardello, L., Rots, J. G., Esposito, R.: Experimental and numerical study of historic masonry with bed joint reinforced repointing, Proceedings of the EURODYN 2020 XI International conference on structural dynamics, Athens, Greece, 2 (2020), pp. 4212-4225

[31] Licciardello, L., Rots, J.G., Esposito, R.: Experimental tests on masonry strengthened with bed joint reinforced repointing, Heron Journal, 66 (2021) 1.

[32] Corradi, M., Speranzini, E., Bisciotti, G.: Out-of-plane reinforcement of masonry walls using joint-embedded steel cables, Bulletin of Earthquake Engineering, 18 (2020), pp. 4755–4782

[33] Corradi, M., Speranzini, E., Borri, A., Bisciotti, G., Agnetti, S.: A new method for out-of-plane reinforcement of masonry walls using high strength steel strand, Proceedings of the 17th International Brick and Block Masonry Conference - IB2MaC 2020, Krakow, Poland, 2020., pp. 89-99

[34] Corradi, M., Castori, G., Borri, A.: Repairing brickwork panels using titanium rods embedded in the mortar joints, Engineering Structures, 221 (2020).

[35] Tomaževič, M.: Earthquake-resistant design of masonry buildings, Imperial College press, 1999.

[36] Corradi, M., Tedeschi, C., Binda, L., Borri, A.: Experimental evaluation of shear and compression strength of masonry wall before and after reinforcement: Deep repointing, Construction and Building Materials, 22 (2008) 4, pp. 463–472

[37] Mustafaraj, E., Yardim, Y., Corradi, M., Borri, A.: Polypropylene as a retrofitting material for shear walls, Materials, 13 (2020) 11, p. 2503

[38] Melinda, A.P., Juliafad, E.: Experimental study of masonry wall strengthened by polypropylene fiber mortar, International Journal on Advanced Science, Engineering and Information Technology, 12 (2022) 3.

[39] Ebrahimzadeh, S., Nasrollahzadeh, K.: Experimental study on performance of repaired and strengthened unreinforced masonry walls using polypropylene bands, Scientia Iranica, (2022).

[40] Nasrollahzadeh, K., Zare, M.: Experimental investigation on axially loaded adobe masonry columns confined by polymeric straps, Construction and Building Materials, 262 (2020), p. 119895

[41] Luccioni, B., Rougier, V.: In-plane retrofitting of masonry panels with fibre reinforced composite materials, Construction and Building Materials, 25 (2011), pp. 1772-1788

[42] Sathiparan, N., Meguro, K.: Shear and flexural bending strength of masonry wall retrofitted using PP-Band mesh, CONSTRUCTII Journal, 14 (2013) 1, pp.3-12

[43] Heydariha, J.Z., Ghaednia, H., Nayak, S., Das, S., Bhattacharya, S., Dutta, S.C.: Experimental and field performance of PP band–retrofitted masonry: Evaluation of seismic behavior, Journal of Performance of Constructed Facilities, 33 (2019) 1.

[44] Elmalyh, S., Bouyahyaoui, A., Cherradi, T., Rotaru, A., Mihai, P.: In-Plane shear behavior of unreinforced masonry walls strengthened with fiber reinforced polymer composites, Advances in Science, Technology and Engineering Systems Journal, 5 (2020), pp. 360-367

[45] Sathiparan, N.: State of art review on PP-band retrofitting for masonry structures, Innovative Infrastructure Solutions, 5 (2020), p. 62

[46] Behera, B., Nanda, R.P.: In-plane shear strengthening of brick masonry panel with geogrid reinforcement embedded in bed and bed-head joints mortar, Engineering Structures, 227 (2021).

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

[48] Maurenbrecher, A.H.P., Trischuk, K., Rousseau, M.Z., Subercaseaux, M.I.: Repointing mortars for older masonry buildings: Design considerations, Construction Technology Update, 67 (2008).

