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Research Paper

Typological and Seismic Code Assessment of Stone Masonry Walls: The Case of Safranbolu Houses

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ABSTRACT

Safranbolu has preserved this texture throughout history by developing spatially and stylistically with the contributions of different civilizations along with its unique qualities and determining features. Safranbolu houses, shaped by traditional values, are important heritage elements that bridge the past and the future. Although these buildings have been exposed to various natural disasters over the years, they have managed to largely preserve their architectural integrity. However, it is estimated that these historical structures in Safranbolu, located approximately 65 km from the North Anatolian Fault, are under threat of earthquakes. Especially the stone masonry walls, which are widely used in Safranbolu houses, are known to be more sensitive to seismic effects and carry a great risk in terms of structural integrity. This study aims to examine in detail the compliance of opening ratios in stone masonry walls with seismic design provisions to protect Safranbolu houses and ensure their safe transfer to future generations. Within the scope of the study, the typology and grouping of the ground floor masonry stonewalls of 100 Safranbolu houses built in the 18th and 19th centuries according to the rules specified in the 2007 "Regulation on Buildings to be Built in Earthquake Zones" were analyzed and structural compliance analysis was performed. The structural compliance analysis revealed that 15% of the masonry walls conformed to modern design standards, while 85% did not, and that structural improvements are needed to reduce seismic vulnerability.

1 Introduction

Turkey is in a geography with a high density of active fault lines, and a large part of the population lives in regions with high earthquake risk. Structural damage and loss of lives because of earthquakes reveal the importance of earthquake-resistant structures. Therefore, making buildings resistant to seismic effects has become a great necessity. Cultural and natural heritage is among the most valuable elements created by humanity and its protection is considered a universal responsibility.

With the widespread use of concrete, there has been a renewed interest in the reuse of these old techniques, often in the context of the repair of heritage buildings, even though traditional methods have been abandoned [1]. However, given that many people around the world still live in stone structures built with traditional techniques [2] it is important that the average

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lifetime of modern reinforced concrete buildings be considered to be approximately 50 years and that historical buildings built with masonry construction techniques have survived for centuries. This situation makes it important to examine the structural qualities of historical buildings and their performance against earthquakes in more detail.

Safranbolu is a district of Karabük province located in the Western Black Sea Region. Safranbolu, which is located in a region where various civilizations ruled and whose roots date back to ancient times, attracts attention with its cultural heritage and touristic values. It is estimated that there were mass settlements in the region after 3000 BC and the oldest civilization was the Gasgas [3]. The spatial layout of Safranbolu has been formed depending on the requirements of the cultural, social and economic functions and service areas within the city. Safranbolu's urban spatial structure consists of three sections: Çukur (Çarşı), Kıranköy (Misakımilli), Bağlar [4]. Safranbolu has gained a unique identity by preserving its original architectural texture shaped by the influence of different civilizations throughout history. Safranbolu houses, which reflect the traditional texture, are among the heritage structures that have survived from the past to the present as an important part of cultural continuity and should be transferred to future generations. Safranbolu, which is an exemplary city of history and culture, has also made a name for itself in the international arena with its inclusion in the World Heritage List by UNESCO in 1994.

These buildings, which have largely preserved their architectural integrity despite being exposed to various natural disasters over time, are under high seismic risk due to the district's close proximity to the North Anatolian Fault. It is known that the stone masonry walls commonly used in Safranbolu houses are more sensitive to earthquakes and carry significant risks in terms of structural integrity. In terms of the sustainability of historical and cultural identities, preserving Safranbolu houses, conducting structural analyses and increasing their seismic resistance is a great necessity.

With concerns such as various interventions to traditional houses and harmonizing them with the new construction by using modern materials, the structures are moving away from their original texture [5]. While this situation leads to negative physical and structural effects in structures that are not under protection, it can also cause damage to the structure if the standards are not followed in earthquake zones. The response and resistance of traditional houses to physical impacts can be measured over time, or their vulnerability to these impacts may emerge spontaneously. However, it is important to evaluate the structural behavior of the traditional housing stock, which ensures the continuity of the architectural heritage against a disaster such as an earthquake that may occur at any time and where life continues to be maintained every day, within the framework of today's design rules and to make the necessary determinations.

Çarhoğlu and Korkmaz [6] evaluated the earthquake behavior of brick masonry structures in rural Turkey by modeling a sample structure using finite element analysis and conducting dynamic tests. Durak [7] examined the general characteristics and structural deficiencies of masonry buildings in the Aegean Region, assessing their compliance with DBYBHY regulations and predicting potential damage and losses. Arslan [8] proposed an interdisciplinary approach to enhance the seismic performance of traditional houses by investigating retrofitting methods for damaged historical buildings. The seismic safety of traditional masonry buildings is a critical research topic not only in Turkey but also in other regions with similar seismic risk, such as the Mediterranean and North Africa. For instance, studies in the historic urban fabric of Oran, Algeria [9], have shown that the existing masonry building stock does not comply with modern seismic codes and exhibits high vulnerability. While Durak's study shares some objectives with ours by focusing on masonry structures in the Aegean Region, our research provides a unique contribution by analyzing the structural properties of Safranbolu houses, evaluating their compliance with earthquake regulations, and developing a novel analytical approach. In this context, our study connects to both national and international literature while highlighting the specific case of Safranbolu houses.

This study presents general information about Safranbolu, with a focus on Safranbolu houses, and examines the earthquake behavior of masonry structures, traditional dwellings, and the region's seismicity. It identifies the typologies of traditional houses in Safranbolu and evaluates their compliance with earthquake regulations. The primary goal of this study is to analyze the opening ratios of masonry walls in accordance with the "Earthquake-Resistant Design Rules for Masonry Buildings" specified in the Regulation on Buildings to Be Constructed in Seismic Zones [10], in order to support the preservation of traditional Safranbolu houses and ensure their safe transfer to future generations. Considering the proximity of Safranbolu to the active fault line, a structural compliance analysis was conducted for the ground floor bearing wall cavities. The study also aims to contribute to recommendations for protecting and retrofitting Safranbolu houses to enhance their earthquake safety.

1.1 Safranbolu Houses and Construction Technique

The traditional houses of Safranbolu are in the Çarşı, Kıranköy and Bağlar regions. These 18th and 19th century houses reflect the cultural, technological and economic changes and lifestyles of their time. Of the approximately 2000 houses with historical features scattered in the above-mentioned regions, 800 are preserved. The land layout of the houses emphasizes the relationship between nature, people and home, as well as the phenomenon of respect, and at the same time, these structures show great harmony with nature [11]. The houses are designed to be suitable for a large family structure and are arranged in such a way that they do not block anyone's view or sunlight. The facades of the houses are usually projecting, and the roofs have wide eaves. The masonry stonewalls forming the ground floor combine with the garden walls to complete the street integrity (Figure 1).



