

RESEARCH ARTICLE

Damage mechanisms of masonry structures: an observation after 19 November Erzurum-Köprüköy Earthquake

İrfan Kocaman^{1*} 

¹ Erzurum Technical University, Department of Civil Engineering, Erzurum, Türkiye

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Abstract

On November 21, 2021, a 5.1 magnitude earthquake occurred with its epicenter in Erzurum-Köprüköy. In the eastern part of our country, most of the building stock in rural areas and certain parts of city center is made up of masonry structures. Most of the masonry structures consist of rubble stone walls with very low tensile strength. These load bearing elements, which are exposed to out-of-plane and in-plane displacements due to earthquakes, can be easily damaged due to their low tensile strength and poor manufacturing. In this study, the damage mechanisms of the masonry structures in the villages of Alaca, Kayabaşı, Marifet, and Sarıtaş have been reported. As a result of field studies, damages are quite prevalent due to inadequate connections between load-bearing walls and roof. Additionally, the weak connection between the leaves of load-bearing walls and lack of connection in the junctions of the walls have contributed to the damages. he observed damages can be generally classified as the quality of workmanship/construction, inadequate material characteristics, weak load bearing walls, lack of proper connections, failure of unconfined or high gable walls, heavy earth roof. Many of the damaged structures have not adhered to regulatory recommendations and are buildings that did not receive engineering services.

1. Introduction

Türkiye is recognized as a seismic country, characterized by the presence of diverse active faults, and has witnessed numerous earthquakes throughout its history. Such seismic events will probably persist in the future. Technological advancements and the availability of satellite data have facilitated the prediction of atmospheric-related disasters in advance. Nevertheless, it is essential to note that no existing technology currently allows for the accurate prediction of earthquakes ahead of time [1]. Consequently, the widely accepted strategy worldwide entails essential efforts to mitigate the impact of potential earthquakes in vulnerable regions.

According to the Turkey Earthquake Zones Map [2] published by the Ministry of Public Works and Settlement, General Directorate of Disaster Affairs, Erzurum falls within the seismic zone of I-III degrees. The updated version of this map, known as the Turkey Earthquake Hazard Map, has been revised by the Earthquake Department of the Disaster and Emergency Management Authority (AFAD). The current practical map provides recommended values for the maximum ground acceleration (PGA) that could be

* Corresponding author (irfan.kocaman@erzurum.edu.tr)

experienced in these areas instead of delineating specific earthquake zones as in the previous version. For Erzurum province, the Turkey Earthquake Hazard Map indicates a PGA range of 0.2 to 0.7g. These values indicate the region's relatively high seismic hazard, particularly along the North Anatolian Fault Zone and the Northeast Anatolian Fault Zone [3].

Erzurum is one of the provinces amidst the North Anatolian Fault Zone (NAFZ) and the Eastern Anatolian Fault Zone (EAFZ). Moreover, it resides within the compressional regime of Eastern Anatolia. The city and its environs are home to a significant number of active faults. Notably, the Erzurum Fault Zone, Horasan-Şenkaya Fault Zone, Palandöken, Karayazı, and Tortum faults play a crucial role in shaping the seismicity of the region [3]. Another seismic event near the EAFZ and NAFZ junction, triggering the investigation, is the Erzurum-Köprüköy earthquake on November 21, 2021. This earthquake originated within an area characterized by multiple local active fault zones.

Masonry structures, renowned for their assembly techniques, material properties, and energy dissipation capacities, manifest fragility when subjected to seismic forces [4,5]. Compounded by these uncertainties, rural constructions lacking adequate engineering intervention and constructed under adverse conditions expose themselves to heightened vulnerability against seismic loads. Researchers have undertaken various studies with the primary objective of elucidating the seismic behavior of masonry structures and unraveling potential mechanisms of damage [6-11]. The collective findings of these studies converge upon the observation that masonry structures tend to exhibit discernible collapse or damage mechanisms under seismic loads.

