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Büyük Depremler Sonrasında Yığma Yapılarda Görülen Tipik Hasar Mekanizmaları

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Öz

Bu çalışma, 1992 ile 2023 yılları arasında Türkiye'deki yığma binaların sismik performansını incelemekte ve büyük depremler sonrasında yapılan hasar değerlendirmelerine odaklanmaktadır. Belirlenen yaygın hasar mekanizmaları arasında, duvarların düzlem dışı göçmesi, dik duvarlar arasındaki bağlantıların yetersizliği, uygunsuz duvar açıklıkları ve hatıl eksikliği yer almaktadır. Kırsal yığma yapılarda sıklıkla kullanılan ağır sıkıştırılmış toprak damlar, atalet kuvvetlerini artırarak sismik zayıflığı önemli ölçüde artırmaktadır. Moloz taşlarının düzensiz kullanımı ve harcın yetersiz aderansı, yapısal bozulmanın erken başlamasına neden olmuştur. Çalışma, yığma binaların sismik dayanıklılığını artırmak için iyileştirilmiş inşaat uygulamaları, deprem yönetmeliklerine uyum ve etkili güçlendirme stratejilerinin gerekliliğini vurgulamaktadır. Geçmiş depremlerden alınan dersler, mühendisler ve politika yapıcılar tarafından, gelecekteki depreme dayanıklı yığma yapı inşaatları için daha sağlam yönergeler geliştirilmesini sağlayabilir.

Anahtar kelimeler: Yığma yapılar, Yapısal hasar, Deprem performansı, Donatısız yığma, Hasar mekanizmaları

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Typical Damage Patterns In Masonry Structures After Various Major Earthquakes

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Abstract

This study examines the seismic performance of masonry buildings in Turkey between 1992 and 2023, focusing on damage assessments after major earthquakes. Common failure mechanisms identified include out-of-plane wall collapse, inadequate connections between perpendicular walls, improper wall openings, and the absence of bond beams. Heavy compacted clay roofs, often used in rural masonry structures, contribute significantly to seismic vulnerability by increasing inertial forces. The irregular use of rubble stones and insufficient mortar adherence led to early structural degradation. The study emphasizes the need for improved construction practices, compliance with seismic codes, and effective retrofitting strategies to enhance the seismic resilience of masonry buildings. Lessons learned from past earthquakes can enable engineers and policymakers to develop more robust guidelines for future earthquake-resistant masonry construction.

Keywords: Masonry structures, Structural damage, Earthquake performance, Unreinforced masonry, Failure mechanisms

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1. Introduction

Masonry structures, among the most ancient human-made structures still operational, have evolved in building methodologies over time. A diverse range of stones, bricks, and blocks has been employed, with or without mortar, in the construction of these structures. The proposed construction methods include the use of two-cell blocks filled with grout, reinforced concrete, horizontal bond beams, and vertical tie beams. Integrating small sections of reinforced concrete both vertically and horizontally enhances the shear and flexural strengths of masonry walls, thereby improving ductility and energy dissipation [1,2]. Various masonry forms demonstrate insufficient tensile strength. Many empirical studies over the last 10 years have focused on investigating the design implications of brick and block masonry [3,4]. Masonry is categorized into unreinforced and reinforced types. A reinforced masonry construction demonstrates tensile strength similar to that of a reinforced concrete building. Consequently, traditional techniques for the design and analysis of reinforced concrete buildings are suitable in these instances, as the influence of nonlinear behaviour becomes less significant. Conversely, unreinforced materials typically exhibit nonlinear constitutive behaviour owing to their low tensile strength [5].

Masonry structures exhibit significant susceptibility to seismic loads and may experience substantial damage even during moderate earthquakes. The collapse of masonry structures results in significant economic losses and jeopardizes human lives. Consequently, implementing seismic retrofitting techniques is crucial for enhancing the safety and integrity of masonry structures [6,7]. Figure 1 illustrates the distribution of URM buildings with the total count of buildings (in millions) throughout European nations. The distribution of URM buildings throughout European countries exhibits considerable variation, with certain regions displaying a greater concentration of these structures than others. This variation can be attributed to differences in historical construction practices, economic development, and urban planning.

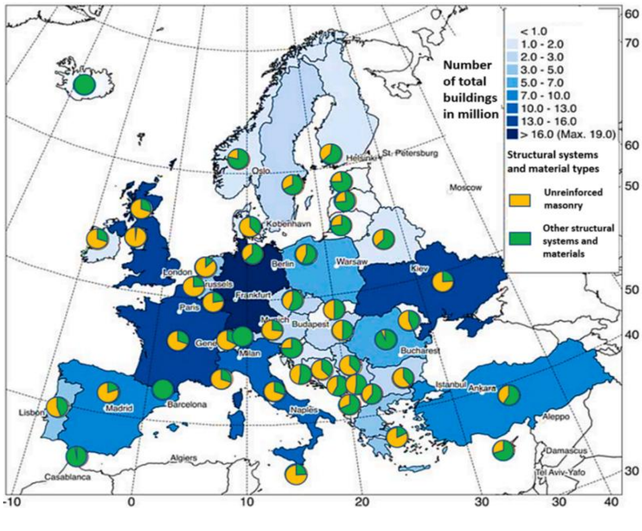


Figure 1. URM building distribution and total building count (in millions) in European countries [8].