Fig. 1 – General view of Safranbolu and traditional Safranbolu houses.

The houses are mostly two or three stories. Ground floors typically serve as stables, living quarters, or storage, while upper floors are living spaces. The foundations, ground floor, and garden walls are built with stone masonry, whereas upper floors use a timber frame system with stone or adobe infill. Ground floor walls, approximately 80 cm thick, are made of stone and mud mortar, with larger, finely chiseled stones at the corner's meter [12]. Horizontal lintels are placed at 1-meter intervals on stonewalls and garden walls, which use stone, mudbrick, or both as materials [13]. Foundations, excavated to solid ground (100-150 cm deep), consist of large stones at the base with mud mortar poured over them. The upper floors feature a wooden carcass system with 10-12 cm thick timbers, with upright spacing of 45-70 cm. In later constructions, spacing was reduced to 20-40 cm, main uprights were thickened, and capitals were retained [14]. Safranbolu houses have hipped roofs built using the wooden sitting roof technique [13].

1.2 Seismicity of Safranbolu

Karabük city center, where Safranbolu district is located, is approximately 55 km from the North Anatolian Fault Line. This fault line starts from the Gerede district of Bolu, passes through İsmetpaşa in Eskipazar district within the borders of Karabük and then extends to Tosya district of Kastamonu. In addition, Karabük province is also under the influence of a second secondary fault line due to its geographical location. This fault line extending along the Amasra-Abdipaşa-Safranbolu-Karabük-Eskipazar line increases the seismic risk of the region. Within this seismic context, the "significant duration" of ground motions becomes a critical factor for structural safety, as long-duration shaking is known to increase damage in light-frame wood structures. Moreover, such prolonged seismic events lead to higher hysteretic energy accumulation in inelastic components, which must be considered in the seismic evaluation of stone masonry walls [15, 16].

Safranbolu, which has been under the influence of the North Anatolian Fault Line from past to present, has experienced various earthquakes in and around Safranbolu and these tremors have also had an impact on the city (Figure 2). The earthquakes in the immediate vicinity did not cause major losses of life and property in Safranbolu but caused different levels of impact and structural damage. However, especially the 7.2 magnitude earthquake in Bolu-Gerede in 1944 [17] and the 7.4 magnitude earthquakes in Kocaeli-Gölcük and 7.2 magnitude earthquakes in Düzce-Kaynaşlı in 1999 were felt effectively in Safranbolu and caused material damages [15].

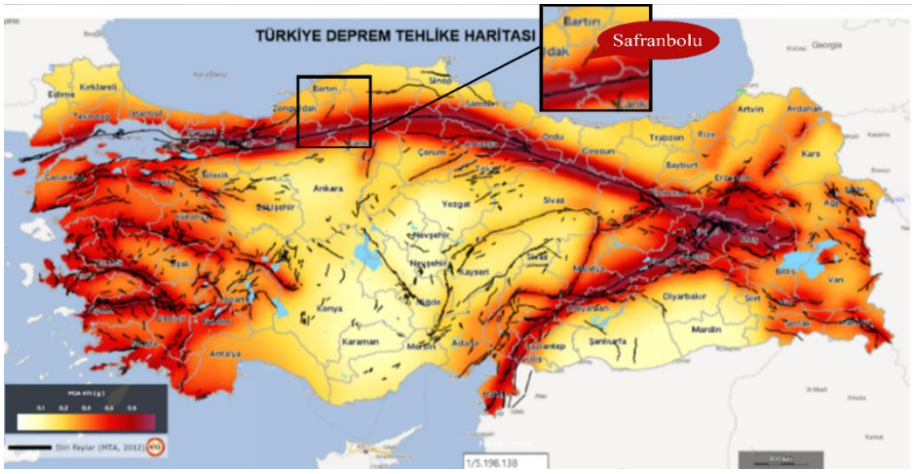


Fig. 2 – Location of Safranbolu according to the North Anatolian Fault in the seismic hazard map (edited from [18]).

1.3 Seismic performance of masonry walls

Due to their rigidity and brittleness, historical masonry structures are highly vulnerable to strong earthquakes [19]. While these materials have moderate to high compressive strength, their tensile strength is weak. When tensile forces exceed compressive forces, cracks form in load-bearing walls, deepening if shear resistance is exceeded, leading to potential collapse [20].

Horizontal loads exceeding shear strength causes cross-shear cracks, particularly on lower floors. On the upper floors, similar loads cause horizontal cracks. In walls with openings, sections between openings experience shear forces, causing damage like diagonal cracks in solid walls. Insufficient wall thickness may also cause buckling cracks under vertical compressive forces [21] (Figure 3, 4).

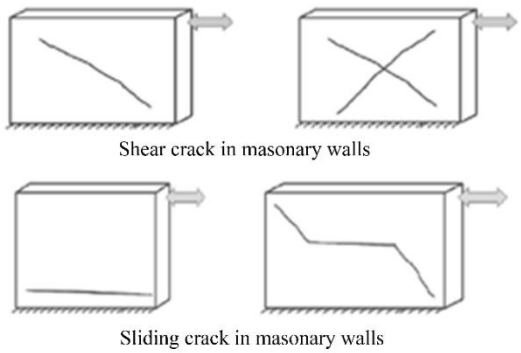


Fig. 3 – Shear and sliding cracks occurring in masonry walls (edited from [20]).

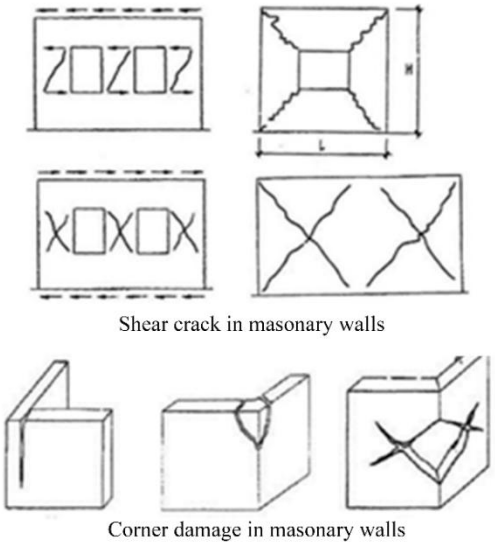


Fig. 4 – Shear cracks and corner damage patterns in masonry walls (edited from [8]).

