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Research Article

Influence of Plan Typology on the Seismic Response of Timber-Masonry Structural Models Derived from Traditional Safranbolu Houses

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Keywords

Seismic behavior,
Plan typology,
Timber-masonry structures,
Traditional Safranbolu houses,
Finite element analysis.

Abstract

Traditional Safranbolu houses represent a distinctive timber-masonry residential architecture with diverse plan typologies. This study evaluates the effect of plan typology on the seismic response of such structures through numerical modeling and finite element analysis. Three representative house models corresponding to inner sofa, corner sofa, and outer sofa layouts were developed based on the most common typological characteristics identified in the traditional housing stock. To ensure a consistent comparison, all models were defined using identical material properties, structural systems, and geometric dimensions, while plan configuration was considered the only variable parameter. Modal analyses and seismic response evaluations were performed using SAP2000 software. The results indicate that plan typology has a limited effect on vibration periods but significantly influences displacement demands, stress concentrations, and masonry wall performance. The outer sofa configuration exhibits the largest lateral displacements and the highest masonry wall stress demands, whereas the corner sofa model produces higher stress concentrations in timber beam elements. In contrast, the inner sofa configuration demonstrates a comparatively more balanced structural response. The findings highlight the importance of spatial organization in the seismic performance of traditional timber-masonry houses and provide useful insights for future conservation and strengthening studies.

1. Introduction

Safranbolu, located in the Western Black Sea Region of Türkiye, is one of the most prominent historic settlements reflecting the traditional residential architecture of the Ottoman period. The city has gained international recognition due to the exceptional preservation of its historic urban fabric and was inscribed on the UNESCO World Heritage List in 1994. A large portion of the traditional houses built during the eighteenth and nineteenth centuries have survived to the present day, forming a unique architectural ensemble. Among nearly two thousand traditional houses documented in the city, approximately eight hundred structures are currently under legal conservation protection, demonstrating the cultural and historical importance of this residential heritage.

Traditional Safranbolu houses are mainly distributed in the historic districts of Çarşı, Bağlar, and Kıranköy, where the original urban texture has largely been preserved. These houses typically exhibit a hybrid structural system consisting of masonry ground floors constructed with stone walls and upper stories built with timber frame systems filled with

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adobe or stone materials. Characteristic architectural elements such as cantilevered projections, timber framing details, and wide eaves define the façade organization of these buildings. From a spatial perspective, Safranbolu houses also demonstrate a rich diversity of plan typologies. The spatial layout of the houses is generally organized around different sofa configurations, including inner sofa, corner sofa, outer sofa, and free sofa plans. These typological variations not only shape the architectural identity of the houses but may also influence their structural behavior under external loads.

Traditional Safranbolu houses exhibit considerable typological diversity in their spatial organization, particularly in sofa-based plan layouts. In addition to their architectural significance, these structures are located in a region that has experienced seismic activity of varying magnitudes throughout history. Considering the inherent vulnerability of traditional construction materials such as masonry and timber, the seismic performance of these historic houses has become an important topic in both structural engineering and cultural heritage conservation. Understanding how typical residential configurations respond to earthquake loading is therefore essential for evaluating their structural safety and for developing appropriate conservation and strengthening strategies aimed at preserving this cultural heritage for future generations.

Previous research on the seismic performance of historic masonry and timber structures indicates that numerical modeling and finite element analysis are widely used tools for evaluating structural behavior under seismic actions. Structural analysis software such as SAP2000 and ANSYS have been frequently employed to perform modal, static, and dynamic analyses of both masonry and timber structural systems. Many studies focusing on masonry structures have primarily investigated monumental buildings, including mosques and minarets, where structural analyses are conducted to assess the seismic performance of existing historical monuments [4-6]. Experimental investigations have also been carried out to validate numerical models, revealing that parameters such as wall openings, material thickness, and mechanical properties play a significant role in damage distribution and energy dissipation capacity [2,7]. Recent peer-reviewed studies have further demonstrated that advanced finite element modelling has become one of the principal approaches for assessing the seismic performance of historic timber-masonry structures, particularly where direct experimental investigation is limited by conservation requirements [1-3].

Timber frame structures have been examined from different perspectives, including frame behavior, the influence of infill materials, and the mechanical performance of connection details [8-14]. Previous studies have demonstrated that timber frames with infill materials generally exhibit higher load-bearing capacity and improved damage control compared to empty frames. In addition, the mechanical behavior of connections between timber members has been identified as a key factor influencing ductility, stiffness, and energy dissipation characteristics of the structural system.