The investigation of damage to structures after earthquakes contains useful information regarding earthquake-resistant building designs. In this respect, post-earthquake field investigations become more important. Disaster risk reduction strategy planning also requires post-earthquake investigation reports. Numerous field observations have been conducted in relation to recent earthquakes. Researchers have studied structural damage and obtained valuable information on the causes of masonry structure failures. Bayraktar et al. [9] analysed the dynamic response of masonry stone structures during the Dogubeyazit (Ağrı) earthquake on July 2, 2004. The patterns of cracking and failure in building stocks are elucidated comprehensively. Ural et al. [21] performed a field examination in Bala town following two significant earthquakes that impacted the region on December 20 and 27, 2007. Ingham and Griffith [11] examined the structural behaviour of unreinforced masonry structures during the 2010 Darfeld earthquake. Their findings indicated that many unreinforced masonry structures and heritage sites sustained significant damage during the 2010 Darfield earthquake. Common damage included collapsed chimneys and parapets, compromised gables and inadequately secured face-loaded walls, as well as in-plane damage to masonry frames following the 2010 Darfield earthquake in Christchurch, New Zealand. Halder et al. [12], examined the primary causes of structure collapse during six earthquakes that transpired in the Northeastern area of India over the past decade. They examined several structural types, including reinforced concrete buildings, masonry structures, and earthen constructions. Various studies have evaluated building-stock failures after the 2011 Simav earthquake (Mw=5.9) [13–15]. They evaluated the damage and failures commonly observed in masonry structures after the earthquake. Inel et al. [16], assessed the damage to reinforced concrete and masonry structures situated in Kütahya, Turkey, following the Simav earthquake on May 19, 2011. The authors evaluate that common damages in reinforced concrete buildings resulted from substandard concrete, incorrect reinforcement detailing, short columns, pounding effect, overhangs, improperly constructed gables, and outer infill wall components. For masonry structures, they stated that typical damage resulted from inadequate connections between orthogonal walls and inappropriate positioning and sizing of openings. Also, a variety of research have been conducted to evaluate the damage mechanisms of structures following the 2011 Van earthquakes [17–28].

Yön [29] examined the failure mechanism of masonry and adobe structures following the Sivrice earthquake on April 4, 2019 (Mw = 5.2). Ten settlements surrounding the epicentre were examined and conducted a detailed assessment of the damage patterns of the structures. Procedures for strengthening were provided at the conclusion of the study. Godínez-Domínguez et al. [30], examined the characteristic damage patterns found in brick homes and apartment complexes after the 2017 Tehuantepec earthquake (Mw = 8.2) among cities and towns in the Mexican states of Chiapas and Oaxaca, situated within a radius of about 250 km from the epicenter. The field assessment revealed that the most observed damage resulted from substandard design, insufficient building practices, poor quality of materials, and low wall density ratios.

Bayrak et al. [31] explored urban centers, neighbourhoods, and rural areas in Elazığ and Malatya following the 2020 Sivrice earthquake. It aims to identify deficiencies and reveal the sources of damages by examining the failure mechanisms of masonry and reinforced structures. Günaydın et al. [32] investigated the collapse processes of masonry structures following the 2020 Sivrice earthquake in rural regions. They determined that almost all damaged structures were not constructed in compliance with the current Turkish earthquake building rules. Mertol et al. [33], evaluated the progression of damage in masonry and mosque-type structures following the 2020 Sivrice Earthquake in Elazığ, Turkey. Common failures included vertical cracks and corner splitting, wedge-shaped corner failures, diagonal wall cracking, out-of-plane wall splitting, and separation of walls from flooring and roofing systems. There are many papers in the literature that evaluated the structural damage of different types of structures after the 2020 Sivrice earthquake (Mw=6.8) [34–43]. Finally, after the 2023 Kahramanmaraş earthquakes, many damage observation studies have been conducted on reinforced concrete, masonry, and steel structures [44–74]. These studies have highlighted the importance of proper reinforcement and material selection in earthquake-resistant design. By incorporating the lessons learned from past earthquakes, buildings can be better constructed to withstand future seismic activity and protect the lives of occupants. The aim of this study is to present the typical damage patterns observed in masonry buildings. For this purpose, studies on the assessment of structural damage of masonry structures after various earthquakes were reviewed.

2. Material and Methods

2.1. Masonry structures

Until the early twentieth century, the majority of structures were constructed from masonry. Due to their benefits, reinforced concrete and steel construction have become increasingly popular. Masonry is common in numerous countries due to its cost-effectiveness, excellent insulating properties, aesthetic, and accessibility. Masonry encompasses a wide range of materials, including bricks, stones, and blocks, together with different types of mortar such as lime and cement mortar, each having distinct mechanical properties. Well-detailed reinforced masonry structures can serve as a primary structural system and can be engineered to withstand seismic stresses. In several countries, the majority of brick and timber structures are built traditionally, with minimal or no involvement from certified engineers and architects. These structures are constructed informally, with little consideration for stability against horizontal seismic forces, and are therefore referred to as non-engineered buildings. Masonry structures are classified into unreinforced and reinforced categories. A reinforced masonry structure can exhibit tensile strength comparable to that of a reinforced concrete structure. However, unreinforced masonry structures are particularly vulnerable to seismic stresses and may sustain damaged during an earthquake.

2.1.1. Behavior of reinforced masonry (RM)

Reinforced masonry walls were engineered to withstand lateral out-of-plane forces and axial loads. These walls mostly extend vertically and convey lateral loads to the roof, floor, or foundation. They are frequently constructed as straightforward beams that extend across the structural supports. The vertical reinforcement must be bent with a 300mm, 90-degree angle. Vertical reinforcing bars integrated into the edges of the wall piers, along with their anchorage in the foundation and roof band, induce slender masonry piers to flex instead of rock (Figure. 2). The vertical bars on broader wall piers enhance their capacity to withstand horizontal seismic stresses and postpone cross-cracking. Moreover, the vertical bars provide protection against wall sliding and prevent collapse in the vulnerable direction.