2 Method

This study analyzes Safranbolu houses based on the 2007 Earthquake Regulation and Earthquake Resistant Design Rules for Masonry Buildings. The research began with data collection, followed by the determination of analysis criteria and the creation of evaluation forms. Sources included academic literature, AFPS [22] guidelines, which are considered a key European reference for assessing the seismic vulnerability of existing buildings, and architectural survey projects of selected

houses.* Typology analysis criteria were established for 100 houses, considering location, number of stories, plan and cantilever type, construction technique, and compliance with seismic design rules. The study focused on the Çarşı, Kıranköy, and Bağlar regions, using quantitative and qualitative methods, including a literature review.

The analysis employed a typological and geometric approach, evaluating the compliance of Safranbolu houses with the geometric rules specified in the regulation based on the architectural plans and on-site surveys of 100 houses. This methodology parallels the simplified seismic vulnerability assessment method proposed by Zacek [23], which was specifically developed for architects. Zacek emphasizes the importance of visually diagnosing the architectural configuration and structural irregularities of buildings before conducting complex engineering calculations. Similarly, our study focused on architecturally guided diagnostics, assessing how the plan layout, wall openings, and structural configuration conform to both national seismic regulations and general principles outlined in international guidelines.

This study specifically examines the load-bearing wall opening ratios of ground floors in Safranbolu houses with stone masonry walls, based on the "Earthquake Resistant Design Rules for Masonry Buildings" in Chapter 5 of the "Regulation on Buildings to be Constructed in Seismic Zones" [10]. Evaluation criteria and forms were developed to assess the structural properties of these houses and their compliance with the regulation's design principles. The study incorporated five design rules from the regulation, assigning reference codes (D1, D2, D3, D4, D5) to each. The analysis considered the length and ratio values for stone masonry walls specified in the regulation, with a focus on Safranbolu's location in seismic zone 1 (Figure 5). Quantitative data collection methods were employed to evaluate compliance with the regulation articles.

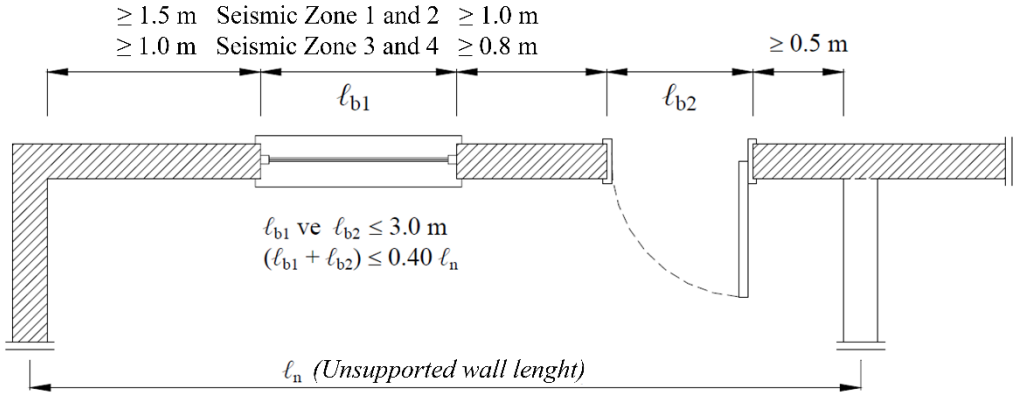


Fig. 5 – Load-bearing wall opening rules (edited from [10]).

The following articles from the Regulation on Buildings to be Constructed in Earthquake Zones are directly relevant to our study:

"Article 5.4.6.1. The length of the part of the solid wall to be left between the window and door closest to the building corner and the building corner in the plan shall not be less than 1.50 m in first- and second-degree earthquake zones and 1.0 m in third- and fourth-degree earthquake zones.

Article 5.4.6.2. The length in planning of the solid wall parts between window and door openings other than building corners shall not be less than 1.0 m in first- and second-degree earthquake zones and 0.80 m in third- and fourth-degree earthquake zones.

Article 5.4.6.4. Except for the corners of the building, the length in plan of the solid wall part to be left between the window or door opening closest to the intersection of the walls cutting each other perpendicularly and the intersection of the walls shall not be less than 0.50 m in all earthquake zones.

Article 5.4.6.5. The length of each door and window opening in plan shall not be greater than 3.0 m.

Article 5.4.6.6 - The sum of the in-plan lengths of door and window openings along the unsupported length of any wall as defined in 5.4.5 shall not exceed 40% of the unsupported wall length."

* Figure references in which floor plans are evaluated: [24-31], architect Ahmet Rauf Bağ's personal archive, architect Elif Hacıalioğlu's personal archive, architect Fatih Dökmeci's personal archive.

The correspondence between Article 5.4.6.1–5.4.6.6 and reference codes D1–D5 was established. Typology analysis and structural compatibility assessment of these articles with Safranbolu's stone masonry walls focused on Article 5.4.6.6, enabling a detailed evaluation of load-bearing wall opening ratios. Facade opening ratios were analyzed individually, and the results were presented accordingly. The reference number defining the Earthquake Resistant Design Rules for Masonry Buildings is provided in Table 1.

Table 1 - Seismic Design Rules for Masonry Buildings and Definitions of reference numbers within the scope of the study.

Ref. No.	Article No.
D1	Article 5.4.6.1
D2	Article 5.4.6.2
D3	Article 5.4.6.4
D4	Article 5.4.6.5
D5	Article 5.4.6.6

3 Findings

The structural compatibility analysis of Safranbolu houses is conducted based on the Seismic Design Rules for Masonry Buildings from Section 5 of the 2007 Regulation on Buildings to be Constructed in Seismic Zones. The corresponding reference numbers for each house are presented in Table 2.

In the evaluation phase after data collection, the typology classification of Safranbolu houses were made, with buildings assigned reference codes from "E1" to "E100." Table 3 presents the characteristics of the 100 houses, including region, number of storeys, plan type, cantilever type, and reference codes for irregularities (D1, D2, D3, D4, D5) indicating non-compliance with Earthquake Resistant Design Rules for Masonry Buildings. Missing data is left blank, and rows are marked with "-" when no relevant features are found.

Table 2. The specific names and analysis reference numbers of the Safranbolu houses analyzed within the scope of the study.