Field observations conducted in the aftermath of earthquakes hold immense significance in determining damage mechanisms exhibited by masonry structures. To this end, numerous studies have been conducted. Milani and Valente [12] undertook field investigations following the 2012 Emilia-Romagna earthquake in Italy, focusing on historic churches to discern the extent of damages incurred. By leveraging finite element models of the structures under scrutiny, they substantiated the alignment between observed post-earthquake damages and those obtained from finite element analyses. Likewise, Decanini et al. [13], Ahmedizadeh and Shakib [14], Bayraktar et al. [15], Sayın et al. [16], Atmaca et al. [17], and Mercimek [18] meticulously examined the damage states of masonry structures in the aftermath of various seismic events, providing comprehensive reports on their findings. Yön and Onat [19], Kocaman and Kazaz [20], and Çelebi et al. [21] conducted studies that examined the damage conditions of rural masonry structures in the vicinity of NAFZ and EAFZ, which are also the focus of this study, following moderate-sized earthquakes in 2015, 2020 and 2021. The reported damage mechanisms in the masonry building stock were documented. The reasons for damage in masonry structures were identified as the lack of adequate engineering services, low material quality, and poor workmanship. Fig. 1 provides examples of damage mechanisms in rural masonry structures following regional earthquakes. The observed primarily damages are separation of masonry walls at their junctions, out-of-plane wall collapse, in-plane diagonal crack lines, and poorly executed wall-roof connections.

This study offers a comprehensive analysis of the damages and corresponding evaluations derived from thorough examinations conducted in the affected residential areas after the earthquake that struck Erzurum-Köprüköy on November 21, 2021. By scrutinizing the incurred damages in various structures, a meticulous evaluation of the seismic response exhibited by the prevalent building stock in the region is presented.

2. Erzurum-Köprüköy Earthquake

2.1. Characteristic of ground motion

At 15:40 on November 19, 2021, according to local time in Turkey, Köprüköy district (Latitude: 39.815N, Longitude: 41.7991E), located in the province of Erzurum, was struck by an earthquake measuring Mw 5.1

in magnitude. The seismic event occurred at a depth of 5.18 km beneath the Earth's surface, 3.04 km away from Alaca village, which stands as the nearest settlement within the affected vicinity (Table 1). Tabulated in Table 2 are the provincial centers closest to the epicenter, along with their respective distances. Following the main shock, six aftershocks ranging from 1.4 to 2.2 magnitudes were recorded until 16:48 on November 19, 2021. AFAD (The Disaster and Emergency Management Authority) officially announced the duration of the earthquake as 12.39 seconds [22].



Separation of masonry walls [20]



Out-of-plan wall collapse [19]



Poor wall-roof connection [20]



In-plan diagonal cracks [19]

Fig. 1. Examples of damage mechanisms observed in masonry structures

Table 1. Nearest settlements to the epicenter [22]

City	County	Village	Distance (km)
Erzurum	Köprüköy	Alaca	3.04
Erzurum	Köprüköy	Kayabaşı	3.35
Erzurum	Köprüköy	Marifet	4.32
Erzurum	Köprüköy	Sarıtaş	4.60
Erzurum	Köprüköy	Topçu	4.88

Table 2. Nearest city centers to the epicenter [22]

City	Distance (km)
Erzurum	51.96
Ağrı	101.12
Muş	125.35
Kars	134.88
Bayburt	148.48

2.2. Earthquake hazard in the region

Over the course of history from 1900 to the present, the region has experienced a total of 359 earthquakes with magnitudes surpassing M_w 4.0, the largest among them measuring 6.9 in magnitude (Fig. 2a). Additionally, a record of 61 pre-1900 ground movements with documented acceleration data exists in the surrounding area of Erzurum province [22]. As delineated by the Turkey Earthquake Hazard Map, implemented in 2018, the seismic peril, including Erzurum city center and its districts, is illustrated in Fig. 2b.

2.3. Recorded acceleration

According to the assessments conducted by AFAD (The Disaster and Emergency Management Authority) following the earthquake, the most significant acceleration was recorded at the accelerometer station with code 2513, amounting to 22.182 gals in the East-West component. Adjacent to the epicentral region of the earthquake, there are a total of five accelerometer stations strategically placed. Fig. 3 graphically illustrates the acceleration values measured at these stations, while comprehensive details about each station can be found in Table 3 [22].