[49] Dumova-Jovanoska, E., Churilov, S., Shendova, V., Kristevska, L.: Report from the research project "Masonry strengthening by joint repointing - STREP", Ss. Cyril and Methodius University in Skopje, Faculty of Civil Engineering – Skopje, Institute of Earthquake Engineering and Engineering Seismology and ADING AD, Skopje, 2021.

[50] MKC EN 771-1: Specification for masonry units: Clay masonry units, ISRSM, 2011.

[51] MKC EN 772-1: Methods of test for masonry units - Part 1: Determination of compressive strength, ISRSM, 2013.

[52] MKS EN 459-1: Building lime - Part 1: Definitions, specifications and conformity criteria, ISRSM, 2015.

[53] MKS EN 1015-11: Methods of test for mortar for masonry - Part 11: Determination of flexural and compressive strength of hardened mortar, ISRSM, 2009.

[54] MKC EN 12190: Products and systems for the protection and repair of concrete structures: Test methods - Determination of compressive strength of repair mortar, ISRSM, 2009.

[55] MKC EN 1504-3: Products and systems for the protection and repair of concrete structures - Definitions, requirements, quality control and evaluation of conformity - Part 3: Structural and non-structural repair, ISRSM, 2006.

[56] MKC EN 1542: Products and systems for the protection and repair of concrete structures: Test methods - Measurement of bond strength by pull-off, ISRSM, 2009.

[57] MKS EN ISO 9001: Quality management systems – Requirements, ISRSM, 2015.

[58] MKS EN 1052-1: Methods of test for masonry - Part 1: Determination of compressive strength, ISRSM, 1998.

[59] Moropoulou, A., Bakolas, A., Moundoulas, P., Aggelakopoulou, E., Anagnostopoulou, S.: Strength development and lime reaction in mortars for repairing historic masonries, Cement & Concrete Composites, 27 (2005), pp. 289–294

[60] ASTM E 519-02: Standard Test Method for diagonal tension (shear) in masonry assemblages, American Society for Testing and Materials, West Conshohocken, PA, USA, 2002.

[61] Drougkas, A., Roca, P., Molins, C.: Compressive strength and elasticity of pure lime mortar masonry, Materials and Structures, 49 (2016), pp. 983–999

[62] Segura, J., Pela, L., Roca, P.: Monotonic and cyclic testing of clay brick and lime mortar masonry in compression, Construction and Building Materials, 193 (2018), pp. 453–466

[63] Thamboo, J.A., Dhanasekar, M.: Assessment of the characteristics of lime mortar bonded brickwork wallettes under monotonic and cyclic compression, Construction and Building Materials, 261 (2020), p. 120003

[64] Thamboo, J.A., Navaratnam, S., Poologanathan, K., Corradi, M.: Characteristics of CFRP strengthened masonry wallettes under concentric and eccentric compression, Case Studies in Construction Materials, 14 (2021).

[65] EN 1996-1-1: Eurocode 6- Design of masonry structures: Part 1- 1 - General Rules for Reinforced and Unreinforced Masonry Structures, CEN, 2005.

[66] NTC: Italian Building Code for Constructions, Ministry of Infrastructure and Transport of Republic of Italy, 2018.

[67] FEMA 306: Evaluation of earthquake damaged concrete and masonry wall buildings, Basic Procedures Manual, Applied Technology Council Redwood City, CA, USA, 1999.

[68] TMS: Building code requirements and specification for masonry structures, (TMS 402/602- 16), The Masonry Society, Longmont, 2016.

[69] International Code Consortium: International Building Code, IBC, Falls Church, VA, USA, 2003.

[70] Masonry Standards Joint Committee: Building code requirements for masonry structures - ACI 530-02/ ASCE 5-02/TMS 402-02, American Concrete Institute, Structural Engineering Institute of the American Society of Civil Engineers, The Masonry Society, Detroit, MI, USA, 2002.

[71] Canadian Standards Association: Design of masonry structures - S304.1, Mississauga, ON, Canada, 2004.