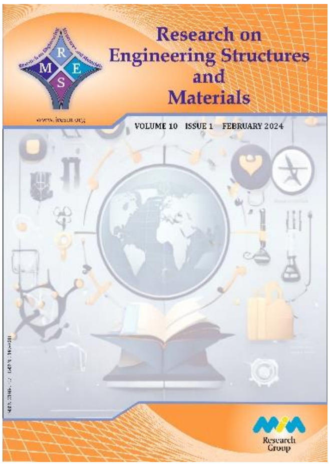
Research on Engineering Structures & Materials
www.jresm.org
Research Group



Observed failure modes in existing URM buildings after November 26, 2019 earthquake in Albania

Enio Deneko, Hüseyin Bilgin

Online Publication Date: 22 January 2024
URL: http://www.jresm.org/archive/resm2024.106ea1202rs.html
DOI: http://dx.doi.org/10.17515/resm2024.106ea1202rs

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

To cite this article
Deneko E, Bilgin H. Observed failure modes in existing URM buildings after November 26, 2019 earthquake in Albania. *Res. Eng. Struct. Mater.*, 2024; 10(3): 1085-1107.

Research on Engineering Structures & Materials
www.jresm.org

Research Article

Observed failure modes in existing URM buildings after November 26, 2019 earthquake in Albania

Enio Deneko[1,a], Hüseyin Bilgin[*2,b]

[1]*Faculty of Civil Engineering, Polytechnic University of Tirana, Tirana, Albania*
[2]*Department of Civil Engineering, EPOKA University, Tirana, Albania*

Article Info

Article history:

Received 02 Dec 2023
Accepted 22 Jan 2024

Keywords:

URM buildings;
Failure modes;
Structural weaknesses;
Retrofitting

Abstract

This study explores the vulnerability of Unreinforced Masonry (URM) structures to seismic events, aiming to uncover the causes of failure and propose reconstruction strategies. Despite often being devastated in powerful earthquakes, URM buildings show damage even in mild to moderate seismic events. Field assessments after a magnitude 6.4 earthquake near Durres, Albania, in 2019, revealed severe damage in masonry buildings and adobe dwellings. Weak structural connections, insufficient roof support, and the absence of bond beams in load-bearing walls were identified as key contributors to the observed damage. The survival of masonry buildings post-earthquake does not guarantee seismic safety. The study recommends reinforcement techniques like shotcrete application, space reduction, and corner reinforcement, along with innovative methods such as Fiber Reinforced Polymer (FRP) use, for existing undamaged unreinforced buildings. These measures aim to prevent damage in the aftermath of destructive earthquakes, offering insights for the resilience of URM structures.

1. Introduction

Albania, located in the southwestern Balkans as depicted in Fig. 1, is susceptible to a variety of moderate and significant earthquakes due to the presence of multiple active fault lines in the region, a characteristic that has been evident throughout its historical record [1]. On September 21 and November 26, 2019, two separate seismic activity occurred, causing a significant damage in Albania, a region characterized by a high seismic hazard [2]. These earthquakes had a profound impact on important cities of the country, including Durres and Tirana. Various types of structural systems experienced damage at different degrees, ranging from minor to severe, or complete collapse [3]. Numerous structures managed to withstand the initial earthquake. However, following the second tremor that occurred three months later, it imposed a greater degree of damage and worsened the extent of destruction [4]. The earthquake sequences in 2019 provided valuable lessons for both reinforced concrete (RC) and masonry structures in urban and rural areas [5].

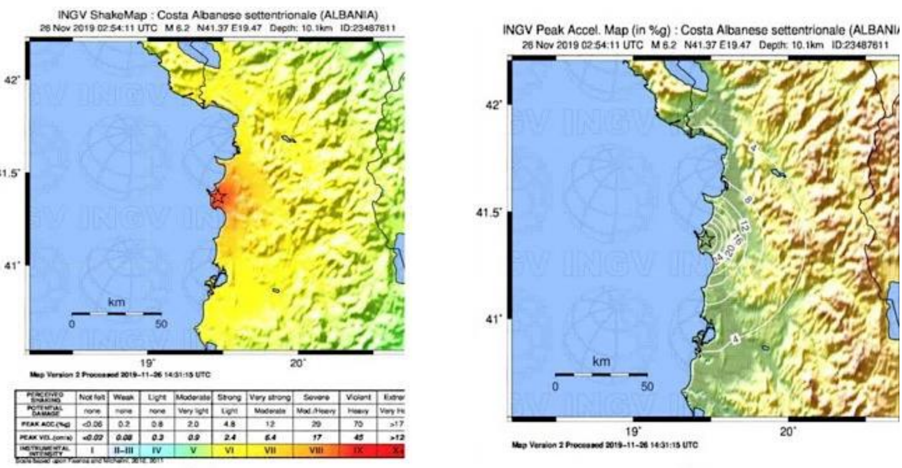
In rural regions, particularly in poor villages, residents often construct their homes using readily available materials. This is a common practice across most of Albania's villages, where dwellings are frequently built using materials like brick, rubble stone, or adobe. Many of these buildings have been in existence for generations, passed down from one family member to the next. As a result, these structures have aged significantly, leading to a loss of strength and stability. Moreover, such structures were typically built without the involvement of essential engineering services. All these factors combine to increase the

*Corresponding author: hbilgin@epoka.edu.al
[a] orcid.org/0009-0000-7236-5242; [b] orcid.org/0000-0002-5261-3939
DOI: http://dx.doi.org/10.17515/resm2024.106ea1202rs

vulnerability of these structures, making them susceptible to damage and destruction even during moderately sized tremors [6-7].

Fig. 1. Active fault map of Albania [1]

The seismic event in Durres on November 26, 2019, registering a magnitude of Mw = 6.4, resulted in substantial damage, as illustrated in Fig. 2. To assess the failures in masonry buildings, field visits were conducted in both major cities and the surrounding villages affected by this earthquake. The Durres district, where these affected villages are situated, is approximately 35 kilometres from the capital centre of Tirana and is located along the Adriatic Sea coast.



(a) (b)

Fig. 2. Intensity map of November 26, 2019 Durres/Albania earthquake (INGV, 2019)

The Earth serves as an exceptional laboratory, enabling the examination of a building's response following seismic events. Identifying structural damage in the aftermath of an earthquake is an essential step in post-disaster management. Consequently, numerous detailed studies have been conducted by researchers after earthquakes. These studies involve the observation of structural damage and the acquisition of valuable insights into the causes of failures.

Fig. 3 illustrates the accelerometric stations associated with the November 26, 2019 earthquake (M6.4), while Table 1 provides a tabulation of the measured acceleration values.

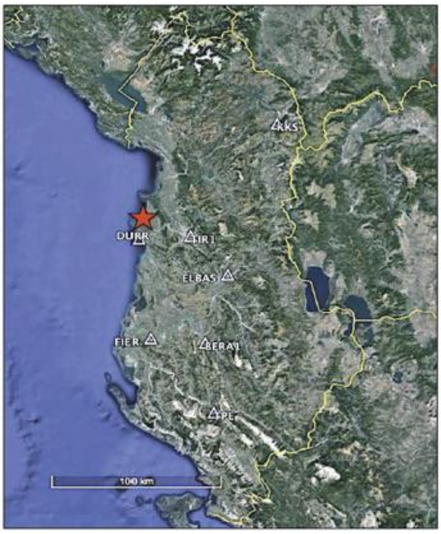


Fig. 3. Dispersion of the nearest accelerometer stations that captured the seismic activity, (red star: epicentre)