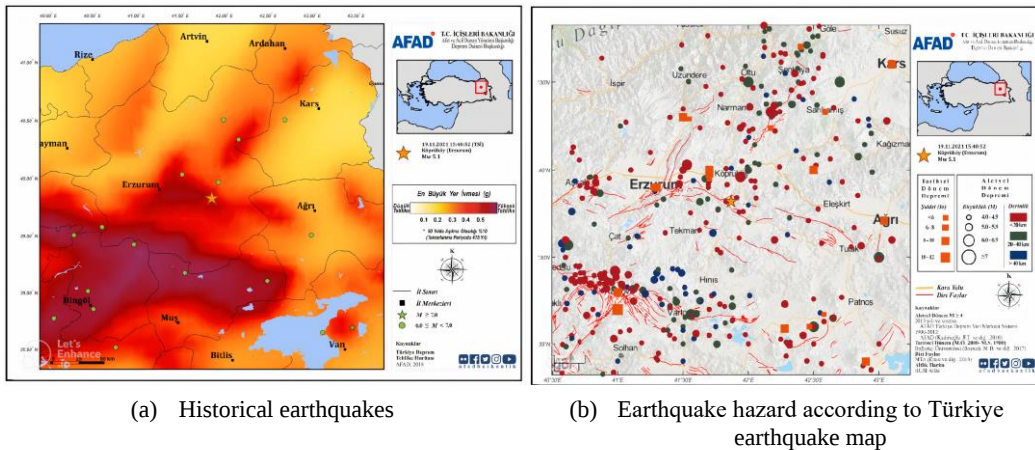


Fig. 2. Erzurum province and its surroundings earthquake hazard [22]

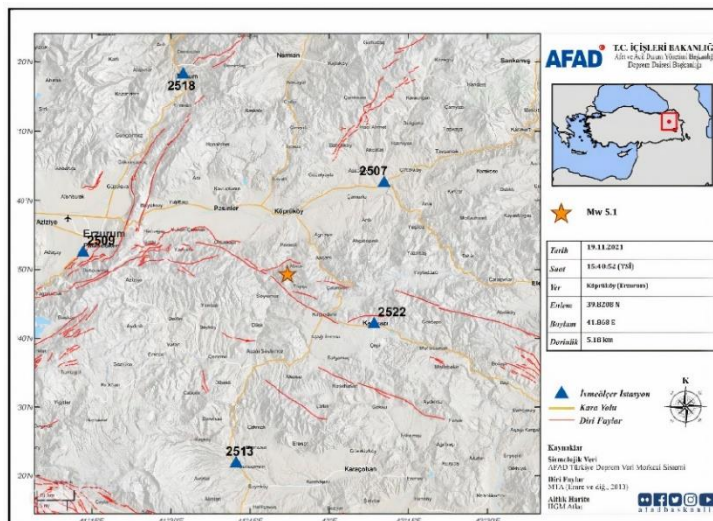


Fig. 3. Location of accelerometers around the earthquake focus [22]

Table 3. Accelerometer stations in the region and the measured acceleration values for the main shock earthquake [22]

Code	Station		Acceleration (gal)			Distance R_{epi} (km)
	Latitude	Longitude	N-S	E-W	Vertical	
2522	39.7005	42.1417	9.24	12.77	6.79	27.28
2507	40.0415	42.1736	12.17	10.53	5.40	34.75
2513	39.3624	41.7060	22.18	20.09	12.37	54.06
2509	39.8733	41.2227	2.35	2.27	1.71	55.61
2518	40.3021	41.5389	3.67	4.94	1.63	59.51

Fig. 4 presents the acceleration-time graphs obtained from two different stations during the main shock of the earthquake. Analysis of the acceleration records from station number 2513 reveals maximum acceleration values of 22.18 gals in the North-South (N-S) component, 20.09 gals in the East-West (E-W) component, and 12.37 gals in the vertical component. Moreover, in light of the measurements acquired at station number 2509, situated within the urban core of Erzurum, the most substantial acceleration values are observed to be 2.35 gals in the N-S component, 2.27 gals in the E-W component, and 1.71 gals in the vertical component.