Ref. No.	Load-Bearing Wall Openings Ratio	Ref. No.	Load-Bearing Wall Openings Ratio	Ref. No.	Load-Bearing Wall Openings Ratio	Ref. No.	Load-Bearing Wall Openings Ratio
E1	Hacıhüseyinler Mansion)	E26	Erbil Ünal House	E51	İrfan Çalıova House	E76	Hacı Mustafa Bey St. No: 45
E2	Arap Hacılar House	E27	Hacı Talip Yılmaz House	E52	Jet Faik House	E77	Hacı Mustafa Bey St. No: 14
E3	Asmazlar Mansion	E28	Saliha Kılıç House	E53	Yedekçioğlu Mansion	E78	Aslanlar St. N: 56
E4	Ömer Semiz House	E29	Emin Ulusoy House (Gümüş Mansion)	E54	Kileciler Mansion	E79	Kurtuluş Cd. No: 21
E5	Katipler House	E30	Emine Sezer House	E55	Kabakçılar Vineyard House	E80	Antep St. No: 3
E6	Saraçoğlu House	E31	Mustafa Kavsa House	E56	Köşeliler House	E81	Harmanlar St. No: 16
E7	Curtlar Şehir House	E32	Blue Mansion	E57	Ayser Çolak House	E82	Harmanlar St. No: 35
E8	Hotel Çeşmeli Mansion	E33	Üzeyirler (Ahmet Can) House	E58	Ak Mansion	E83	No: 13
E9	Karaüzümler House	E34	Paçacıoğlu Mansion	E59	Erbaklar House	E84	Hamamcıoğlu St. No: 2
E10	Kadıoğlu Şehzade Mansions I	E35	Gökçüoğlu Mansion	E60	Mustafa Candan House	E85	Parcel 8, Block 383
E11	Aygıroğlu Mehmet Özgün House	E36	Asmazlar Vineyard House	E61	Selahattin Avcı House	E86	Unidentified
E12	Ali Atmaca House	E37	Emir Hocazade Ahmet Beyler House	E62	Sami Kavsaoğlu House	E87	Unidentified
E13	F. Ertuğrul House	E38	Raşitler Vineyard House	E63	Ayşe Kunt Ataoğlu House	E88	Unidentified

Ref. No.	Load-Bearing Wall Openings Ratio	Ref. No.	Load-Bearing Wall Openings Ratio	Ref. No.	Load-Bearing Wall Openings Ratio	Ref. No.	Load-Bearing Wall Openings Ratio
E14	Halo Mehmetler Mansion	E39	Hacı Bakizade Şükrü Efendiler House	E64	Ayşe Türkan Akçasu House	E89	Unidentified
E15	Sepetoğlu Hüseyin Bozkurt House	E40	Hacı Salih Ağa House	E65	Uzunkır St. No: 1	E90	Mehmet Sıtkı Nergis House
E16	Sayınlar Selvili I Mansion	E41	Raufbeyler Mansion	E66	Akçasu St. No: 15	E91	Meral Uğur House
E17	Yedekçioğlu Mansion	E42	Hacı Salih Paşa Bağ House	E67	Akçasu St. No: 3	E92	Belkız Sarıhan House
E18	Necati Sağlam House	E43	Taşatarlar Şehir House	E68	Natiptarla St. No: 10	E93	Recep Yücel House
E19	Hacıkadılar House	E44	Saraçlar Şehir House	E69	Cincihanı St. No: 10	E94	Osman Bayrı House
E20	Asmazlar Mansion	E45	Bassam Elhage House	E70	Kemeraltı St. No: 11	E95	M. Kemal Sarıtunç House
E21	Yörüklü Nuri (Mustafa Akıncı - Hüseyin Alagöz) House	E46	Kazancılar Et Entegre Gıda Sanayi House	E71	Aşağıtabakhane St. No: 7	E96	Abdullah Arslan House
E22	Şerafettin Uğur House	E47	Faik Çelik House	E72	Tabakhane St. No: 45	E97	Betül Erener House
E23	Selmin Kangal House	E48	Hakkı Cihan House	E73	Akseki St. No: 9	E98	Emin Yavuz House
E24	Osman Akın House	E49	Kemal Deniz House	E74	Cambaz St. No: 35	E99	Ali Demirezen House
E25	Leyla Hanım Mansion	E50	Peri Mansion	E75	Değirmen St. No: 2	E100	Safran Mansion

Table 3. Classification of Safranbolu houses.

Ref. No.	Region	No of Fl.	Plan Type – Sofa Type	Cantilever Type	Opening Rules Reference No.				
					D1	D2	D3	D4	D5
E1	Çarşı	3	Interior	Central	X	X	X		X
E2	Çarşı	3	Mezzanine Floor-Free-standing, Upper Floor-Interior	Central	X			X	X
E3	Çarşı	3	Interior	_	X	X			
E4	Çarşı	3	Interior	Central - Corner		X		X	X
E5	Çarşı	3	Corner	Central	X				X
E6	Çarşı	3	Interior	Central - Corner			X	X	X
E7	Çarşı	3	Corner	Central	X	X	X		X
E8	Çarşı	3	Corner	Central		X	X		X
E9	Çarşı	3	Interior	Central			X		
E10	Çarşı	3	Interior	Miter - Central		X	X		
E11	Çarşı	3	Corner	Central			X		
E12	Çarşı	3	Mezzanine Floor-Interior, Upper Floor-Corner	Miter			X		X
E13	Çarşı	3	Exterior	Miter			X		X
E14	Çarşı	3	Mezzanine Floor-Free-standing, Upper Floor-Interior	Central	X				
E15	Çarşı	2	Interior	Miter - Central	_	_	_	_	_
E16	Çarşı	3	Mezzanine Floor-Interior, Upper Floor-Corner	Miter - Central	X	X	X		
E17	Çarşı	3	Interior	Corner - Central	X			X	X
E18	Çarşı	3	Corner	Miter - Central			X		X
E19	Çarşı	3	Corner	Miter			X		
E20	Çarşı	3	Mezzanine Floor-Exterior, Upper Floor-Corner	Central	_	_	_	_	_