Structural behaviour of URM buildings was studied in the aftermath of 2010 Christchurch earthquake in New Zealand [8]. Kaplan and colleagues investigated the damage, both structural and non-structural, to different buildings in the aftermath of the 2009 L'Aquila earthquake in Italy [9]. Following the 2010 Chile earthquake, earthquake behaviour of masonry buildings was analysed by Astrosa and co-authors [10]. Basset and Guardiola investigated the damages inflicted by the 2011 earthquake, to masonry dwellings in Spain [11]. Saha et al. investigated seismic damage to buildings after the 2017 Tripura earthquake in Bangladesh [12]. Chen and collaborators evaluated structural damage in the aftermath of the 2014 Yunnan earthquake in China [13]. Sorrentino and colleagues investigated the behaviour of typical masonry buildings in response to seismic events in Italy in 2016 [14]. Gautam and Chaulagain explored structural performance during the Gorkha earthquake in Nepal on April 25, 2015, and shared the lessons learned [15]. Shakya and Kawan evaluated the building damage in Nepal - Kathmandu earthquake [16]. Aras and Düzci studied the earthquake response of commonly encountered traditional masonry houses in Çanakkale following seismic activities [17]. Vlachakis and co-authors assessed the damage and failure mechanisms of masonry houses in the aftermath of the 2017 Greece earthquake [18]. Bayraktar and colleagues conducted on-site observations to assess how masonry structures performed during the 2011 Earthquakes in eastern part of Turkey [19]. Atmaca et al. evaluated the performance of building structures in Turkey considering previous earthquake events [20]. Valente [21] explored the seismic response of two historic masonry palaces through 3-D structural analyses. The results of structural analyses shown a significant dependence of damage distributions and seismic response on the dynamic and geometric characteristics of the structures. Isık et al. [22] examined the masonry damages in Adıyaman province following the 2023 Kahramanmaraş earthquakes in Türkiye. They asserted that the predominant cause of structural damage is attributed to weak structural features.

Table 1. Accelerometric stations and measured acceleration values of November 26, 2019 Earthquake (M6.4) (Fig. 3)

Station	Recording Station	Vs30 (m/s)	Site	Measured PGA (cm/s²) / PGV (cm/s) / PGD (cm)									Dist. to epicentre
Code	Location			N-S			E-W			V			km
DURR	Durres	200	Free field	192.0	38.55	14.0	122.3	14.4	4.52	114.5	7.18	4.39	15.6
TIR 1	Tirana	310	Free field	110.0	6.65	1.77	113.9	7.57	1.80	43.49	2.16	0.73	33.7
BERA1	Berat	1.010	Free field	10.65	0.68	0.16	15.10	0.92	0.29	7.91	0.53	0.13	93.7
ELBAS	Elbasan	405	2-story building	19.75	1.70	0.44	13.69	0.87	0.22	11.88	0.96	0.23	65.8
FIER	Fier	375	2-story building	17.83	1.20	0.57	17.39	1.50	0.59	8.80	0.74	0.35	83.2
KKS	Kukes	750	1-story building	7.87	0.79	0.40	7.87	0.95	0.51	-	-	-	105
TPE	Tepelene	690	2-story building	6.28	0.79	0.22	5.36	0.72	0.26	3.88	0.37	0.11	128.2

The primary objective of this paper is to centre on the recognition of damage patterns and the proposal of seismic reinforcement strategies for pre-existing unreinforced masonry structures following the earthquake that occurred on November 26, 2019. This research involves an evaluation of the structural deficiencies and performance of masonry buildings. The observed damage patterns are categorized into four main types: entire collapse, damage on corners, in-plane, and out-of-plane failures.

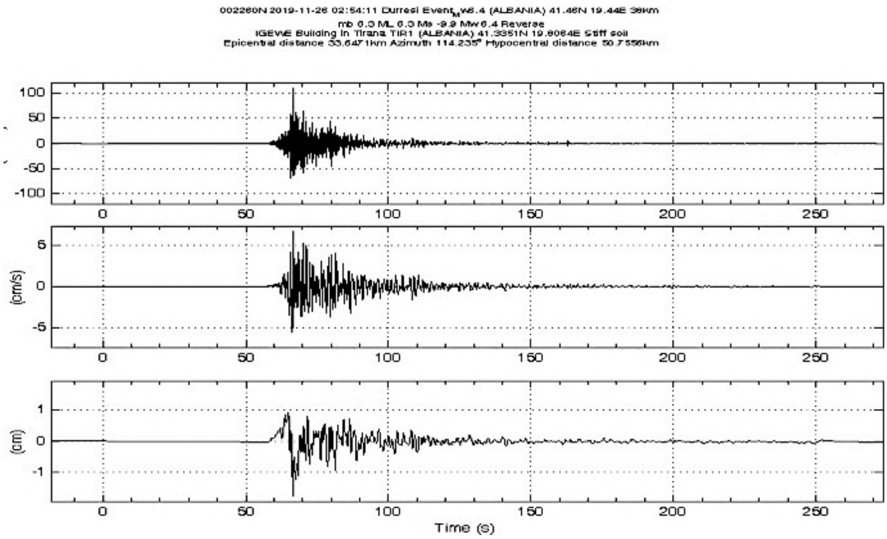
2. Features of November 26, 2019 Earthquake

On November 26, 2019, at 03:54 CET, Durres city experienced a notable seismic event. This earthquake was characterized as moderately strong, with a magnitude of Mw = 6.4. The intensity map, depicted in Fig. 2, illustrates the affected zones, with active faults indicated by red lines. displayed. Detailed acceleration values recorded at different locations can be found in Table 1.

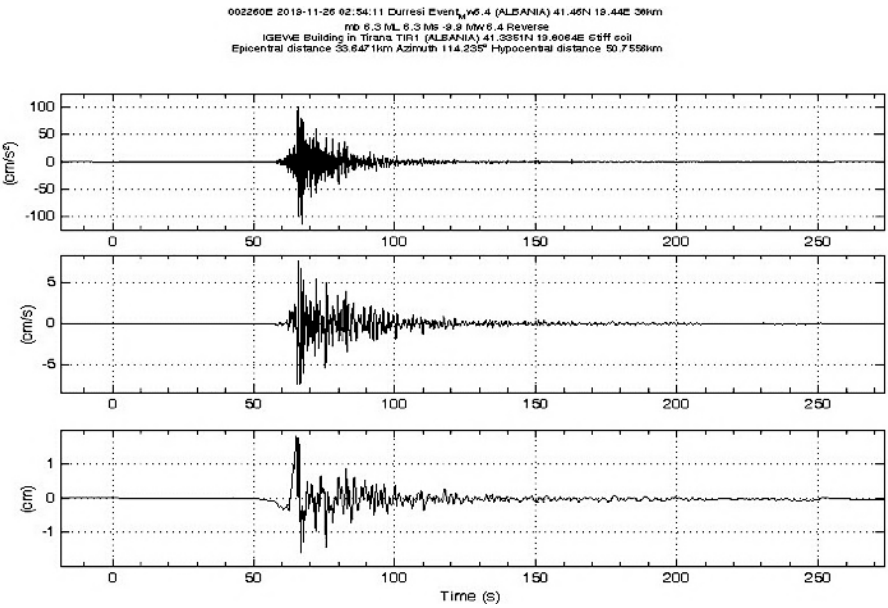
Durres station recorded the highest ground acceleration values, measuring 192.0 cm/s^2 for the North–South (N–S) component, 122.30 cm/s^2 for the East–West (E-W) component, and 114.5 cm/s^2 for the vertical component. Acceleration recordings, encompassing three components and obtained from the provided site address, can be observed in Fig. 4.

Furthermore, Fig. 5 presents a comparative assessment of the response spectra in the East–West and North–South directions, contrasting them with the specifications outlined in Eurocode 8 [23].