3. Earthquake behavior of masonry buildings

It has been ascertained through on-site observations that masonry structures are susceptible to earthquakes. This section aims to shed light on the seismic behavior of such structures. Masonry constructions rely on walls constructed from materials such as stone, bricks, or adobe to withstand both horizontal and vertical loads. Typically found in the seismic region, these buildings predominantly consist of single-story structures with wooden or concrete roofing. It is important to note that the majority of the building stock in this area has been built using traditional construction techniques, often lacking the intervention of professional engineering services. Recent field observations conducted after several seismic events reveal the alarming vulnerability of rural masonry structures, even in the face of moderate-sized earthquakes, in the eastern and southeastern regions of Türkiye [11,19,20].

In masonry structures, seismic loads are transmitted to the foundation through the walls, which act as load-bearing elements capable of resisting axial forces, bending moments, and shear forces [23]. When masonry walls are constructed in accordance with engineering service, they can exhibit limited damage under seismic loads. However, if irregularities in wall placement, low material strength, or other factors come into play, the structure becomes vulnerable to earthquakes. The behavior of the roof elements in masonry structures is also crucial in seismic events. Properly connecting the roof to the walls creates a rigid diaphragm effect, contributing to the distribution of lateral forces among all load-bearing walls. Fig. 5 illustrates examples of damage mechanisms that may occur in masonry structures due to lateral loads.

In Fig. 5, damage mechanisms because of in-plane and out-of-plane movements of the walls can be observed. Especially, the crack pattern varies based on the position of door and window openings. The in-plane rocking motion in masonry walls causes damage at the toe of the wall. Additionally, due to the out-of-plane movement of masonry walls, damages are expected in the middle-upper part of the wall.

3.1. Recommendations for masonry structures in Turkish Building Earthquake Code 2018

The TBEC-18 [24] classification distinguishes masonry buildings into four distinct types: unreinforced masonry buildings, reinforced masonry buildings, confined masonry buildings, and reinforced panel masonry buildings. Among these categories, unreinforced masonry buildings encompass structures where load-

bearing walls are exclusively constructed using masonry units and mortar without incorporating any reinforcement elements. To ensure the seismic performance of masonry walls, TBEC-18 specifies specific geometric requirements, as presented in Table 4. Within the prescribed limits concerning wall thickness (t_{ef}) and wall height (h_{ef}), it is recommended that unreinforced masonry buildings adhere to a minimum t_{ef} value of 350 mm, while the h_{ef}/t_{ef} ratio should not exceed 9. These guidelines aim to enhance the structural integrity and seismic resilience of such constructions.

Fig. 6 provides information on the use of horizontal and vertical tie beams in masonry structures and their geometric limitations, as outlined by TBEC-18. Besides, the spacing between vertical tie beams should not exceed a maximum of 4 meters. Furthermore, the inclusion of reinforcement in all tie beams is strongly advised. The positioning of horizontal tie beams at the beginning and end of each floor and the consolidation of tie intersections with stirrups are emphasized. However, it is crucial to acknowledge that post-earthquake field investigations have revealed a noteworthy discrepancy: a substantial number of scrutinized masonry structures were devoid of tie beams, while in cases where tie beams were present, they were predominantly composed of unreinforced concrete or timber materials.