Ref. No.	Region	No of Fl.	Plan Type – Sofa Type	Cantilever Type	Opening Rules Reference No.				
					D1	D2	D3	D4	D5
E21	Çarşı	3	Mezzanine Floor-Interior, Upper Floor-Corner	Central	X		X		X
E22	Çarşı	3	Free-standing	Miter	X		X		
E23	Çarşı	3	Corner	Central	X	X	X	X	X
E24	Çarşı	3	Interior	Corner	X			X	X
E25	Çarşı	3	Interior	Central	_	_	_	_	_
E26	Çarşı	3	Mezzanine Floor-Corner, Upper Floor-Interior	_	X				
E27	Çarşı	3	Mezzanine Floor-Corner, Upper Floor-Exterior	Central			X		
E28	Çarşı	3	Interior	Central		X	X		
E29	Çarşı	3	Mezzanine Floor-Corner, Upper Floor-Interior	Central		X	X		
E30	Çarşı	3	Mezzanine Floor-Interior, Upper Floor-Corner	Miter	_	_	_	_	_
E31	Çarşı	2	Interior	Central - Corner	X	X		X	X
E32	Kıranköy	3	Mezzanine Floor-Corner, Upper Floor-Interior	Central	X		X		X
E33	Kıranköy	3	Interior	Miter - Central	X		X		X
E34	Bağlar	3	Interior	Central	X				
E35	Bağlar	3	Interior	Corner	X		X	X	X
E36	Bağlar	3	Interior	Central - Corner	X		X	X	X
E37	Bağlar	3	Mezzanine Floor-Exterior, Upper Floor-Interior	Central - Corner	_	_	_	_	_
E38	Bağlar	3	Interior	Central	X	X	X		
E39	Bağlar	3	Exterior	Central - Corner - Miter	X	X	X	K	
E40	Bağlar	2	Exterior	Central	X		X	X	
E41	Bağlar	3	Mezzanine Floor Free-standing - Upper Floor-Interior	Central - Corner	X	X	X	X	
E42	Unidentified	3	Mezzanine Floor-Corner, Upper Floor-Interior	Central - Corner	X	X		X	X
E43	Çarşı	3	Corner	Miter	X			X	X
E44	Unidentified	3	Interior	Central - Corner			X	X	X
E45	Çarşı	3	Corner	Central	X	X	X		G
E46	Çarşı	3	1st Floor-Corner, Upper Floor-Free-standing	Central	X	X	X	X	X
E47	Çarşı	3	Interior	_ Unidentified		X			
E48	Çarşı	2	Interior	Miter - Central	X	X	X	X	X
E49	Çarşı	4	Interior	Miter - Central	X	X	X		X
E50	Çarşı	3	Interior	Miter - Central	X	X	X	X	X
E51	Çarşı	2	Exterior	Central	X				X
E52	Çarşı	3	Mezzanine Floor-Corner, Upper Floor-Free-standing	Miter - Central	X		X		X
E53	Çarşı	2	Interior	Corner	X		X		
E54	Çarşı	3	Interior	Central - Corner	X				X
E55	Bağlar	3	Mezzanine Floor-Exterior, Upper Floor-Corner	Miter - Central				X	X

Ref. No.	Region	No of Fl.	Plan Type – Sofa Type	Cantilever Type	Opening Rules Reference No.				
					D1	D2	D3	D4	D5
E56	Çarşı	3	Free-standing	Central	_	_	_	_	_
E57	Bağlar	2	Exterior	Miter - Central	X			X	X
E58	Bağlar	2	Corner	Central - Corner	X				
E59	Bağlar	2	Corner	Central	X			X	X
E60	Bağlar	2	Corner	Central					X
E61	Bağlar	2	Corner	Central	_	_	_	_	_
E62	Bağlar	2	Interior	Central	_	_	_	_	_
E63	Bağlar	2	Interior	Central	_	_	_	_	_
E64	Bağlar	3	Mezzanine Floor-Exterior, Upper Floor-Interior	Central	_	_	_	_	_
E65	Çarşı	3	Corner	Central	X				X
E66	Çarşı	2	Free-standing	Central	X				
E67	Çarşı	3	Mezzanine Floor-Free-standing, Upper Floor-Corner	Miter - Central	X			X	X
E68	Çarşı	3	Mezzanine Floor-Free-standing, Upper Floor-Interior	Central	_	_	_	_	_
E69	Çarşı	3	Mezzanine Floor Free-standing, Upper Floor-Interior	Central - Corner			X	X	X
E70	Çarşı	3	Mezzanine Floor-Free-standing, Upper Floor-Interior	Central	X	X	X	X	X
E71	Çarşı	3	Corner	Central	X	X	X	X	
E72	Çarşı	2	Corner	Central	_	_	_	_	_
E73	Çarşı	3	Mezzanine Floor-Free-standing, Upper Floor-Corner	Central			X		
E74	Kıranköy	3	Free-standing	Central	X				
E75	Çarşı	3	Mezzanine Floor-Exterior, Upper Floor-Interior	Central	X		X	X	
E76	Bağlar	3	Interior	Central		X	X		
E77	Bağlar	2	Corner	Central			X		
E78	Bağlar	3	Interior	_ undetermined			X		
E79	Bağlar	3	Corner	Central			X		X
E80	Bağlar	3	Free-standing	Miter - Central	X		X	X	X
E81	Bağlar	3	Mezzanine Floor-Corner, Upper Floor-Free-standing	Central	X			X	X
E82	Bağlar	3	Interior	Central			X		X
E83	Bağlar	3	Mezzanine Floor-Interior, Upper Floor-Free-standing	Corner	X			X	X
E84	Bağlar	2	Corner	Miter - Corner	X			X	
E85	Çarşı	2	Corner	Miter - Central	X		X		X
E86	Çarşı	3	Mezzanine Floor-Exterior, Upper Floor-Interior	Central	X			X	X
E87	Çarşı	3	Mezzanine Floor-Interior, Upper Floor-Free-standing	Central	X		X	X	X
E88	Çarşı	3	Free-standing	Central	X		X	X	X
E89	Çarşı	2	Interior	Central	X	X		X	X
E90	Bağlar	3	Free-standing	Central	X		X		

Ref. No.	Region	No of Fl.	Plan Type – Sofa Type	Cantilever Type	Opening Rules Reference No.				
					D1	D2	D3	D4	D5
E91	Çarşı	2	Free-standing	Miter - Central	X	X	X		X
E92	Çarşı	2	Corner	Miter - Central	X		X		
E93	Bağlar	3	Exterior	Central			X	X	
E94	Unidentified	3	Interior	Central	_	_	_	_	_
E95	Bağlar	3	Mezzanine Floor-Exterior Upper Floor-Interior	Central	X				
E96	Çarşı	4	Mezzanine Floor- Corner, 1st Floor Free-standing, 2nd Floor Interior	Central	_	_	_	_	_
E97	Bağlar	3	Interior Sofa	Central	X	X			
E98	Çarşı	3	1st Floor-Corner, Upper Floor-Interior	Central		X			X
E99	Bağlar	3	1st Floor- Interior, 2nd Floor Free-standing	Central	X			X	X
E100	Bağlar	3	Free-standing	_ undetermined	_	_	_	_	_

The typological characteristics of the 100 dwellings analyzed in this study show that 62 are in Çarşı, 32 in Bağlar, and 3 in Kıranköy, while the region of 3 remains undetermined. In terms of storey count, 77 houses have three storeys, 21 have two storeys, and 2 have four storeys. Regarding plan types, 56 houses feature interior sofas, 39 have corner sofas, 14 include exterior sofas, and 24 freestanding sofas. Cantilever types consist of center cantilevers in 84 houses, corner cantilevers in 18, and miter cantilevers in 24 (Figure 6). Due to the change in the type of sofa between floors, several plan types were observed in one example and the number of plan types was evaluated accordingly. Likewise, since there are examples with different cantilever types in a dwelling, the proportions of cantilever types are also considered accordingly.