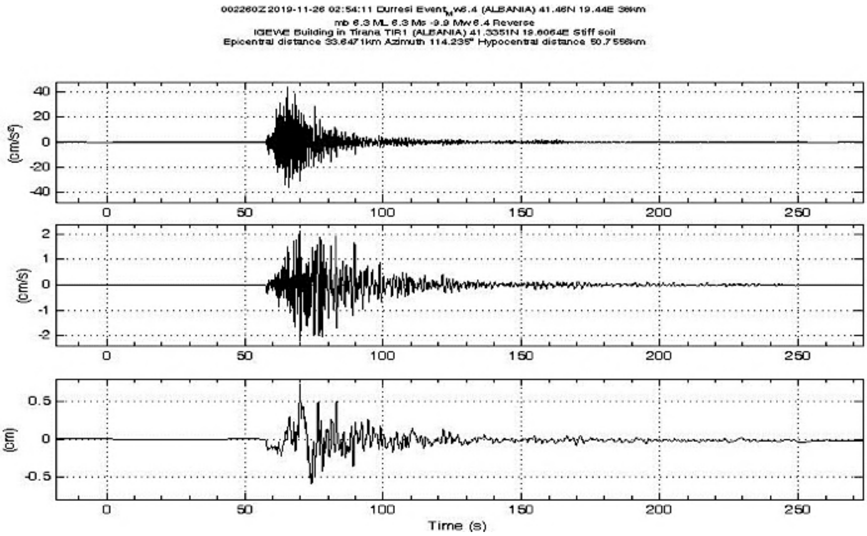
It's worth noting that, despite the earthquake's response spectra registering relatively lower values compared to the EC-8 design spectra, the observed villages still experienced significant structural failures and asset losses. Moreover, the spectral accelerations derived from the recorded data, as depicted in Fig. 5, consistently exhibit values 1.5 - 2.0 times greater than the spectral periods ranging from 0.2 - 0.8 seconds, as specified by the building code. This observation is noteworthy, given that the fundamental periods of many buildings in the affected areas typically fall within this range.



a) November 26, 2019 Earthquake North-South component



b) November 26, 2019 Earthquake East-West component



c) November 26, 2019 Earthquake Vertical component

Fig. 4. Time histories of acceleration in Tirana (TIR1 Station, https://www.geo.edu.al/tirana_record/

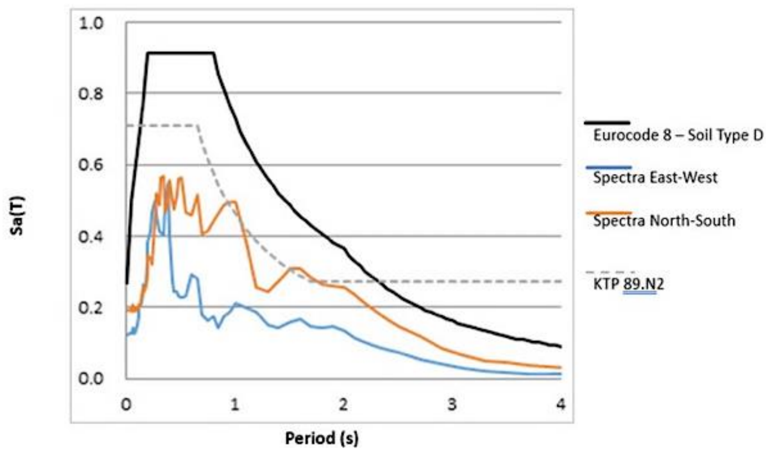


Fig. 5. Comparison of response spectrum with design spectra (EC-8) [23-24]

3. Identified Collapse Mechanisms in Pre-Modern URM Buildings and Solution Methods

In the significant urban regions of Albania [25], there were approximately 44,500 dwellings, including adobe, masonry, and RC structures. Many of the masonry buildings in the affected regions were of low to moderate height and were constructed in various time periods. These structures were primarily composed of adobe, stone, and brick-briquette masonry, with mortar in the walls containing cement. The documented failures in masonry structures can be classified into four primary types: entire failure, damage on corners, in-plane and out-of-plane failures. The following section provides a detailed account of these structural deficiencies and failures. The amounts of damage sustained by these dwellings because of the earthquake on November 26, 2019, are presented in Table 2, adopted from EMS-98 [26]. Upon examining this table and figure, it becomes evident that the masonry buildings experienced severe damage due to the earthquake in 2019.

Table 2. Classification of damage in masonry structures in accordance with EMS-98 [26]

Classification of Damage to Masonry Buildings				
Grade	**Damage Level**	**Schematic**	**Sample**	**Description**
1	Slight			No structural damage, slight non-structural damage
2	Moderate			Slight structural damage, moderate non-structural damage
3	Heavy			Substantial to heavy damage, moderate structural damage, heavy non-structural damage
4	Very Heavy			Heavy structural damage, very heavy non-structural damage
5	Destruction			Very heavy structural damage, total or near total collapse

The criteria for categorizing post-earthquake building damage inventory and usability involve classifying buildings into five damage degrees. The initial two levels, DS1 (Grade 1) and DS2 (Grade 2), designate buildings that are immediately usable after the earthquake and do not require repair. These structures exhibit minor non-structural damage and extremely isolated and negligible structural damage. The subsequent levels, DS3 (Grade 3) and DS4 (Grade 4), categorize buildings as temporarily unusable. Such structures display extensive non-structural damage and significant structural damage yet have a repairable structural system. The final level, DS5 (Grade 5), classifies buildings as unusable. These structures are either destroyed or have experienced partial or complete collapse of the structural system. The regulations and recommendations regarding the investigation process also provide a detailed damage description for each damage degree, facilitating a thorough examination of the building.

A post-earthquake damage assessment was conducted over 44,000 buildings (Table 3) using a methodology outlined in reference [26]. This approach was designed to identify damage levels and collapse mechanisms in various architectural elements of the investigated structures, as outlined in Table 3. Approximately 90% of the examined buildings were deemed suitable for immediate occupancy, while the remaining portion was classified as unsuitable for occupancy [27].

Table 3. Number of buildings investigated by Construction Institute and corresponding damage states [27]

City	DS0	DS1	DS2	DS3	DS4	DS5	TOTAL
DURRES	22,605	2,761	2,384	1,735	1,855	626	31,966
Durres	13,737	1,801	1,210	804	582	205	18,339
Kruje	1,672	529	582	454	690	137	4,064
Shijak	7,196	431	592	477	583	284	9,563
LEZHE	494	364	421	326	402	43	2,050
Kurbin	343	244	294	196	215	28	1,320
Lezhe	150	110	112	126	166	9	673
Mirdite	1	10	15	4	21	6	57
TIRANE	5,651	1,560	1,258	737	974	386	10,566
Kamez	138	233	163	46	65	18	663
Kavaje	18	89	137	126	108	12	490
Tirane	207	528	481	348	458	60	2,082
Vore	5,288	710	477	217	343	296	7,331
TOTAL	28,750	4,685	4,063	2,798	3,231	1,055	44,582

3.1 Entire or Partial Destruction

This category of destruction occurs once the structural integrity of a building is compromised by the impact of out-of-plane mechanisms. In rural areas of Albania, especially in the countryside, dwellings frequently feature roofing systems constructed from locally sourced materials. Many of these masonry buildings employ timber logs for their roofing and flooring systems. Over time, these structures, which are typically old and have been exposed to various environmental conditions, experience a decline in the strength of their walls.

The collapse of these buildings can be attributed to several factors, one of which is the weight of the heavy earthen roofs. To keep the structure away from rain and snow, additional layers of soil are frequently added to the roof. Consequently, the thickness and mass of the earthen roofs gradually increase, resulting in a higher load borne by the building during an earthquake.

Fig. 6. Collapse of masonry buildings

The structural walls and timber logs are unable to withstand this heightened horizontal load, causing the walls to shift out-of-plane and leading to a complete collapse.Fig. 6 visually illustrates the observed damage of this particular type across different regions. To reduce the risk of total collapse, it is crucial to refrain from using adobe buildings and earthen roofs. Instead, consider implementing lighter roofing systems that incorporate horizontal and vertical bond beams during construction. This approach helps distribute the loads more effectively and enhances the building's seismic resilience.

3.2 Damages on Corners

Effective wall connections are essential for preventing both widespread and localized damage in masonry structures. Unfortunately, this aspect is often overlooked, with traditional connections persisting in wall construction. It is of paramount importance to give special consideration to these connections [28].

One common consequence of inadequate connections between structural walls is the occurrence of corner damages. These damages commonly occur at connections between walls, primarily due to the lack of strong links between them. Problems such as the utilization of low-quality materials, inferior workmanship, and insufficient provision of bond beams have contributed to the failure of adobe and stone masonry residences. Damage on corners was a prevalent issue observed in buildings within the earthquake affected areas.

Fig. 7. Observed corner damages

In numerous cases, inadequate wooden beams and improper ties were noted at the junctions of the affected buildings. The structural failures were significantly influenced by the weak bonds between the walls, compounded by the lack of horizontal or vertical bonding ties. Fig. 7 depicts a visual representation of the corner damage observed in masonry dwellings during the earthquake in Albania.