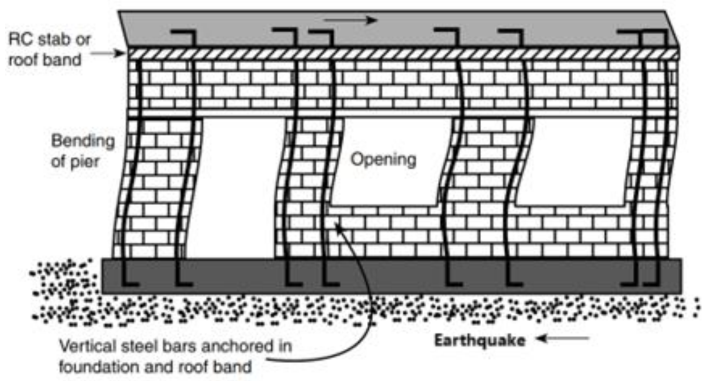


Figure 2. Behaviour of RM [75]

In addition to the vertical reinforcement, horizontal reinforcement in the form of bond beams is also crucial for strengthening masonry walls against lateral forces. These bond beams help to distribute the forces uniformly throughout the wall, reducing the risk of localized failure. By combining both vertical and horizontal reinforcement, masonry walls can be significantly improved in their ability to withstand seismic events and other external pressures. Properly reinforced masonry walls are essential for ensuring the safety and stability of a structure during earthquakes or other disasters.

2.1.2. Behaviour of unreinforced masonry (URM)

Unreinforced masonry structures are vulnerable to strong earthquakes. The lack of reinforcement in unreinforced masonry (URM) structures makes them particularly vulnerable to collapse during seismic events. Due to the brittle nature of unreinforced masonry walls, these structures have a higher risk of collapse under earthquake loads. Therefore, ensuring the strength and stability of masonry walls through proper reinforcement is crucial for withstanding seismic events and other external loads. The roof, wall, and foundation are the three fundamental parts of a masonry structure (Figure 3).

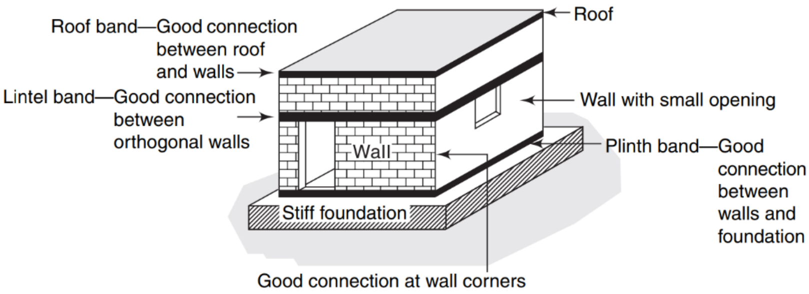


Figure 3. The components of URM [75]

The inertial forces propagate to the foundation via the roofs and walls. Inertial forces arise in both the x and y axes. A wall is exerted upon horizontally at the top in a direction orthogonal to its plane (weaker direction). It readily collapses. This phenomenon is referred to as an out-of-plane failure (Figure 4a). Nonetheless, a wall offers increased resistance when exerted along its length (primary direction). This is referred to as the in-plane resistance (Figure 4b).

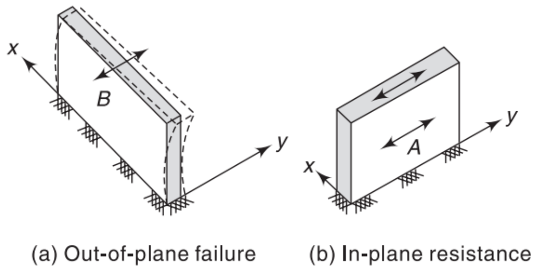


Figure 4. Failures of masonry walls [75]

2.2. Examination of masonry buildings

The seismic susceptibility of masonry structures is an important topic particularly after major earthquake. Comprehending the behaviour of these structures during seismic events is essential for evaluating their resilience and guiding retrofitting plans to reduce possible damage. Structural evaluation is a methodical procedure that entails examining structures about their present strength, performance, and future dependability. Masonry structures necessitate routine examinations to define their structural integrity and reduce the failure. Next section provides a comprehensive classification of damage levels in masonry structures (Section 2.2.1) for damage classification.

2.2.1. Categorization of damage degree in masonry structures

Damage is described as alterations in the geometric qualities or material properties of a structure, impacting its present and future performance. Diverse forms of deterioration have been noted in masonry structures due to various incidents. The insufficient tensile strength of these constructions has been recognized as the primary reason leading to deterioration. The seismic susceptibility of masonry constructions is affected by various variables, including [76, 77].

- Inadequate integrity among load-bearing elements.
- Inadequate wall connections resulting in the failure of box operation.
- Significant asymmetrical spaces diminish the capacity to withstand lateral forces.
- Cantilever walls' behavior in large, unsupported configurations.

The European Macroseismic Scale (EMS-98) provides a standardized method for assessing damage in masonry structures following earthquakes or other seismic events. It categorizes damage severity into five classes, each associated with certain types and levels of damage.

- Grade 1: Defined by minimal to minor damage, with no structural integrity compromised. Only modest non-structural concerns, including minor non-structural cracks in several walls or sporadic detachment of small plaster fragments, may be noted.
- Grade 2: Damage is more evident, characterized by cracks in multiple walls and the separation of bigger plaster fragments. Chimneys may undergo partial failure.
- Grade 3: Indicates significant to severe damage, characterized by large wall cracks, displaced roof tiles, and fractured chimneys at the roofline. Structural components, including partitions and gable walls, may experience failure.
- Grade 4: Signifies extensive damage, characterized by significant wall collapses and partial structural collapse of roofs and floors.
- Grade 5: Signifies total destruction, characterized by entire or nearly complete collapse, reflecting severe structural damage [78].