Despite the increasing number of studies on historic masonry and timber buildings, the seismic behavior of hybrid residential structures combining masonry ground floors and timber frame upper stories has not been sufficiently investigated. In particular, limited attention has been given to how architectural typology and plan configuration may influence the seismic response of such hybrid systems. Most previous research has concentrated on either masonry or timber structures individually, or has focused on specific existing buildings, without systematically examining typological variations within traditional residential architecture. Although recent studies have considerably improved the numerical assessment of historic timber-masonry buildings, comparative investigations focusing specifically on the influence of architectural plan typology on seismic behavior remain very limited. The present study addresses this gap by comparatively evaluating representative sofa-based plan configurations developed under identical modelling conditions.

Safranbolu offers a particularly valuable case for such investigations due to two important characteristics. First, the city preserves a large number of traditional houses that represent a wide variety of plan typologies, providing a rich architectural reference for typological analysis. Second, the settlement is located in a seismically active region of Türkiye, which increases the importance of understanding the structural behavior of these historic residential systems under earthquake loading. The combination of typological diversity and well-preserved architectural examples makes Safranbolu an appropriate reference context for investigating how spatial configuration may affect structural response.

In response to this need, the present study evaluates the seismic behavior of representative structural models derived from traditional Safranbolu houses. Instead of investigating a particular building, the analysis is based on prototype models developed from the common architectural and structural characteristics identified within the housing stock. Three representative sofa typologies-inner sofa, corner sofa, and outer sofa-were selected for comparison. To ensure that the observed differences are associated solely with plan organization, all models were defined using the same material properties, structural system characteristics, and geometric parameters.

Finite element modeling techniques are employed to simulate the hybrid timber-masonry structural system, and numerical analyses are conducted using structural analysis software. Through modal and structural analyses, the study evaluates the dynamic characteristics, displacement behavior, and stress distribution patterns associated with each plan configuration. By comparing the seismic responses of typology-based structural models, the research aims to reveal how variations in spatial organization may influence the structural performance of traditional timber-masonry residential systems. The findings are expected to contribute to a better understanding of the seismic behavior of traditional housing typologies and to support future structural assessment and conservation strategies for historic residential buildings located in earthquake-prone regions. The present research adopts a comparative numerical modelling approach rather than the structural assessment of a specific existing building. Accordingly, the developed finite element models are intended to evaluate the relative

influence of plan typology while maintaining identical material properties, structural systems, and geometric characteristics. Therefore, the emphasis of the study is placed on identifying comparative behavioral trends instead of predicting the exact seismic response of individual historic buildings.

2. Architectural and Structural Characteristics of Safranbolu Houses

Safranbolu is a historic district situated in Karabük Province within the Western Black Sea Region of Türkiye (Figure 1). Owing to its strategic location, the area has hosted numerous civilizations throughout history and has developed a rich cultural and architectural heritage. Archaeological findings indicate that human settlement in the region dates back to the Bronze Age, with the earliest known inhabitants believed to be the Gasgas. Safranbolu is particularly known for its well-preserved traditional urban fabric and historic houses, which reflect centuries of cultural continuity and architectural development [15]. The settlement is characterized by a traditional urban pattern that evolved in harmony with the natural topography. The historic residential areas are predominantly located on sloping terrain, where buildings were arranged to maximize access to sunlight and maintain visual relationships with the surrounding landscape. This layout reflects a planning approach that successfully integrates environmental conditions with the social and functional requirements of daily life. It is estimated that Safranbolu contains nearly 2,000 traditional houses, approximately 800 of which are officially registered and protected due to their cultural and architectural significance [16].