To mitigate corner failures, it is recommended to avoid the use of adobe or stone rubble in the construction of structural walls. Instead, hewn stone or brick materials should be employed, accompanied by the incorporation of reinforced concrete (RC) bond beams in both orthogonal directions. Adhering to modern seismic guidelines, it is crucial to maintain uniform thickness for these beams and walls, especially at the structure's edges. Fig. 8 illustrates the application of bond beams in masonry constructions as a preventive measure against corner damages.

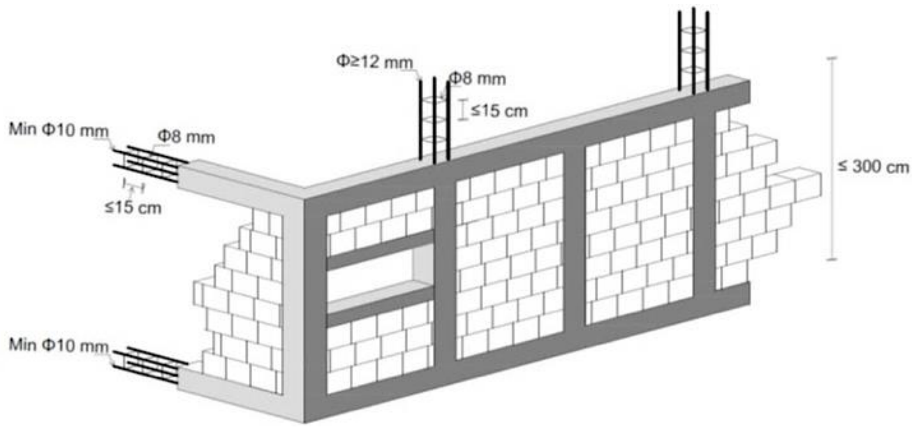


Fig. 8. Detailed design of horizontal and Vertical tie beams in load-bearing walls [modified from source 29]

For these beams, it is imperative that the concrete used possesses a minimum compressive strength of 20 MPa, along with the inclusion of Ø8 stirrups. The spacing between these stirrups should not exceed 15 cm, and a longitudinal bar must be included. Additionally, for the creation of a sturdy diaphragm, an RC flat plate with a minimum thickness of 10 cm should be constructed. In accordance with Eurocode-8 [23] standards, the linkage between slabs and walls should be established with steel connections or RC ring girders. Flat RC beams must be furnished with longitudinal rebars, with a cross-sectional area not less than 2 cm^2.

On the other hand, the utilization of the confined system is recommended for newly constructed masonry structures in Eurocode 8, ensuring the integrity of the building. However, applying this technique to existing buildings poses challenges and comes with high costs.

3.3 Out-of-Plane Damages

Masonry walls exhibit notably better structural performance within the structure's plane than in the perpendicular, out-of-plane behaviour, due to their inherent in-plane rigidity. These walls exhibit flexibility when subjected to forces perpendicular to the earthquake motion. Consequently, shear forces become influential within the plane of the wall, leading to in-plane mechanisms. Additionally, a flexural mechanism emerges in the weaker direction, giving rise to out-of-plane mechanisms.

This situation often results in out-of-plane mechanisms, which are considered undesirable due to their brittle behaviour when compared to in-plane mechanisms. Various factors, including insufficient connections between neighbouring walls, weak wall-to-floor connections, unsupported wall lengths, and inadequate vertical and horizontal bond beams, can contribute to the development of out-of-plane mechanisms. These mechanisms are characterized by their inability to resist tensile shear forces on the wall face.

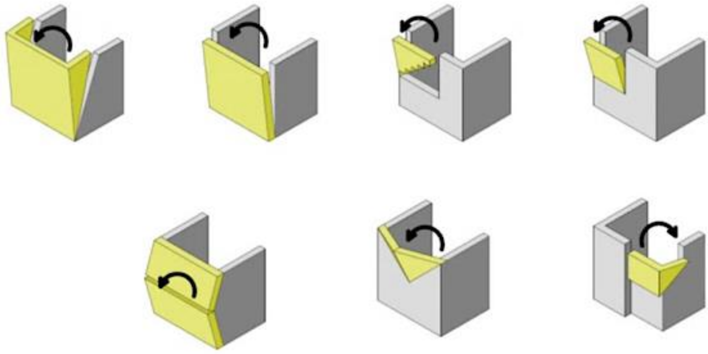


Fig. 9. Various out-of-plane mechanisms

A significant contributor to out-of-plane mechanisms is the positioning of timber logs that bear the load of the building's floors in a single direction. This arrangement results in the transfer of earthquake loads from perpendicular walls to the timber logs, making walls without support from these logs susceptible to out-of-plane overturning. Fig. 9 schematically outlines various out-of-plane mechanisms, while Fig. 10 illustrates observed out-of-plane mechanisms in unreinforced masonry (URM) buildings across different villages following the November 26, 2019, earthquake in Albania.

To prevent these mechanisms and ensure proper wall connection, it is crucial to establish a rigid diaphragm, particularly when structural walls lack reinforced concrete bond beams. Otherwise, partial or total failure mechanisms can occur.

To mitigate the occurrence of this out-of-plane mechanism, several measures can be taken. Firstly, it is crucial to limit the unsupported length of a load-bearing wall. Additionally, incorporate reinforced concrete horizontal and vertical bond beams into the construction, as illustrated in Fig. 11. Moreover, it is vital to ensure the presence of bearing walls in both the x- and y-directions, as recommended in reference [23].

Fig. 10. Observed out-of-plane collapses of walls

Specifically, vertical bonding girders should be positioned at the edges of the building, extending the full height of the storey. Moreover, these vertical beams should be spaced along the wall at intervals of approximately 4 meters [23, 30-31]. It's advisable to avoid the use of tall and lengthy unsupported walls.

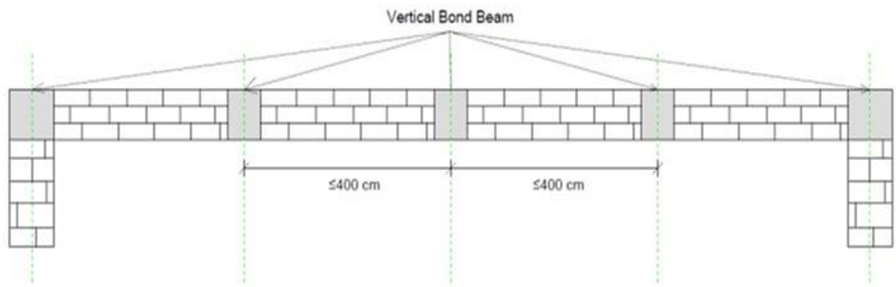


Fig. 11. Management of vertical bonding beams within the layout. Adapted from [30]

Fig. 12 provide visual examples illustrating the presentation of vertical bonding girders. Detailed designs for flat bonding girders at the intersection wall (a) and the angle wall (b) are also showcased. These measures are designed to improve the seismic resilience of the structure and decrease the risk of out-of-plane mechanisms.

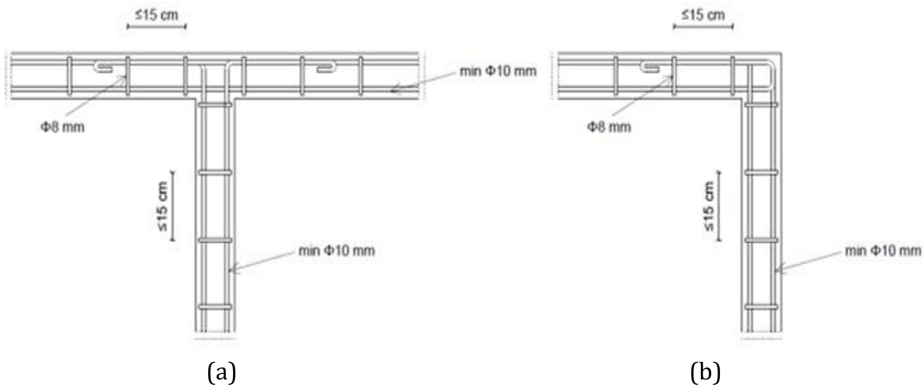


Fig. 12. The design details for horizontal bonding girders at a joint (a) and a junction (b) are outlined. Adapted from [30]

3.4 In-Plane Mechanisms

In-plane mechanisms can develop from various forms of structural failures, encompassing sliding, tensile, flexural-bending, crushing, and shear. It's important to note that these different failure modes can sometimes occur concurrently. Additionally, an increase in vertical load on the wall can lead to the development of cracks. In an in-plane mechanism, lateral seismic forces cause shear forces to act within the structure's plane. Fig. 13 schematically illustrates the distribution of in-plane loading, depicting a scenario where vertical loading is the sole influencing factor.