Table 1. The most common types of damage to masonry structures [79-83]

Disabilities	Most prevalent cause(s)	EMS-98 grade	May affect structural integrity.	Study
Cracking	Settlement, ground deformation, and inadequate preparation of mortar	1 to 4	✓	[79,80]
Moisture Penetration	Highly permeable material, humid atmosphere, freezing and thawing	1	✓	[81]
Bond Failure	Adhesion loss within materials	2 to 4	✓	[82]
Displacement	Insufficient lateral support anchors - Corrosion of steel components - Freeze-thaw cycles	2 to 4	✓	[83]

2.2.2 Common failure mechanisms in masonry structures

Damage patterns in masonry buildings can be classified into structural and non-structural failures.

- Structural Deformation:
  - Shear cracking: Diagonal fissures resulting from lateral seismic forces, prevalent in walls without sufficient protection.
  - Out-of-plane failure: Detachment and overturning of walls due to inadequate connections between orthogonal walls.
  - Corner failures: Detachment at building corners resulting from inadequate bond strength.
  - Collapse of roof and floor: Failure at the interface between wall and roof or wall and floor, especially in constructions devoid of horizontal diaphragms.
- Non-Structural Damage:
  - Plaster separation and cracking: Arises from severe deformation or moisture-induced deterioration.
  - Failures of chimneys and parapets: Frequent in old structures with inadequately fixed masonry components.
  - Distortions of doors and windows: Deformation of openings resulting from unstable load distribution.

Typical failure mechanisms are shown in Figure 5.

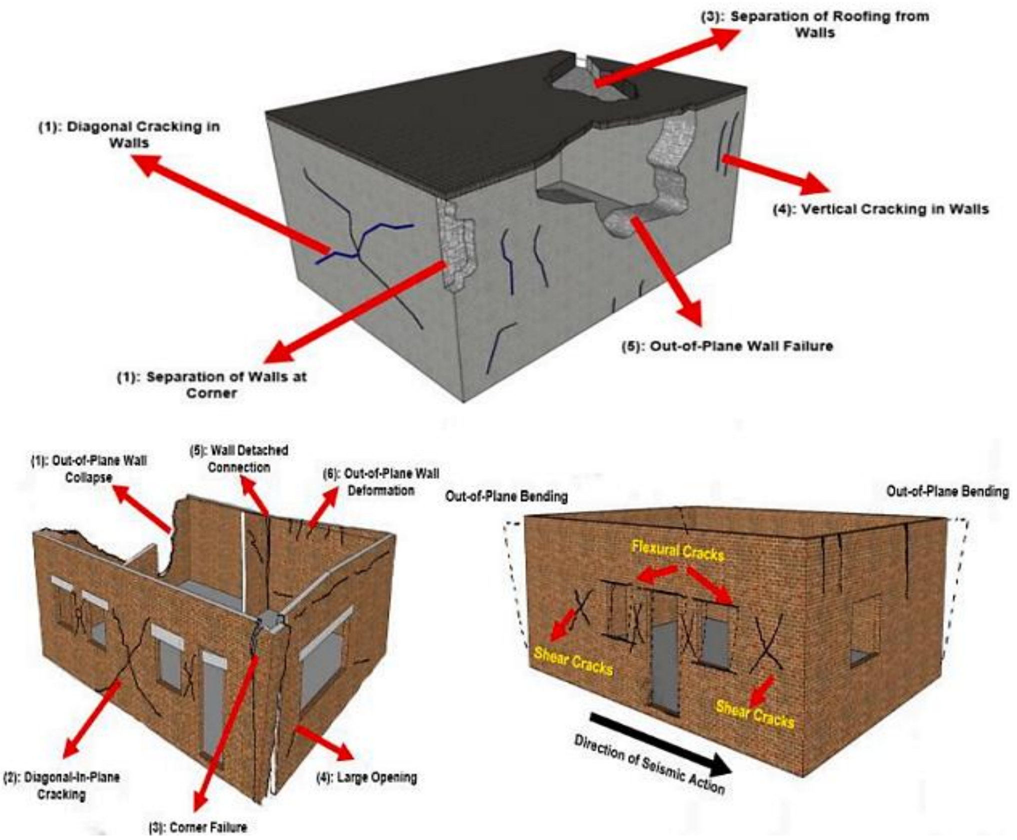


Figure 5. Typical causes of masonry structure failures [84]

2.3. Seismic code comparisons and evaluations

The evaluation of damage observations concerning seismic code restrictions offers essential insights into the effectiveness and limitations of current design provisions. A thorough assessment entails comparing recorded damage patterns with seismic design standards, identifying structural inadequacies in old masonry buildings, and analysing the potential for damage reduction through enhanced code compliance. This chapter offers a systematic comparison of national and international seismic codes, specifically the Turkish Earthquake Code (TBEC 2018) and Eurocode 8, emphasizing their various advantages and limitations in mitigating the seismic sensitivity of masonry structures. Turkish Earthquake Code (TBEC 2018) and Eurocode 8 regarding the seismic vulnerability of masonry structures entails assessing recorded damage patterns in relation to seismic design standards, determining inadequacies in older masonry structures, and examining how enhanced compliance with building regulations can reduce potential damage.

General design rules of masonry structures for TBEC 2018 and Eurocode 6&8 were given in Table 2. TBEC 2018, Eurocode 6, and Eurocode 8 define different classifications and design requirements for masonry structures. TBEC 2018 focuses on earthquake resistant building design and categorizes masonry as unreinforced, reinforced, confined, and panel systems. Eurocode 6 provides general structural design rules for masonry structures, while Eurocode 8 provides specific seismic design regulations for improved ductility and safety in earthquake-prone areas [85–87].