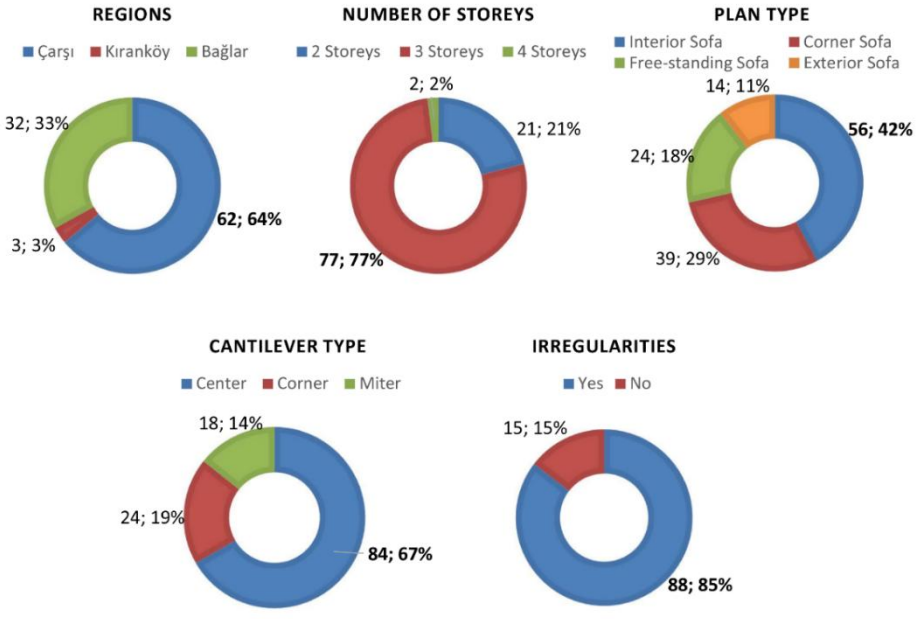


Fig. 6 – Classification of Safranbolu houses.

The construction systems of the 100 Safranbolu houses (E1–E100) were analyzed, revealing that all ground floors are stone masonry, while upper floor infill materials vary. Most commonly, mudbrick was used, but exceptions exist. Mudbrick infill is found in E1, E9, E45, E46, E54, E86, and E87, while E13 and E47 have brick infill, and E48 combines both materials. E58 features wood infill, whereas E49, E50, E51, E85, E88, and E89 use stone infill. The upper floor materials of E2, E4, E5, E6, E7, E8, E10, E12, E14, E44, E66, E67, E69, E77, E83, and E84 remain undetermined. Additionally, in E20, E45,

E46, E48, E51, E58, E90, E92, E95, E97, and E100, some ground-floor facades incorporate a wooden frame system. No material information was found for other houses. In the other houses, no information on the materials could be found.

Analysis of irregularities (D1–D5) shows that most houses exhibit at least one. Among the 100 houses, 85 have at least one irregularity (D1, D2, D3, D4, or D5), while 15 comply with design rules. Irregularities were found in 58 houses for D1, 27 for D2, 51 for D3, 35 for D4, and 51 for D5. The most common are D5 (29%), followed by D1 (24%), D3 (21%), D4 (15%), and D2 (11%) (Figure 7).

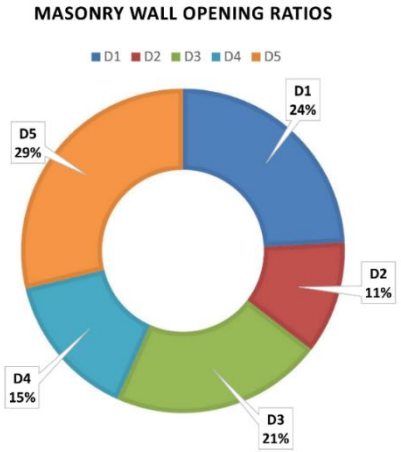


Fig. 7 – Distribution of masonry wall irregularities in Safranbolu houses.

The distribution of the masonry wall irregularities of the traditional Safranbolu houses evaluated within the scope of the study was also investigated. The facades were identified by coding them with the initials of their directions and the analysis of these irregularities according to the facade of the houses that do not comply with the Earthquake Resistant Design Rules for Masonry Buildings is given in Table 4. In the table, the rows belonging to the samples that do not have any of the reference features are left blank.

Table 4. Distribution of irregularities in traditional Safranbolu houses according to facades.

Ref. No.	Earthquake Resistant Design Rules for Masonry Buildings Ref. No.																			
	D1				D2				D3				D4				D5			
	N	S	E	W	N	S	E	W	N	S	E	W	N	S	E	W	N	S	E	W
E1	X		X	X	X		X	X	X			X					X			X
E2				X												X				X
E3		X				X														
E4				X								X								X
E5	X																X			
E6												X	X				X			X
E7		X				X				X								X		
E8				X				X												X
E9									X											
E10					X				X											
E11												X								
E12										X								X		
E13												X								X

Ref. No.	Earthquake Resistant Design Rules for Masonry Buildings Ref. No.																			
	D1				D2				D3				D4				D5			
	N	S	E	W	N	S	E	W	N	S	E	W	N	S	E	W	N	S	E	W
E14			X																	
E15																				
E16		X		X	X				X	X										
E17		X												X				X		
E18										X										
E19									X			X								
E20																				
E21				X		X												X		
E22			X								X									
E23			X				X				X	X			X				X	
E24		X		X												X		X		
E25																				
E26			X																	
E27										X										
E28								X			X	X								
E29					X				X											
E30																				
E31		X				X								X				X		
E32	X		X						X								X	X		
E33		X								X							X			
E34		X	X	X																
E35	X			X							X					X	X			X
E36	X	X	X								X	X		X	X				X	
E37																				
E38		X		X		X					X	X								
E39	X			X	X							X	X							
E40	X	X		X						X			X			X				
E41	X			X	X				X				X			X				
E42		X		X				X								X				X
E43		X	X												X				X	
E44										X						X		X		X
E45	X				X				X									X		
E46		X	X	X								X		X		X		X		X
E47							X													
E48		X								X				X				X		
E49				X				X			X									X
E50	X				X		X		X				X				X			