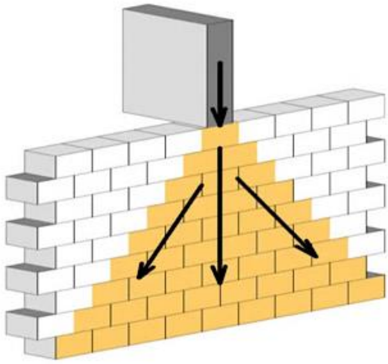
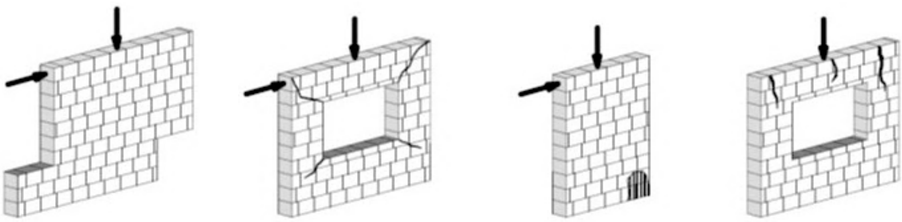


Fig. 13. Illustration of the distribution of in-plane loading. Adapted from [32]

In-plane loading can give rise to different types of damage, including flexural and shear cracks, or a combination of both. In Fig. 14a, sliding damage is portrayed, characterized by the gradual development of lateral cracks along the bed-joints of the masonry wall. This process divides the wall in two segments that move alongside the fracture plane. The formation of tensile cracks along an oblique of the bed-joints gives rise to diagonal shear cracks, ultimately dividing the wall in two segments. If shear cracks propagate by the in-plane direction of the wall, it becomes unstable, resulting in a loss of load-bearing capacity. Fig. 14b schematically illustrates this failure.



(a) Sliding Shear (b) Shear (c) Toe Crushing (d) Tensile

Fig. 14. Common in-plane failing modes observed on walls due to the combination of earthquake and imposed loading. Adapted from [33]

Fig. 14c showcases toe-crushing, a type of damage characterized by perpendicular compression and lateral tensile cracks concentrated at the base or "toe" of the wall segment. Lastly, Fig. 14d presents splitting damage, which results from in-plane vertical loading. When the tensile stress induced by earthquake forces is greater than the tensile strength of the wall, vertical cracks appear along the elevation of the wall.

The prevalence of the in-plane mechanism involving sliding shear in masonry buildings can be attributed to the inadequate shear strength of the masonry walls and the absence of appropriate reinforced concrete (RC) bond beams. Fig. 15 visually presents examples of in-plane failures observed in masonry dwellings across various villages. This type of failure underscores the importance of reinforcing masonry structures to enhance their resilience during seismic events.

Fig. 15. Shear failure

The existence of bond beams is essential for establishing structural integrity, but numerous masonry structures in the earthquake-affected villages lacked adequate and suitable bonding girders to enhance the complete horizontal shear capacity of their walls. Moreover, these structures featured sizable openings, which led to a reduction in wall stiffness and an amplification of shear effects. To mitigate this form of damage, it is advisable to incorporate reinforced concrete (RC) bond beams and decrease the size of openings in the load-bearing walls. Fig. 16 visually depicts this type of damage, emphasizing the significance of addressing these structural deficiencies to enhance the seismic resilience of masonry buildings.

Fig. 16. Shear effect in masonry buildings

Crushing failure represents another type of in-plane failure, manifesting when the vertical part of earthquake motion is greater than the compressive strength of the load-bearing wall. Initially, vertical cracks propagate across the vertical transverse segment of the wall, followed by splitting along the longitudinal partition. Fig. 17 visually demonstrates the total loss of internal structural integrity in a masonry wall caused by crushing damage resulting from the dividing crash of the masonry segment.

Fig. 17. Crushing failure of the walls

This kind of damage is frequently witnessed in adobe and multi-leaf debris stone wall segments, mainly because of the absence of appropriate flat bonding planks. In other words, insufficient interlocking between connecting bearing walls at corners leads to the occurrence of this type of damage. To prevent this type of failure, it is essential to incorporate proper horizontal bond beams, which can enhance the seismic resilience of these structures.

4. Recommendations for Repairing and Retrofitting Masonry Structures

URM buildings that are susceptible to complete collapse or have been identified as having poor earthquake resistance ought to be dismantled. Instead, new structures should be constructed in adherence to contemporary engineering standards and prevailing seismic regulations.

Extensive research has been conducted to explore ways of enhancing the strength and durability of URM structures. The primary objective of all retrofitting methods is to improve their ability to resist loads or extend the time it takes for them to collapse when subjected to unexpectedly high external forces. Retrofitting masonry structures involves three key concepts: i) mitigating external forces; ii) upgrading existing buildings; and iii) enhancing integrity. The initial two concepts have been succinctly covered and demonstrated in a handful of research documents [34-35], while the third concept has received limited attention. This section will delve into a detailed presentation of some of the commonly encountered concepts and their practical applications.

4.1 Retrofitting Masonry Buildings

The primary objective of all retrofitting methods is to bolster the horizontal load bearing capacity of the walls. On the other hand, an additional contribution can be achieved by reducing the weight of the roof through the installation of a lighter roofing material, instead of an earthen roof. One of the commonly employed methods for surface treatment is the application of shotcrete and ferrocement. It involves initially covering the structural wall with a steel mesh secured by cotters. Subsequently, high-strength cement mortar is sprayed onto the wall's surface, creating a uniform new layer. This method can be applied to one or both surfaces of the wall and provides increased performance to the wall.

Shotcrete is run by spraying it over a mesh of wire installed on the surface of the masonry wall, as depicted in Fig. 18. Typically, the overlay thickness falls within the range of 7 cm to 15 cm [36-37]. Shear dowels are commonly required to facilitate shear transfer between the masonry-shotcrete interface. Prior to applying shotcrete, it is essential to remove wythes of bricks and fill the voids. Enhancements to the retrofitting of shotcrete can be achieved when the substrate surface becomes notably rough following the removal of loose or deteriorated portions [38].

While this approach is applicable to various masonry buildings to enhance the strength and stiffness, including those made of adobe, stone, and brick, it's worth noting that employing this method in older buildings may not always be cost-effective. On the other hand, this method has drawbacks, including time-consuming application and the alteration of original aesthetics. Consequently, it is deemed unsuitable for the retrofitting of masonry historical monumental structures. In such cases, demolishing the old structure and constructing a new one could be a more suitable approach.

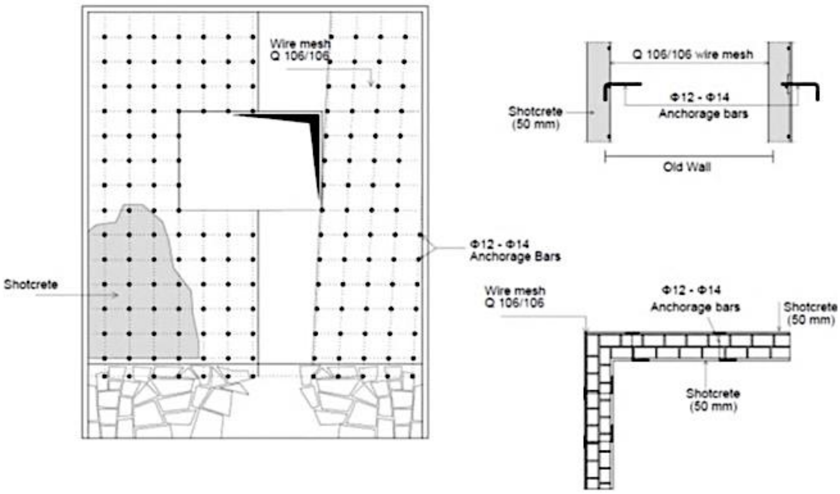


Fig. 18. Diagram depicting the application of shotcrete. Adapted from [39]

Fig. 19 illustrates another method called mesh reinforcement, which involves strengthening an URM wall segment by confining it with bonding struts and applying fibre-reinforced polymer (FRP) from one corner to the other. The initial application of FRP composite for retrofitting or reinforcing existing structures was in the realm of concrete. Subsequently, its usage has been expanded to include other types of structures such as masonry and timber. This extension has garnered important attention in research, with thorough studies deployed on its application across various structural materials [40].