Table 2. Material and structural requirements for TBEC 2018 and Eurocode 6&8 [85–87]

Property	TBEC 2018	Eurocode 6 & 8
Material Requirements		
Minimum compressive strength of masonry units	5 MPa for units oriented perpendicular to bed joints. - 2 MPa parallel to the bed joints.	5 MPa perpendicular to bed joints - 2 MPa parallel to bed joints.
Mortar strength	5 MPa (M5) for unreinforced masonry; 10 MPa (M10) for reinforced masonry.	5 MPa for unreinforced masonry; 10 MPa for reinforced masonry.
Reinforcement steel	S420, B420C, or B500C steel classifications.	The same grades of reinforcement steel employed.
Seismic Design Considerations		
Categories of masonry for seismic design	Standards reinforced or constrained masonry in high-seismic regions.	Restricts the utilization of unreinforced masonry in high-seismic regions, promoting the usage of reinforced and confined masonry.
Minimum wall thickness	350 mm for stones and 240 mm for other masonry.	Same requirements as TBEC 2018.
Ductility and energy absorption	Employs ductility factors (R values) contingent upon the type of masonry.	Behaviour factors (q values) are as follows: - 1.5 for unreinforced masonry - 2.0–3.0 for confined masonry - 2.5–3.0 for reinforced masonry.
Wall connections and ties	Requires horizontal ties and vertical reinforcement.	Requires horizontal ties or ring beams every 4 m vertically.
Structural Analysis and Load Considerations		
Load combinations	Uses load factors for seismic and gravity loads.	Uses partial safety factors for materials and loads.
Shear strength of masonry	Based on material properties and vertical stress level.	Characteristic shear strength values defined, with additional checks for seismic loads.
Out-of-Plane wall stability	Requires verification against overturning and buckling.	Requires checks for lateral stability due to wind and seismic forces.
Detailing and Execution		
Wall openings	Requires reinforced vertical confining elements around large openings.	Openings >1.5m² must have vertical confinement elements.
Minimum reinforcement	Specifies minimum reinforcement ratios for reinforced and confined masonry.	Similar reinforcement requirements in Eurocode 6.
Connection of walls	Requires ties or reinforced concrete ring beams to ensure integrity.	Horizontal ties or ring beams are mandatory in seismic zones.

Both TBEC 2018 and Eurocode 8 require reinforced or confined masonry in high-seismic zones, while unreinforced masonry is limited to low-seismicity areas. Both codes have similar compressive strength and mortar class requirements, minimum reinforcement steel grades, and emphasize minimum wall thickness, shear wall design, and ring beam requirements for seismic design.

2.4. Data sources and selection criteria

Diverse data sources, such as field observations, structural damage evaluations, and prior study findings, have been employed to ascertain common failure causes in masonry structures. The criteria for selecting the studies included in this research are as follows:

- Earthquakes having a magnitude of $M_w \geq 5.0$ that substantially impacted masonry structures.
- Case studies that offer comprehensive damage assessments and visual documentation (e.g., photographs, structural diagrams).
- Investigate engineering evaluations and structural performance assessments.
- Research analyzing damage patterns in relation to seismic codes and standards. Examine the effectiveness of current building codes in earthquake-prone regions.

3. Typical Failures of Masonry Buildings

Adobe and unreinforced masonry structure are the predominant constructions. They are specifically constructed in rural areas. They may be categorized as informal structures due to their typical assembly by homeowners or construction workers employing substandard techniques without competent assistance. These buildings are often constructed using materials such as adobe and unreinforced masonry sourced from rural areas [17]. Vertical loads from the roof and floors are immediately transferred to the foundations by the load-bearing walls in these structures. Nevertheless, bearing walls are susceptible to in-plane, out-of-plane, and in-plane shear effects when exposed to horizontal seismic loads. Such structures are highly vulnerable to significant damage and complete or partial failure when exposed to lateral forces generated by seismic waves, due to the brittle nature of the load-bearing walls and their inadequate shear and flexural strengths [88–90]. The primary damages noted in the masonry and adobe structures were the utilization of substandard bricks, construction of walls with improper dimensions, absence of adequate reinforcing at wall junctions, irregularly positioned wall openings, and inadequately constructed roofs.

3.1. Poor workmanship/construction and inappropriate material

In rural areas, masonry buildings are the preferred construction method. On the other hand, they are generally constructed with poor workmanship and inappropriate materials. The smooth rubble stones used to construct these structures were gathered from the surrounding area and were often irregularly shaped. As a result of the lack of adequate friction between the masonry elements, the masonry buildings became seismically unstable. Various views of the current damage are shown in Table 3.

Table 3. Poor workmanship and inappropriate material

Ref.	Earthquake Name	Photos
[91]	2010 Kovancılar, Palu (Mw:6.0)	
[92]	2011 Van (Mw:7.2)	

Table 3. (Continue) Poor workmanship and inappropriate material

Ref.	Earthquake Name	Photos
[32]	2020 Sivrice (Mw:6.8)	 

The shear strength of masonry walls mostly depends on the adhesion provided by the mortar connecting individual masonry units. Previous Turkish Codes, TEC (1998–2007), specified that lime mortar reinforced with cement or cement mortar may be used as the binding in load-bearing walls. Moreover, according to TBEC 2018 and Eurocode 8, the recommended minimum strength values are 5 MPa for unreinforced and 10 MPa for reinforced masonry. Previous investigations indicate that a mud mortar binder was utilized in nearly all stone masonry structures (Table 4). These structures have low compressive strength due to the use of mud mortar, which is not as strong as cement mortar. Additionally, the lack of proper reinforcement in wall intersections weakened the overall stability of these buildings.