Ref. No.	Earthquake Resistant Design Rules for Masonry Buildings Ref. No.																			
	D1				D2				D3				D4				D5			
	N	S	E	W	N	S	E	W	N	S	E	W	N	S	E	W	N	S	E	W
E51		X	X															X		
E52												X								X
E53		X		X					X	X										
E54		X																X		
E55															X			X	X	
E56																				
E57			X												X				X	
E58		X																		
E59		X													X			X	X	
E60																	X			
E61																				
E62																				
E63																				
E64																				
E65	X	X																X		
E66		X																		
E67		X		X										X				X		
E68																				
E69											X			X				X	X	
E70		X		X		X		X				X				X				X
E71	X	X		X	X				X	X						X				
E72																				
E73										X										
E74			X																	
E75				X								X				X				
E76					X	X			X	X										
E77									X											
E78									X											
E79										X							X	X		
E80		X								X					X				X	
E81			X	X												X				X
E82											X								X	
E83	X	X	X										X		X		X		X	
E84	X												X		X					
E85				X								X								X
E86	X	X											X				X			
E87		X									X	X		X				X		

Ref. No.	Earthquake Resistant Design Rules for Masonry Buildings Ref. No.																			
	D1				D2				D3				D4				D5			
	N	S	E	W	N	S	E	W	N	S	E	W	N	S	E	W	N	S	E	W
E88			X	X								X		X				X		
E89		X	X			X									X				X	
E90				X						X										
E91		X	X	X		X						X							X	
E92		X										X								
E93												X		X	X					
E94																				
E95			X																	
E96																				
E97				X				X												
E98						X												X		
E99				X												X				X
E100																				

The distribution of irregularities in traditional Safranbolu houses by facade reveals that D1 irregularity is present on the north facade of 15 houses, south of 32, east of 19, and west of 28. D2 irregularity was found on the north facade of 10 houses, on the south facade of 10 houses, on the east facade of 4 houses and on the west facade of 7 houses. The D3 irregularity was observed on the north facade of 15 houses, the south facade of 16 houses, the east facade of 10 houses and the west facade of 21 houses. D4 irregularity was found on the north facade of 18 houses, south facade of 10 houses, east facade of 11 houses and west facade of 13 houses, while D5 irregularity was found on the north facade of 11 houses, south facade of 22 houses, east facade of 12 houses and west facade of 16 houses. The percentage distribution of these irregularities is presented in Figure 8.

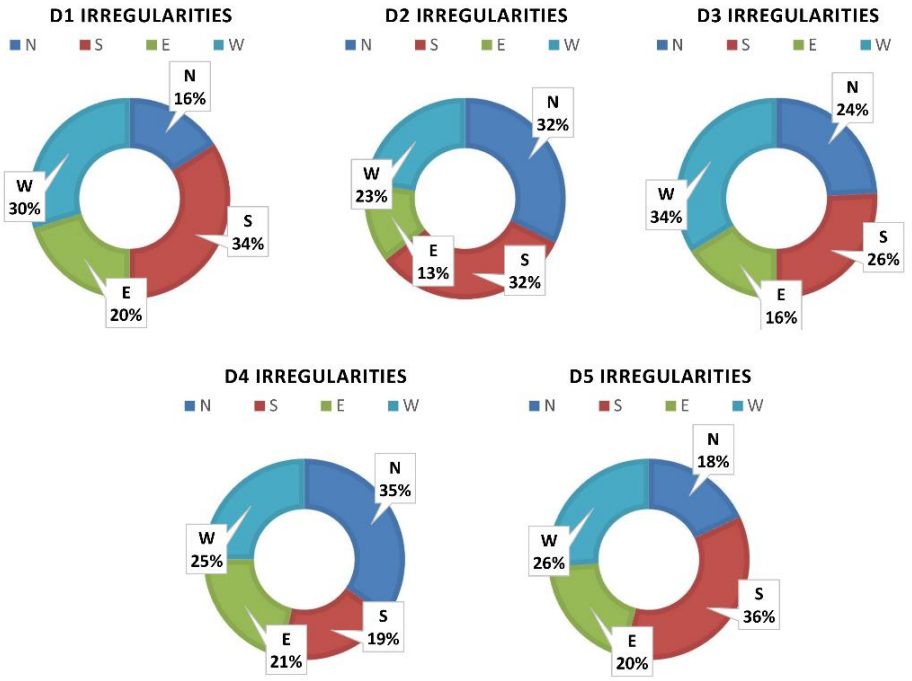


Fig. 8 – Distribution of D1-D5 irregularities on the facades of the houses.

Due to the large openings on the ground floors of Safranbolu houses, which may compromise structural integrity by disrupting the continuity of masonry walls under seismic forces, D5 irregularity was examined in detail. Table 5 presents the analysis of opening ratios in ground floor walls and their distribution across facades. As per seismic design regulations, openings below 40% comply with standards, while those between 40% and 50% are categorized separately due to their proximity to the limit. Openings between 50% and 90% are evaluated in 10% increments. The examples between 50% and 90% are evaluated in increments of 10 points.

Table 5. Classification of opening ratios of masonry stonewalls of Safranbolu houses.