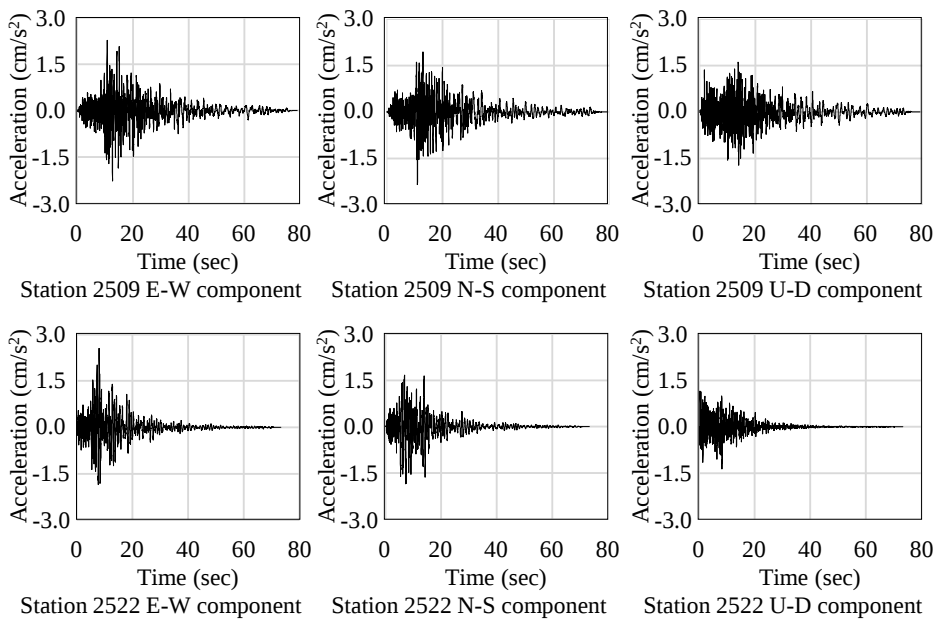


Fig. 4. Acceleration records of the components of the 19 November 2021 Köprüköy earthquake

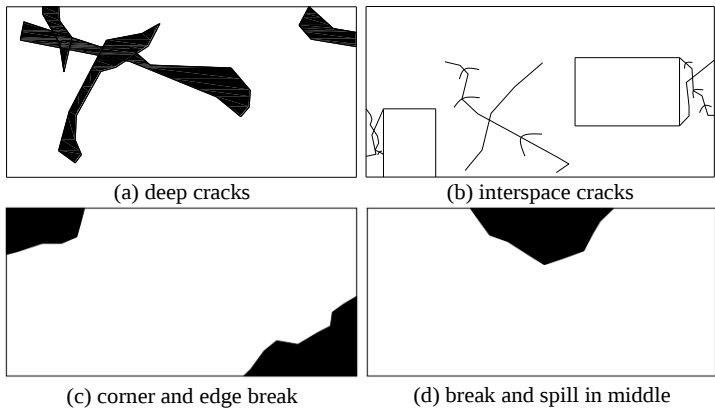


Fig. 5. Severely damaged wall samples

Table 4. Geometric requirements for masonry walls proposed in TBEC-18 [24]

Masonry type	Minimum t_{ef} (mm)	Maximum h_{ef}/t_{ef}
Unreinforced masonry with cut stone	350	9
Unreinforced masonry with other units	240	12
Confined masonry	240	15
Reinforced masonry	240	15
Reinforced panel system	200	15

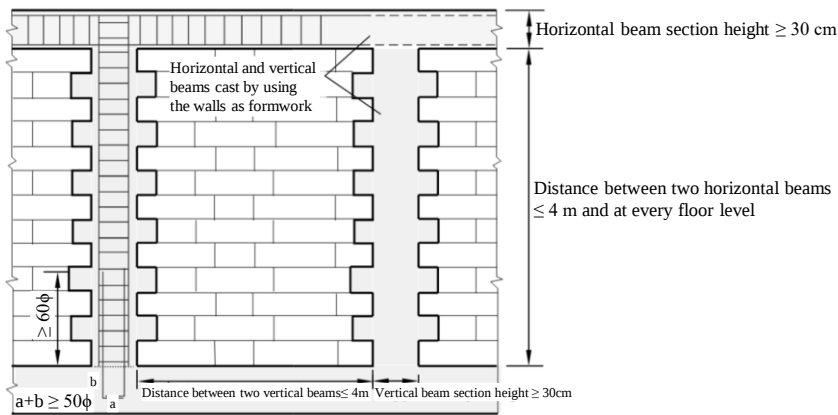
**Fig. 6.** Recommended girder sizes [24]

Fig.7 provides details on the horizontal and vertical joint configurations recommended for tie beams in masonry structures. It is observed that the intersection of horizontal and vertical tie beams should involve overlapping of stirrups, with a maximum stirrup thickness of 150 mm. Furthermore, the use of tie beams in walls is advised, particularly in detailing internal tie beam intersections. Ensuring the sound construction of junctions in masonry walls enhances their resistance to out-of-plane overturning.