Table 4. Structural failures attributable to mud mortar binder

Ref.	Earthquake Name	Photos
[91]	2010 Kovancılar, Palu (Mw:6.0)	
[32]	2020 Sivrice (Mw:6.8)	 

3.2. Heavy compacted earthen roof system

Another important reason for the collapse of masonry structures is heavy compacted earthen roof system. This type of system is commonly constructed to address harsh environmental conditions. The aim of this application was to isolate the earthen roofs for the water leakage. The thickness of the roof increases over time, and this heavy roof significantly increases the mass of the structure, thereby increasing the seismic forces acting on the structure during an earthquake. Moreover, the wooden bond beams of the roof system were supported in one direction to the load bearing walls. These walls are subjected to vertical loads because of the heavy earthen roof. Other walls which are not supported with wooden logs behave as cantilever components are vulnerable to seismic loads. Out-of-plane failures may occur in these walls. To prevent this type of damage, roof systems should be constructed with lighter elements and wooden bond beams should be supported in two perpendicular directions. Examples of failures caused by heavy earthen roofs are presented in Table 5.

Table 5. Heavy earthen roof system damages

Ref.	Earthquake Name	Photos
[9]	2004 Doğubeyazıt (Mw:5.2)	 
[91]	2010 Kovancılar, Palu (Mw:6.0)	
[19]	2011 Van (Mw:7.2)	
[93]	2011 Simav (Mw:5.9)	

Table 5. (Continue) Heavy earthen roof system damages

Ref.	Earthquake Name	Photos
[29]	2019 Elazığ (Mw:5.2)	

3.3. Irregular shapes of masonry

In rural areas, structural walls consist of inner and outer layers, which are generally formed with stones of different sizes. However, these walls constructed without an interlocking component. For this reason, cavities are observed between the inner and outer walls. These cavities further reduce the shear strength of the walls, thereby increasing their vulnerability during an earthquake. Although the proportion of cavities was not determined or measured, previous field observations have shown that when the cavity ratio is greater than 10–15%, remarkable reductions can occur in the shear capacity of the walls [21]. Typical earthquake-resistant wall cross sections are shown in Figure 6, and examples of this type of damage are given in Table 6.

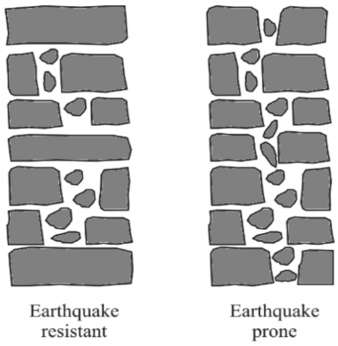
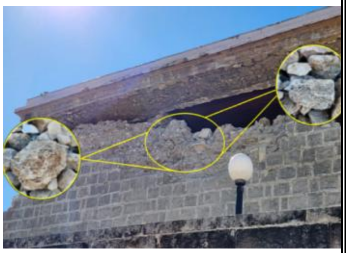


Figure 6. Typical earthquake resistant wall cross section [93].

Table 6. Damages of irregular shapes of masonry

Ref	Earthquake Name	Photos	Ref	Earthquake Name	Photos
[92]	2011Van (Mw:7.2)		[94]	2011 Simav (Mw:5.9)	

Table 6. (Continue) Damages of irregular shapes of masonry

Ref	Earthquake Name	Photos	Ref	Earthquake Name	Photos
[95]	2023 Kahramanmaraş (Mw:7.6 and 7.7)		[96]	2020 Sivrice (Mw:6.8)	

3.4. Splitting and failures of corners

Insufficient connections between perpendicular walls and the absence of vertical and horizontal bond beams can lead to severe corner damages, especially under seismic loading. TBEC 2018, Eurocode 6, and Eurocode 8 emphasize the importance of effective wall connections, mechanical interlocking, and bond beams to mitigate these vulnerabilities. TBEC 2018 mandates the application of horizontal and vertical bond beams to reinforce intersections and prevent corner failures, while Eurocode 6 emphasizes the importance of mechanical interlocking between masonry walls to maintain structural integrity. Eurocode 8 provides additional regulations for enhancing ductility and energy dissipation capacity of masonry structures, requiring the use of horizontal tie beams or ring beams at every floor level to strengthen wall intersections and resist lateral forces. It categorizes unreinforced masonry as low-ductility construction and discourages its use in high-seismicity regions unless confined or reinforced. The absence of these essential design elements results in a high vulnerability to lateral loads, leading to severe damage in the form of corner separations, instability, and structural collapse. Compliance with these regulatory provisions is essential to provide the structural integrity and seismic resilience of masonry buildings. Some corner damages are given in Table 7.

Table 7. Corner damages

Ref	Earthquake Name	Photos	Ref	Earthquake Name	Photos
[74]	2023 Kahramanmaraş (Mw:7.6 and 7.7)		[32]	2020 Sivrice (Mw:6.8)	
[74]	2023 Kahramanmaraş (Mw:7.6 and 7.7)		[19]	2011 Van (Mw:7.2)	

Table 7. (Continue) Corner damages

Ref	Earthquake Name	Photos	Ref	Earthquake Name	Photos
[93]	2011 Simav (Mw:5.9)		[10]	2007 Bala (Mw:5.4)	 

3.5. Improper location of openings (windows and doors)

The incorrect placement of openings constitutes a primary form of damage. The Turkish Building Earthquake Code 2018 (TBEC 2018) imposes some restrictions concerning the spacing between openings, the dimensions of windows and doors, and the distance from openings to the wall corners. In masonry structures, walls are the sole components that resist to interior and exterior loads. Figure 7 shows the required standards for openings in load-bearing walls, as given in TBEC 2018. Most masonry constructions were damaged due to the inadequate distance between the opening and the building corner. This category of damage is given in Table 8.