FRP is a composite material that comprises high-strength fibres like carbon, glass, and aramid. When employed for reinforcing existing masonry structures, FRP demonstrates superior strength and ductility compared to traditional materials. This technique enhances the in-plane load-bearing capacity of the wall while preventing out-of-plane damage.

Retrofitting unreinforced masonry (URM) walls with FRP composites can result in a significant improvement in strength, typically ranging from 1.1 to 3 times [41, 42]. Research has shown that the resistance of masonry walls can be enhanced by 13-84% through an analysis of walls retrofitted with carbon fibre. The degree of improvement may vary depending on the specific structure undergoing retrofitting. In another study [43], FRP was observed to increase the shear resistance of masonry buildings by 3.3 times.

Although reinforcing masonry panels with FRP offers advantages such as minimal added mass, low disruption, and a relatively substantial enhancement in strength, this technique has drawbacks, including its high cost, the need for advanced technical expertise, and alterations to the structure's appearance. The initial cost of FRP material is approximately 5 to 10 times higher than that of steel [44], posing a significant consideration in the selection of retrofitting approaches.

Nevertheless, it's important to acknowledge that attaining the smooth surface necessary for the use of FRP in masonry buildings constructed with rough stone can pose a challenge. As a result, strengthening with FRP may not be feasible for such structures. Additionally, due to the higher cost of FRP compared to concrete and steel, applying FRP to masonry buildings constructed using conventional techniques in rural areas may not be a cost-effective solution. In such cases, shotcrete application could be a more practical alternative.

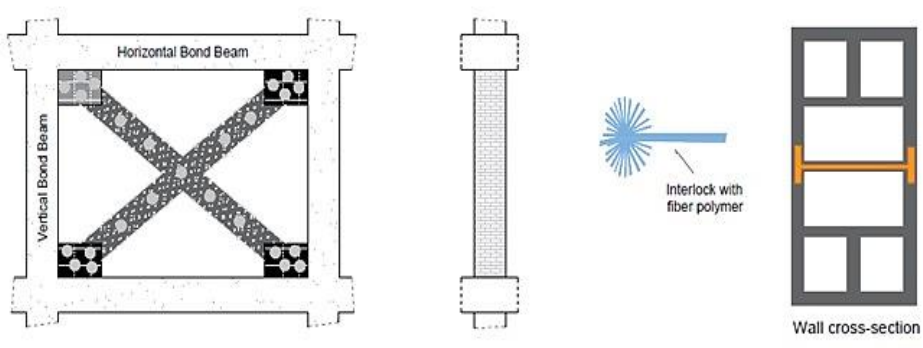


Fig. 19. Reinforcing URM segments using FRP polymer. Adapted from [39]

One effective method for enhancing structural integrity involves minimizing the size of openings or sealing off excess spaces, such as oversized spaces and entrances. Based on the modern guidelines (TEC-2018), it is recommended to restrict the width of openings within a wall plane to less than 3 meters. Furthermore, the proportion of the total length of open spaces to the length of unsupported wall within the wall plane should not surpass 40%. Additionally, in compliance with EC8, the ratio of wall length to the greater net height of adjacent spaces must adhere to specific minimum values (0.50 for stonemasonry and 0.40 for other brick categories).

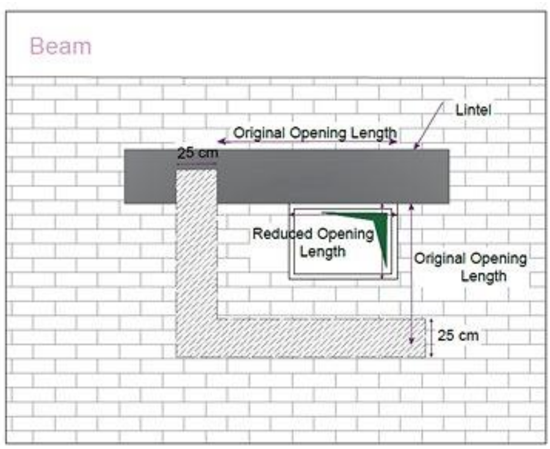
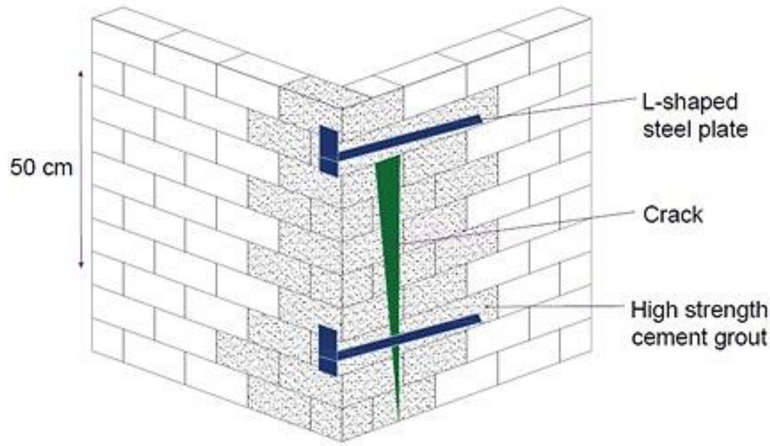


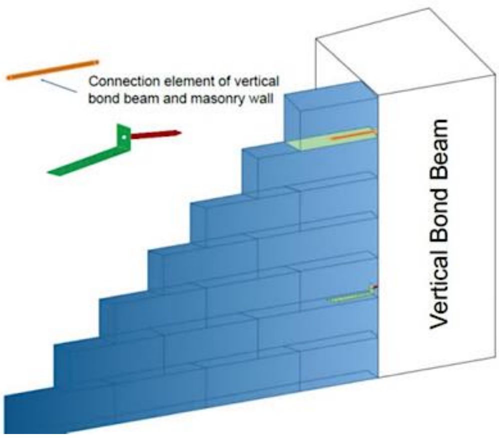
Fig. 20 Reduction of space in a wall segment. Adapted from [39, 45]

Among the various reinforcement techniques, this approach stands out as one of the most practical and applicable to whole masonry constructions. Its application improves the overall in-plane resistance of the load bearing wall, significantly contributing to structural performance during seismic events. Fig. 20 offers a schematic representation of this reinforcement approach.

Figs. 21a and 21b demonstrate strategies for strengthening the junctions of masonry blocks and establishing links between wall segments and vertical bonding joists, respectively. In the case of wall corners, connecting them with steel plates and anchoring them together is recommended. Subsequently, any pin holes in the walls should be sealed by prepared mortar shot. The method depicted in Fig. 21a is feasible and cost-effective, suitable for application in all masonry buildings to prevent corner damages. On the other hand, the approach shown in Fig. 21b necessitates the presence of a vertical bond beam for implementation.



(a)



(b)

Fig. 21. (a) Schematic depiction of reinforcing the corner link among walls, and (b) Strengthening the connection between a wall and a vertical bond beam [adopted from [39]

A study on masonry structures confined with constructional columns and ring beams, as outlined in [46], suggests that such structures exhibit favourable performance during earthquakes. The study concludes that the mechanical performance, including ductility and strength, of the masonry panels is primarily upheld by the confining elements.

4.2 Repairing Existing URM Buildings

Maintaining masonry buildings is of utmost importance to safeguard them against the impact of earthquakes. Consequently, even minor cracks should not be overlooked and must be promptly repaired. To tackle such maintenance, U-formed steel tools and mortar injections are utilized. Small cracks, typically those with a width smaller than 2 mm, are reinforced with the steel components and then filled with mortar.