The collapse of retaining walls in masonry structures stands as a widely observed damage mechanism. To address this issue, the TBEC-18 [24] guidelines propose a recommended solution in cases where the height of the retaining wall resting upon the uppermost tie beam or wall surpasses 80 cm. Specifically, the installation of vertical and inclined tie beams, as delineated in Fig. 8, is advised.

4. Observed structural damage

Despite their composition of a limited number of materials, Masonry structures pose challenges in determining their seismic behavior due to the lack of material homogeneity and the presence of anisotropic forms. This section evaluates the damages observed in masonry buildings following the Erzurum-Köprüköy earthquake (November 21, 2021) by considering field observations. All identified damaged masonry structures are situated in the rural village centers of Köprüköy. The rural constructions in the region predominantly consist of two-wall rubble masonry complemented by sections of cut stone. Furthermore, it is worth mentioning that although adobe structures have witnessed a gradual decline in recent years, their presence can still be discerned across the region. Damages have been observed in the masonry buildings of Topçu, Sarıtaş, and Marifet villages, characterized by their single-story nature and representation of the local architectural style.

The detachment of wall elements from the roof covering is a widely observed damage mechanism in masonry structures, as Kocaman and Kazaz [20] extensively discussed. Upon examining the distinctive

architectural landscape of the region, it becomes apparent that, generally, the roof covering rests upon wooden supports. However, inadequate execution of the junction between stone walls and wooden beams has damaged these areas. Fig.9 depicts a residential building constructed with unused rubble walls. The failure of the retaining wall is evident, accompanied by a diagonal crack originating from the upper corner of a window and extending towards the roof. Despite being unused, the structure has maintained its integrity, but the lack of proper integration between the masonry wall and roof systems has resulted in damage. This example illustrates the recommendation proposed by TBEC-18 [24] and detailed in Fig. 9, where tie beams are suggested for retaining walls.

In masonry structures, inadequate connection details between walls can lead to the formation of vertical and diagonal cracks and the separation of walls from each other [11]. Fig. 10 serves as an illustration of this phenomenon. The prevalent typology of rubble walls dominates the landscape of masonry structures within the earthquake-prone region. The junction damages manifest similarly across different structures in various villages. This situation can be attributed to the lack of engineering services during past construction practices and/or prevailing poor workmanship in the region.

Masonry structures exhibit diverse configurations, with variations encompassing both single-leaf and multi-leaf masonry walls. The proper execution of the junction between this leaf profoundly influences the structural response, particularly concerning out-of-plane resistance a subject examined by Binda et al. [25]. The typology of masonry structures in the region predominantly revolves around the utilization of two-leaf rubble walls. Fig.11 presents observed out-of-plane displacement mechanisms in two different structures. The two leaf in these walls do not work together but separate under the influence of out-of-plane loading. Factors such as the strength of the bonding material used in rubble walls, interlocking arrangement of stones, and proper execution of roof junctions contribute to the improved interaction between leaves.

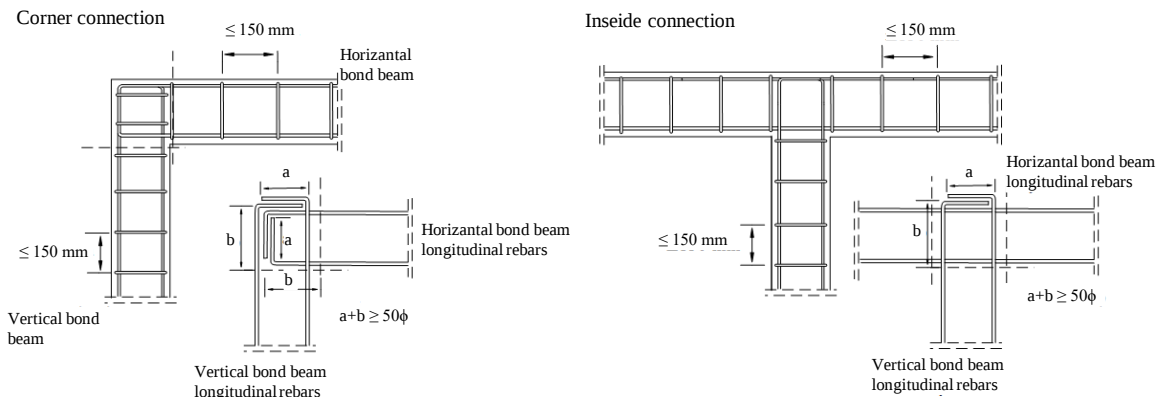


Fig. 7. Recommended girder joints details [24]