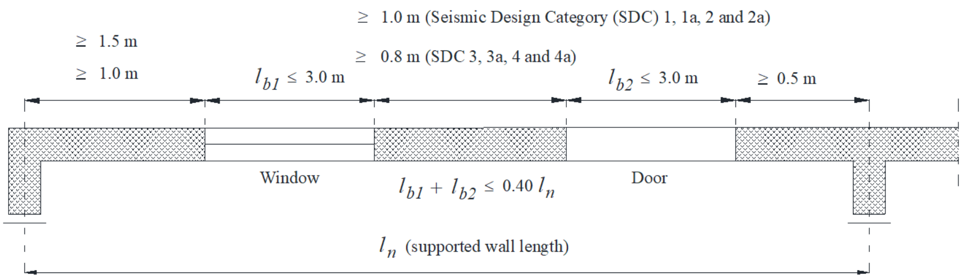


Figure 7. Required standards for door and window openings (TBEC 2018)

Table 8. Improper location of openings

Ref	Earthquake Name	Photos	Ref	Earthquake Name	Photos
[32]	2020 Sivrice (Mw:6.8)		[32]	2020 Sivrice (Mw:6.8)	

Table 8. (Continue) Improper location of openings

Ref	Earthquake Name	Photos	Ref	Earthquake Name	Photos
[97]	2003 Bingöl (Mw:6.4)		[20]	2011 Van (Mw:7.2)	
[34]	2020 Sivrice (Mw:6.8)		[94]	2011 Simav (Mw:5.9)	

3.6. Damages of gable walls

The majority of the gable walls were constructed without bond beams. They are vulnerable to earthquakes. This damage is not the primary structural damage falling parts of wall may be cause loss of lives and properties.

The primary causes of this type of damage include extensive unsupported wall length, insufficient wall-to-wall connections, and inadequate wall-to-floor contact. The Turkish Seismic Code 2018 mandates the vertical and inclined reinforced concrete bond beams to prevent damage at gable walls that exceed 2 meters in height. Schematic view of the gable wall utilizing reinforced concrete bond beam is given in Figure 8. Table 9 is shown the failures of the gable walls.

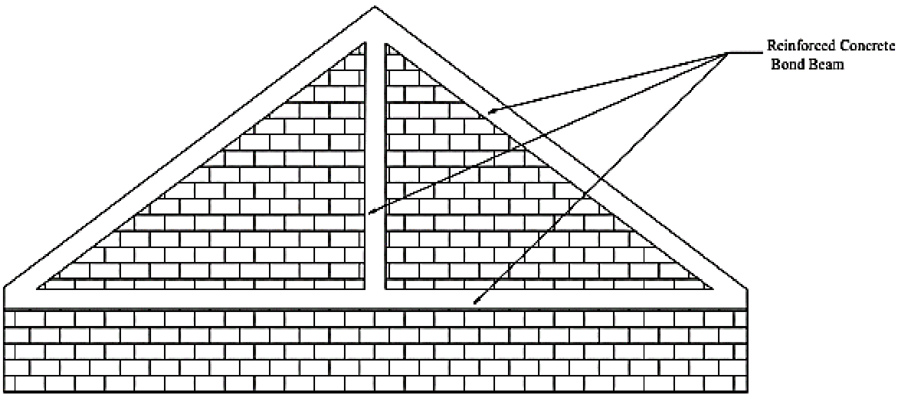


Figure 8. Using proper reinforced concrete bond beams on the gable wall (TBEC 2018)

Table 9. Gable wall damages

Ref	**Earthquake Name**	**Photos**	**Ref**	**Earthquake Name**	**Photos**
[21]	2011 Van (Mw:7.2)		[32]	2020 Sivrice (Mw: 6.8)	
[19]	2011 Van (Mw:7.2)		[34]	2020 Sivrice (Mw: 6.8)	
[98]	2023 Kahramanmaras (Mw: 7.6 and 7.7)		[99]	2023 Kahramanmaras (Mw: 7.6 and 7.7)	

3.7. Out of plane failure

Out-of-plane failure is common damage type which observed in masonry structures. This type of damage is generally seen by poor wall-to-wall connection, long unsupported wall length, not using vertical and horizontal beams, lack of rigid diaphragm, and poor adherence between wall units. To prevent these damages in masonry structures, the TBEC stipulates that the maximum unsupported wall length must not exceed 5.5 m in Seismic Design Categories (SDC) 1, 1a, 2, and 2a, and 7.5 m in SDC 3, 3a, 4, and 4a in plan view (Figure 9.a). Each 4-meter-long vertical bond beam should be added into the plan. Also, the unsupported wall length must not exceed 16 m (Figure 9.b) (TBEC 2018).

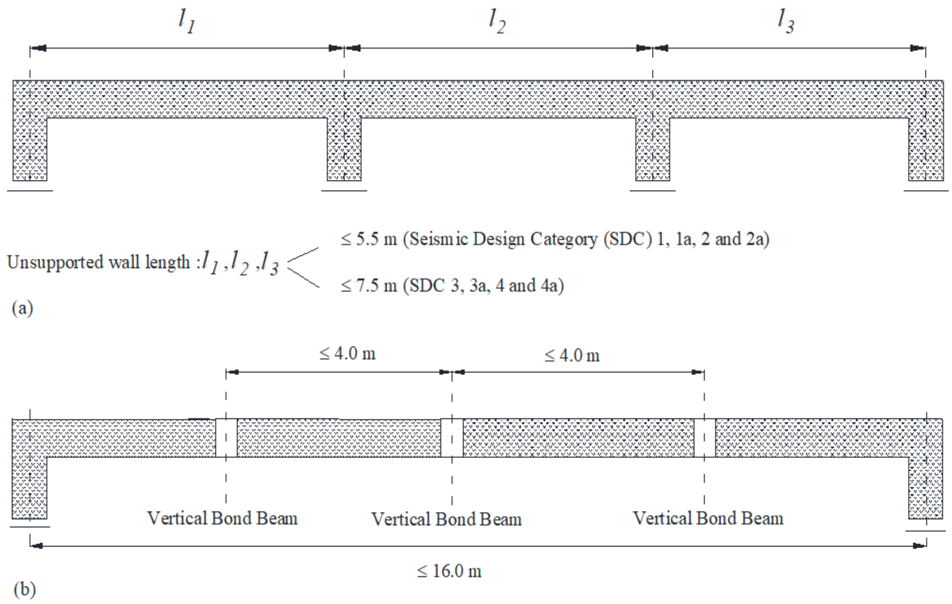


Figure 9. The maximum length of an unsupported wall and the distance between vertical bond beams

Fig. 10 shows a diagram of various out-of-plane mechanisms, and examples of out-of-plane damage are given in Table 10.