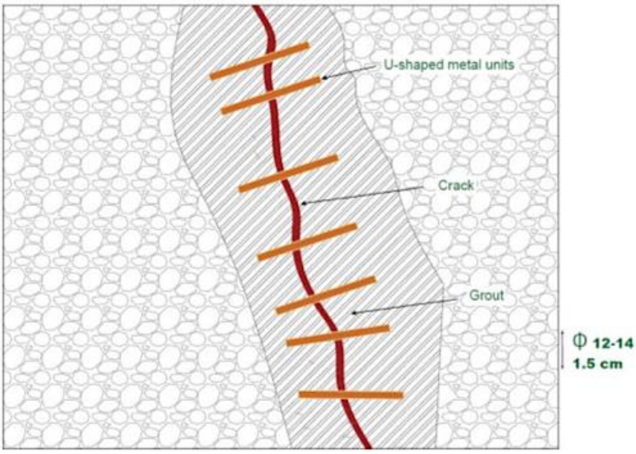


Fig. 22. Diagram depicting the repair of minor cracks. Adapted from [39, 45]

Fig. 22 provides both a schematic and a visual representation of the healing process. This repair method is applicable to all existing masonry buildings and can help prevent further deterioration, ensuring the longevity and stability of these structures.

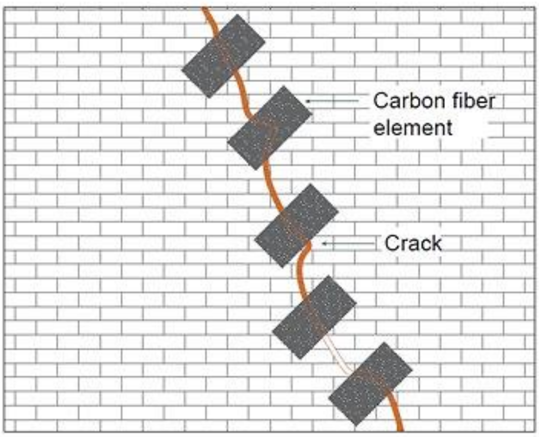


Fig. 23. Diagram depicting the repair of minor cracks. Adapted from [39, 45]

Another method for repairing masonry structures involves the use of Fiber Reinforced Polymer (FRP). FRP components are applied alongside the cracks, making this technique suitable for cracks with a width of less than 1 mm. As a result, this method effectively prevents the further expansion of cracks. Fig. 23 offers a schematic representation of the application process. This repair technique is suitable for brick masonry structures. Nevertheless, this is crucial to highlight that the challenges of obtaining a smooth plane on rough stone may limit the applicability of this method to buildings constructed with such materials.

Apart from strengthening the superstructure, certain reinforcement methods can be applied to the soil and foundations. One approach involves lowering the groundwater level to a depth below the foundation by using drainage techniques. During the implementation of this approach, it is essential to take precautions to avoid differential settlements within the building.

Another way to reinforce the foundation system is by expanding the footing size and redirecting the structural loads to deeper, more stable layers using an appropriate system. Additionally, the load-bearing capability of the ground can be increased through techniques like jet grouting. However, it's important to note that this method of strengthening can be costly.

5. Conclusions and Recommendations

The literature discusses the failure modes in URM structures during earthquakes, especially following destructive ones. This study highlights that URM structures, often built by unqualified individuals, exhibit poor earthquake response and are susceptible to destruction even in mid-size earthquakes. Therefore, this paper assesses the potential damage that could occur during a catastrophic earthquake and presents various strengthening options.

The Durres/Albania earthquake (M_w = 6.4) resulted in significant damage patterns. To assess this damage, urban centers and their surrounding areas near the earthquake's epicenter were visited, and various building typologies were examined. Site visits revealed that the earthquake response of the affected structures fell below expectations, primarily because they were not built in accordance with engineering standards and modern seismic guidelines. Consequently, the anticipated structural behaviour was not accomplished, even when subjected to mid-sized tremors. The primary causes of these failures were identified, and recommendations to prevent life losses and mitigate assets losses are as follows:

The observed failures in the surveyed dwellings can be attributed to several factors. These include the inhesion of earthen roofs, which significantly contributed to the damage. Weak detailing of connections between walls, encompassing both wall-to-wall and wall-to-roof connections, further exacerbated the structural issues. Additionally, the absence or inadequacy of bonding struts within the load-bearing walls played a crucial role in the failures. Both out-of-plane and in-plane mechanisms were identified as failure modes, showcasing the structural vulnerabilities. Building on sloping land aggravated these issues, and foundation collapses were also observed as critical factors in the overall failures.

Here are some recommendations to avoid future damage:

- If replacing heavy roofs with lighter roofing systems is not possible, it is advisable to consider demolishing these structures. Subsequently, new houses should be constructed using advanced construction practices and adhering to seismic code specifications.
- In cases of localized corner damages, the recommended method involves fixing separations in the corner walls and reinforcing them. However, if the damage is extensive and compromises the structural integrity, it is advisable to reconstruct the walls.

- To mitigate the damage induced by out-of-plane actions to a masonry wall, several measures could be implemented. These include applying FRP polymer from one corner to another, reducing the size of large openings, and reinforcing corners with iron anchor coats. Moreover, an additional protective measure for the masonry wall involves enveloping it with a steel mesh and fastening it securely with cotters prior to the application of shotcrete.
- To prevent in-plane failures, it's vital to reinforce structural walls along the wall plane. The recommended strategies for addressing out-of-plane mechanisms are equally applicable to in-plane mechanisms.
- To prevent damages related to loose soil, it is imperative to construct buildings on level ground and establish robust footings. Effectively addressing these concerns involves lowering the groundwater level below the foundation and expanding the foundation width.
- To protect buildings from potential earthquakes, it is crucial to prevent the formation of microcracks, and any existing micro-cracks should be carefully fixed using U-formed steel apparatus and cement injections.
- A considerable portion of masonry buildings predates the 1990s, constructed in accordance with the building code requirements of that era. This has led to the development of diverse construction practices and significant technical deficiencies in these buildings. While masonry structures demonstrate robustness under vertical loads, they exhibit fragility and are vulnerable to severe damage when subjected to horizontal loads, such as those encountered during earthquakes.

This paper has revealed that URM structures situated in active earthquake regions in Albania exhibit notably poor seismic performance. Even a moderate earthquake resulted in considerable structural damage. To avert potential harm in rural areas, it is imperative to construct earthquake-resistant dwellings in accordance with contemporary seismic codes and construction practices, while also retrofitting existing undamaged structures.

References

[1] Bilgin H, Hysenlliu M. Comparison of near and far-fault ground motion effects on low and mid-rise masonry buildings. Journal of Building Engineering. 2020; 30: 101248. https://doi.org/10.1016/j.jobe.2020.101248

[2] Bilgin H. Effects of near-fault and far-fault ground motions on nonlinear dynamic response and seismic damage of masonry structures. Engineering Structures. 2024;300:117200. ISSN 0141-0296. https://doi.org/10.1016/j.engstruct.2023.117200

[3] Leti M, Bilgin H. Predicting the Seismic Performance of Typical R/C Residential Buildings. In: Ademović N, Mujčić E, Mulić M, Kevrić J, Akšamija Z (eds) Advanced Technologies, Systems, and Applications VII. IAT 2022. Lecture Notes in Networks and Systems. Springer, Cham. https://doi.org/10.1007/978-3-031-17697-5_2

[4] Leti M, Bilgin H. Damage potential of near and far-fault ground motions on seismic response of RC buildings designed according to old practices. Research on Engineering Structures and Materials. 2022;8(2). http://dx.doi.org/10.17515/resm2022.392ea0123

[5] Bidaj A, Bilgin H, Hysenlliu M, Premti I, Ormeni R. Performance of URM structures under earthquake shakings: Validation using a template building structure by the 2019 Albanian earthquakes. Engineering Structures and Materials. 2022. http://jresm.org/archive/resm2022.440ea0531

[6] Shkodrani N, Bilgin H, Hysenlliu M. Influence of interventions on the seismic performance of URM buildings designed according to pre-modern codes. Journal of

Research on Engineering Structures and Materials. 2021;7(2):315-330. https://doi.org/10.17515/resm2020.197ea0331

[7] Freddi F, Novelli V, Gentile R, et al. Observations from the 26th November 2019 Albania earthquake: the earthquake engineering field investigation team (EEFIT) mission. Bulletin of Earthquake Engineering. 2021; 19: 2013-2044. https://doi.org/10.1007/s10518-021-01062-8

[8] Ingham J, Griffith M. Performance of unreinforced masonry buildings during the 2010 Darfield (Christchurch, NZ) earthquake. Australian Journal of Structural Engineering. 2010;11(3):207-224.