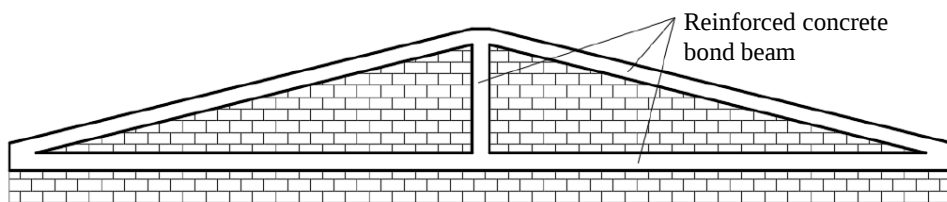


Fig. 8. Recommended girder application on gable walls [24]



Fig. 9. Example of damage caused by poor connection between roof and walls



Fig. 10. Segregation damages at junction areas

Within the earthquake-affected region, masonry structures typically feature earthen roof coverings, known as thatched roofs. However, in recent years, masonry structures have been replaced by reinforced concrete buildings due to improved economic conditions and urban transformation projects. Fig. 12 depicts examples of completely collapsed structures following the prevalent local architectural style.

The field observations conducted in the villages revealed the presence of single-story reinforced concrete buildings, as depicted in Fig. 13. Remarkably, these structures were found to be free from any discernible damage. It was observed that there is a noticeable shift in the building stock from masonry structures towards single-story reinforced concrete, indicating an abundance in the number of the latter.



Fig. 11. Disconnection damage in multi-leaf walls



Fig. 12. Collapsed masonry structures



Fig. 13. Undamaged reinforced concrete structures

5. Concluding remarks

The Erzurum-Köprüköy earthquake, which took place on November 21, 2021, is categorized as a moderate-sized seismic event. Its impact was felt in the villages of Alaca, Kayabaşı, Marifet, Sarıtaş, and Topçu, located within the Köprüköy district of Erzurum province. The observed level of damage to residential structures in light of the earthquake's magnitude indicates the inadequacy of the local building stock in terms of seismic resilience. Notably, the rural areas of the eastern and southeastern regions of Türkiye are predominantly characterized by traditional masonry constructions, lacking professional engineering services. These structures commonly employ earthen mortar instead of cement mortar, resulting in a significant limitation of tensile strength and displacement capacity within the region's building stock, both in-plane and out-of-plane.

During seismic events, masonry structures display inadequate performance when subjected to in-plane and out-of-plane forces. Consequently, the utilization of reinforced concrete horizontal and vertical ties is recommended in these buildings. However, it is worth noting that tie elements primarily consist of wood in the region. Additionally, there are numerous instances where wooden ties are insufficient or completely lacking. The absence of proper ties leads to widespread damage mechanisms, particularly crack formations originating from door and window openings in these structures. When considering at the observed damages in masonry structures, it is possible to classify them as the following: the quality of workmanship/construction, inadequate material characteristics, weak load-bearing walls, lack of proper connections, and failure of unconfined or high gable walls, heavy earth roof.

The rural areas in the region have experienced several earthquakes, impacting these masonry structures. In the aftermath of the recent Elazığ-Sivrice, Bingöl-Karlıova, and Erzurum-Köprüköy earthquakes, field investigations have revealed that reinforced concrete structures constructed using modern materials and techniques remained undamaged. As part of ongoing expropriation policies, there is an evident demand for more structurally suitable reinforced concrete buildings in earthquake-prone regions. This study underscores the crucial importance of rural buildings receiving professional engineering services and being designed in compliance with regulations as the primary means of mitigating damage and reducing casualties caused by earthquakes.

Conflict of interests

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Data availability statement

No new data were created or analyzed in this study.

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