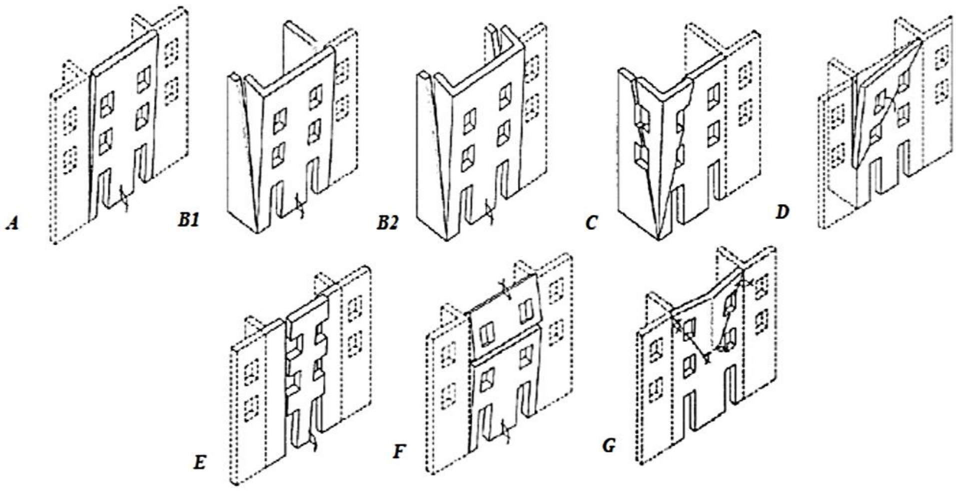


Figure 10. Schematic view of different out of plane mechanisms [100]

Table 10. Out of plane damages

Ref	Earthquake Name	Photos	Ref	Earthquake Name	Photos
[34]	2020 Sivrice (Mw: 6.8)		[101]	2023 Kahraman-maras (Mw: 7.6 and 7.7)	

Table 10. (Continue) Out of plane damages

Ref	Earthquake Name	Photos	Ref	Earthquake Name	Photos
[96]	2020 Sivrice (Mw: 6.8)		[73]	2023 Kahramanmaras (Mw: 7.6 and 7.7)	
[94]	2011 Simav (Mw:5.9)		[29]	2019 Elâzığ (Mw: 5.2)	

3.8. Low strength masonry units

According to previous earthquake codes (TEC-1998 and TEC-2007), natural stones, solid bricks, vertically perforated bricks, solid concrete briquettes, and adobe bricks could be used in load-bearing walls. However, TBEC (2018) prohibited the use of hollow concrete briquettes, infill bricks, adobe bricks, and rubble stones as load-bearing wall elements. The TBEC 2018 and Eurocode 6&8 stipulate that the minimum compressive strength of masonry units must be 5 MPa. When the compressive force exceed the compressive strength of the masonry units, minor vertical cracks may develop in the masonry components. Table 11 presents various examples of this damage.

Table 11. Low strength masonry units

Ref	Earthquake Name	Photos	Ref	Earthquake Name	Photos
[102]	2003 Denizli (Mw: 5.6)		[32]	2020 Sivrice (Mw: 6.8)	

4. Conclusion

An examination of the building stock in Turkey reveals that reinforced concrete and masonry structural systems comprise the predominant portion of the building stock in both urban and rural areas. In this study, the failure of unreinforced masonry buildings has been evaluated after the significant earthquakes, in Turkey. The results demonstrate that unreinforced masonry structures constructed by local residents have inadequate seismic performance and sustain significant damage, even during small earthquakes.

The behavior of various structural types, damage patterns in structural elements, collapse processes, and soil responses can be readily studied following earthquakes. Consequently, information obtained from previous earthquakes is essential for mitigating casualties and property damage in future seismic events. The main reasons for the failures of the masonry structures were:

- The rubble stones utilized in the construction of these masonry walls were provided from the vicinity and generally irregular in shape. For this reason, sufficient adhesion between the stones and mortar was not provided.
- In rural regions, heavy clay roofs were built for insulation against snow and rain. These roofs significantly increased the mass of the structure, hence the increased roof mass caused more seismic load during an earthquake.
- In masonry structures, the junctions between orthogonal walls are essential for decreasing both global and localized damage. Insufficient connections between bearing walls and the absence of vertical and horizontal bond beams may result in corner failures.
- The incorrect placement of openings constitutes a primary category of damage. Various building codes exhibit certain limits to openings. The majority of masonry structures did not comply with the limits for openings.
- The majority of the gable walls were constructed without bond beams. Consequently, they are vulnerable to earthquakes.
- Out-of-plane failure is a common form of damage observed in masonry structures. Load bearing walls may experience total or partial collapse due to this problem.

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6. Author Contributions

All authors contributed to the study conception, investigation, writing and design.

7. Ethics Committee Approval and Conflict of Interest

“There is no conflict of interest with any person/institution in the prepared article. Additionally, ethics committee approval is not required for this study.” The authors have no relevant financial or non-financial interests to disclose

8. Ethical Statement Regarding the Use of Artificial Intelligence

During the writing process of this study, the artificial intelligence tool "ChatGPT," developed by "OpenAI," was used only for limited purposes of linguistic editing and translation. The scientific content, analyses, and results belong entirely to the authors.

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