[9] Kaplan H, Bilgin H, Yilmaz S, Binici H, Oztas A. Structural Damages of L'Aquila Earthquake. Hazards Earth Syst Sci. 2010; 10: 499-507. https://doi.org/10.5194/nhess-10-499-2010

[10] Astroza M, Moroni O, Brzev S, Tanner J. Seismic performance of engineered masonry buildings in the 2010 Maule earthquake. Earthquake Spectra. 2012;28:385–406.

[11] Basset-Salom L, Guardiola-Víllora A. Seismic performance of masonry residential buildings in Lorca's city centre, after the 11th May 2011 earthquake. Bulletin of Earthquake Engineering. 2014;12(5):2027-2048.

[12] Saha R, Debnath R, Dash S, Haldar S. Engineering reconnaissance following the magnitude 5.7 Tripura earthquake on January 3, 2017. Journal of Performance of Constructed Facilities. 2020;34(4):04020052.

[13] Chen H, Xie Q, Dai B, Zhang H. Seismic damage to structures in the Ms=6.5 Ludian earthquake. Earthquake Engineering and Engineering Vibration. 2016;15(1):173-186.

[14] Sorrentino L, Cattari S, Porto F, Magenes G, Penna A. Seismic behaviour of ordinary masonry buildings during the 2016 central Italy earthquakes. Bulletin of Earthquake Engineering. 2019;17(10):5583-5607.

[15] Gautam D, Chaulagain H. Structural performance and associated lessons to be learned from world earthquakes in Nepal after 25 April 2015 (MW 7.8) Gorkha earthquake. Engineering Failure Analysis. 2016; 68: 222-243.

[16] Shakya M, Kawan CK. Reconnaissance based damage survey of buildings in Kathmandu valley: an aftermath of 7.8 Mw, 25 April 2015 Gorkha (Nepal) earthquake. Engineering Failure Analysis. 2016; 59: 161-184.

[17] Aras F, Düzci E. Seismic performance of traditional stone masonry dwellings under Çanakkale seismic sequences. Journal of Performance of Constructed Facilities. 2018;32(4):04018029.

[18] Vlachakis G, Vlachaki E, Lourenço PB. Learning from failure: damage and failure of masonry structures, after the 2017 Lesvos earthquake (Greece). Engineering Failure Analysis. 2020;104803.

[19] Bayraktar A, Altunışık AC, Muvafık M. Field investigation of the performance of masonry buildings during the October 23 and November 9, 2011, van earthquakes in Turkey. Journal of Performance of Constructed Facilities. 2016;30(2):04014209.

[20] Atmaca B, Demir S, Günaydın M, et al. Lessons learned from the past earthquakes on building performance in Turkey. Journal of Structural Engineering & Applied Mechanics. 2020;3(2):61–84.

[21] Valente M. Seismic behavior and damage assessment of two historical fortified masonry palaces with corner towers. Engineering Failure Analysis. 2022; 134: 106003.

[22] Isık E, Avcil F, Büyüksaraç A, et al. Structural damages in masonry buildings in Adıyaman during the Kahramanmaraş (Türkiye) earthquakes (Mw 7.7 and Mw 7.6) on 06 February 2023. Engineering Failure Analysis. 2023; 151: 107405.

[23] Eurocode 8: design of structures for earthquake resistance - Part 1: general rules, seismic actions and rules for buildings.

[24] KTP-N.2-89, Technical aseismic regulations. Publication of Academy of Sciences and Ministry of Constructions (in Albanian). Tirana, Albania (1989).

[25] Bilgin H, Shkodrani N, Hysenlliu M, Ozmen HB, Işık E, Harirchain E. Damage and performance evaluation of masonry buildings constructed in 1970s during the 2019 Albania earthquakes. Engineering Failure Analysis. 2022; 131: 105824. https://doi.org/10.1016/j.engfailanal.2021.105824
[26] Grünthal G (Ed.). European Macroseismic Scale 1998 (EMS-98), European Seismological Commission, subcommission on Engineering Seismology. Conseil de l'Europe, Cahiers du Centre Europeen de Geodynamique et de Seismologie. 15, Luxembourg, 1998-1999.
[27] Hysenlliu M. Vulnerability Assessment of Current Masonry Building Stock in Albania, Ph.D. thesis, EPOKA University, Department of Civil Engineering.
[28] Jasinski R, Galman I. Testing joints between walls made of AAC masonry units. Buildings. 2020;10(4):69.
[29] Ural A, Doğangün A, Sezen H, Angın Z. Seismic performance of masonry buildings during the 2007 Bala, Turkey earthquakes. Natural Hazards. 2012;60(3):1013–1026.
[30] Turkish Seismic Code, 2007, Ankara, Turkey (in Turkish).
[31] Turkey Building Earthquake Code 2018, Ankara, Turkey (in Turkish).
[32] McKenzie WM. Design of Structural Masonry, Palgrave, New York, 2001.
[33] Tomazevic M. Earthquake-resistant Design of Masonry Buildings, vol. 1, World Scientific, 1999.
[34] Chuang SW, Zhuge Y. Seismic retrofitting of unreinforced masonry buildings-a literature review. Australian Journal of Structural Engineering. 2005;6(1):25-36. https://dx.doi.org/10.1080/13287982.2005.11464942
[35] Bhattacharya S, Nayak S, Dutta SC. A critical review of retrofitting methods for unreinforced masonry structures. International Journal of Disaster Risk Reduction. 2014; 7:51-67. https://dx.doi.org/10.1016/j.ijdrr.2013.12.004
[36] Abrams DP. New perspectives on seismic rehabilitation. Proceedings of the Asia-Pacific workshop on Seismic Design and Retrofit of Structures, 1998 Taipei, Taiwan.
[37] Karantoni F, Fardis M. Effectiveness of seismic strengthening techniques for masonry buildings.
[38] Augenti N, Nanni A, Parisi F. Construction failures and innovative retrofitting. Buildings. 2013;3(1):100-121. https://dx.doi.org/10.3390/buildings3010100
[39] Celep Z. Introduction to Earthquake Engineering and Earthquake Resistivity Design, Beta Press and Distribution Corporation, Istanbul, 2018 (in Turkish).
[40] Teng JG, Chen JF, Smith ST, Lam L. Behaviour and strength of FRP-strengthened RC structures: A state of the art review. Proc. Inst. Civ. Eng., Struct. Build. 2003;156(1):51-62. https://dx.doi.org/10.1680/stbu.2003.156.1.51
[41] Alcaino P, Santa-Maria H. Experimental response of externally retrofitted masonry walls subjected to shear loading. Journal of Composites for Construction. 2008;12(5):489-498. https://dx.doi.org/10.1061/(ASCE)1090-0268(2008)12:5(489)
[42] ElGawady MA, Lestuzzi P, Badoux M. A review of retrofitting of unreinforced masonry walls using composites. Proceedings of the 4th International Conference on Advanced Composite Materials in Bridges and Structures, 2004 Calgary, Alberta.
[43] Mahmood H, Ingham J. Diagonal compression testing of FRP-retrofitted unreinforced clay brick masonry wallettes. Journal of Composites for Construction. 2011;15(5):810-820. https://dx.doi.org/10.1061/(ASCE)CC.1943-5614.0000209
[44] "Does FRP have an economic future?", Proceedings of the 4th conference on advanced composite materials in bridges and structures, 2004 Calgary, Alberta.
[45] ACI (American Concrete Institute). Specification for Masonry Structures, vol. 530, ACI, Farmington Hills, MI, 1998; 1–98. ASCE 6-98/TMS 602-98.
[46] Okail H, Abdelrahman A, Abdelkhalik A, Metwaly M. Experimental and analytical investigation of the lateral load response of confined masonry walls. HBRC Journal. 2016;12:33-46. https://dx.doi.org/10.1016/j.hbrcj.2014.09.004