Ref. No.	Opening Ratios	Ref. No.	Opening Ratios	Ref. No.	Opening Ratios	Ref. No.	Opening Ratios
E1	North facade %50 and West facade %90	E26	40% and less	E51	South facade %70	E76	40% and less
E2	West facade %70	E27	40% and less	E52	West facade %44	E77	40% and less
E3	40% and less	E28	40% and less	E53	40% and less	E78	40% and less
E4	West facade %70	E29	40% and less	E54	South facade %50	E79	North facade %45 and East facade %60
E5	North facade %90	E30	40% and less	E55	South facade %70 and East facade %50	E80	East facade %50
E6	North facade %60 and West facade %90	E31	South facade %70	E56	40% and less	E81	West facade %80
E7	South facade %90, %50, %50	E32	North facade %43 and South facade %70	E57	East facade %80	E82	East facade %41
E8	West facade %90	E33	North facade %50	E58	40% and less	E83	North facade %50 and East facade %60
E9	40% and less	E34	40% and less	E59	South facade %50 and East facade %80	E84	40% and less
E10	40% and less	E35	North facade %50 and West facade %60	E60	North facade %50	E85	West facade %44
E11	40% and less	E36	East facade %90	E61	40% and less	E86	North facade %60
E12	South facade %46	E37	40% and less	E62	40% and less	E87	South facade %70
E13	West facade %44	E38	40% and less	E63	40% and less	E88	South facade %50
E14	40% and less	E39	40% and less	E64	40% and less	E89	East facade %70
E15	40% and less	E40	40% and less	E65	South facade %50	E90	40% and less
E16	40% and less	E41	40% and less	E66	40% and less	E91	East facade %70
E17	South facade %50	E42	West facade %90	E67	South facade %70	E92	40% and less
E18	South facade %50	E43	East facade %80	E68	40% and less	E93	40% and less
E19	40% and less	E44	South facade %60 and West facade %60	E69	South facade %45 and East facade %60	E94	40% and less
E20	40% and less	E45	South facade %50	E70	West facade %80	E95	40% and less
E21	South facade %41	E46	South facade %70 and West facade %80	E71	40% and less	E96	40% and less
E22	40% and less	E47	40% and less	E72	40% and less	E97	40% and less
E23	East facade %90	E48	South facade %80	E73	40% and less	E98	South facade %43
E24	South facade %50	E49	West facade %50	E74	40% and less	E99	West facade %80
E25	40% and less	E50	North facade %80	E75	40% and less	E100	40% and less

Analysis of cavity rates in ground floor masonry walls shows that 49 houses comply with regulations, having a cavity rate of 40% or below. Among the non-compliant cases, 10 houses have 40–50% openings, 17 have 50%, 7 have 60%, 11

have 70%, 9 have 80%, and 8 have 90%. The highest concentration of non-standard cavity rates is observed at 50%. Figure 9 presents the distribution of masonry wall cavity ratios.

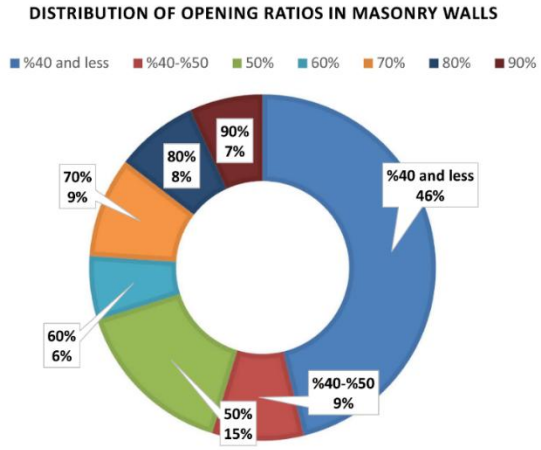


Fig. 9 – Distribution of masonry wall cavity ratios.

4 Conclusion

Safranbolu houses are important heritage structures that reveal the social and cultural structure of the period, carry the traces of the past, and transfer them to the future. These houses are among the original examples of the traditional Ottoman urban fabric and are of great value in terms of aesthetics, functionality, and authenticity. These unique structures of Safranbolu, which have survived to the present day, are not only residences but also important cultural symbols that carry the lifestyle, construction techniques, and aesthetic understanding of the past to the present.

As a result of the analyses carried out within the scope of this study, analysis criteria were established to examine the status of Safranbolu houses in terms of earthquake safety and to examine their structural properties. Accordingly, the traditional housing typologies of Safranbolu were determined, the earthquake behavior of masonry structures was discussed, and the compatibility of these structures with the earthquake regulations was analyzed. Clear data were obtained regarding the extent to which the ground floor bearing systems consisting of stone masonry walls comply with the Earthquake Resistant Design Rules for Masonry Buildings specified in the Regulation on Buildings to be Constructed in Earthquake Zones published in the Official Gazette dated March 6, 2007, and numbered 26454. Since Safranbolu's close proximity to the North Anatolian Fault, it was determined that the load-bearing wall opening ratios in the ground floors are a critical factor in terms of structural safety. In addition, design and application errors frequently encountered in masonry structures were identified, and the distribution of these errors was determined.

When the irregularities D1–D5 are analyzed, it is seen that most of the houses have at least one of these irregularities. When the compliance of the masonry stonewalls on the ground floor with the design rules is evaluated, it is found that 85 houses have at least one of the irregularities D1, D2, D3, D4, or D5, while the remaining 15 houses comply with the design rules. When the houses are analyzed in terms of the design rules on the façades, it is seen that most of the examples (29%) are gathered in the D5 irregularity. In this case, it is understood that most of the examples do not comply with the principle: “The sum of the lengths of the door and window openings in the plan along the unsupported length of any wall shall not exceed 40% of the unsupported wall length.” On the one hand, this irregularity reveals the vulnerability of the dwellings to earthquakes; on the other hand, the fact that this irregularity manifests mostly on the south (36%) and least on the north (18%) façades shows that climate determinants were considered in a dominant way in traditional Safranbolu houses.

The 85% rate of non-compliance with modern earthquake regulations detected in Safranbolu houses is consistent with studies conducted in other historic settlements in the Mediterranean basin, such as the historic urban fabric of Oran, Algeria [9]. Evaluations performed in these regions using methods like Zacek [23] and AFPS [22] also confirm that the existing historic building stock carries high seismic risk and requires urgent rehabilitation. In this context, the use of architectural-based diagnostic methods proposed by Zacek [23] at the urban scale by local authorities is recommended for the development

of risk reduction strategies aimed at preserving the historic fabric of Safranbolu. Such simplified approaches can serve as strategic filtering tools to identify which buildings should be prioritized for more detailed engineering analyses (e.g., pushover analysis) in dense historic settlements like Safranbolu.

The findings of the study reveal that Safranbolu houses do not have a reliable structural design within the scope of the current earthquake code, and the structural system properties need to be better understood. This study emphasizes the importance of preserving historical and cultural heritage as well as re-evaluating the masonry walls of traditional buildings in terms of earthquake safety. The analyses clearly show that the structural performance of these structures should be brought in line with current earthquake codes. Making traditional Safranbolu houses earthquake resistant will not only increase the seismic resistance of these structures but also ensure their safe transfer to future generations. In this context, our study provides an important contribution to the comprehensive assessment of traditional buildings in terms of earthquake safety and paves the way for the development of strategies for retrofitting these buildings in line with modern engineering principles. The obtained results show that an interdisciplinary approach should be adopted to achieve a balance between the preservation of historic buildings and modern earthquake safety requirements. In this respect, future studies are expected to contribute to more detailed analysis of the structural systems of traditional buildings, development of appropriate intervention methods, and extension of existing regulations to cover such structures.

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Conflicts of interest

The authors declare that they have no potential conflicts of interest in this paper.

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