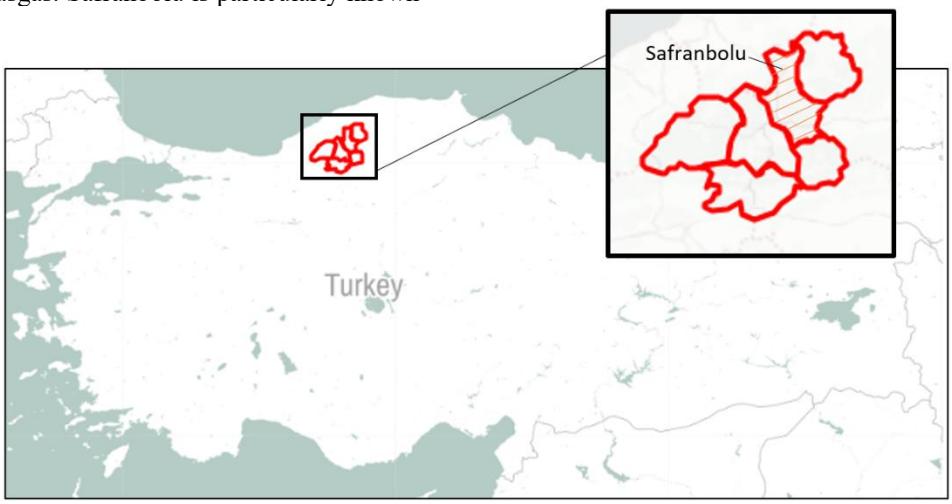


Figure 1. Location of Safranbolu within Türkiye and Karabük province

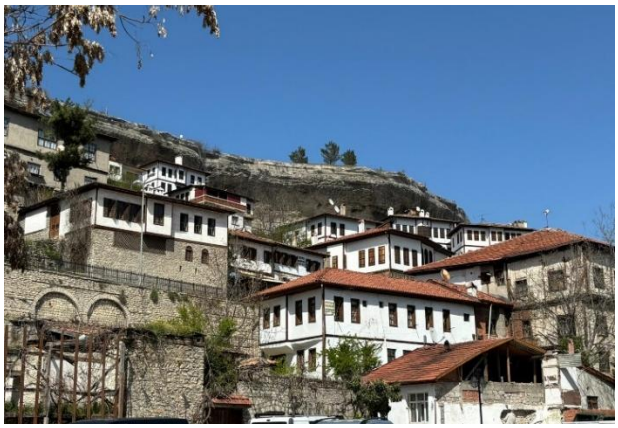


Figure 2. Traditional Safranbolu houses

The traditional houses are primarily concentrated in the historic districts of Çarşı, Bağlar, and Kıranköy. Within these areas, the spatial organization of the urban fabric reflects a settlement pattern that establishes a balanced relationship between built structures, natural environment, and daily life. The street-level floors of the houses are generally constructed using stone masonry and integrated into the street alignment, while the upper floors extend outward through timber cantilevered projections. These architectural features contribute significantly to the distinctive appearance of the historic settlement and represent characteristic elements of Safranbolu's residential architecture [17] (Figure 2).

From an architectural perspective, Safranbolu houses typically consist of two- and three-story residential buildings, which represent the most common building configurations preserved within the historic urban fabric. The internal spatial organization of these houses is generally structured around a central circulation space known as the sofa. This space functions as the primary organizing element of the floor plan and serves both circulation and communal living purposes. Based on the spatial arrangement of the sofa, Safranbolu houses are generally classified into three principal plan typologies: external sofa, internal sofa, and central sofa configurations [18]. Rooms are typically arranged around the sofa and designed as multifunctional living spaces. While the ground floors are mostly used for service-related functions such as storage and auxiliary spaces, the main living areas are generally located on the upper floors [19].

In structural terms, traditional Safranbolu houses exhibit a hybrid construction system composed of masonry ground floors and timber frame upper stories. The ground-floor walls are typically constructed using stone masonry and are often strengthened with horizontal timber tie beams placed at regular intervals within the wall sections to enhance

structural integrity and improve load distribution [20]. This construction technique contributes to the stability of the masonry walls while also providing a connection between the timber and masonry components of the building.

The upper stories are commonly built using timber frame construction systems. In these systems, vertical timber posts and horizontal members form the primary load-bearing framework, while the spaces between the structural elements are filled with adobe or stone infill materials. Due to its relatively lightweight and flexible characteristics, the timber frame system can provide a more favorable structural response under seismic loading compared to purely masonry construction [21].

The main construction materials used in traditional Safranbolu houses include natural stone, timber, adobe, and clay roof tiles. Stone masonry is predominantly used in the ground floors, whereas timber frame construction with adobe or stone infill is generally employed in the upper stories. Timber has been extensively utilized in the structural system due to the availability of forest resources in the surrounding region. Tree species such as fir (Abies), Scots pine (Pinus sylvestris), and black pine (Pinus nigra) are commonly used for structural elements including beams, columns, and framing components [22]. In wall construction, mud mortar and lime-based mortars are typically applied as binding materials between masonry units [23].

Türkiye is situated within an active tectonic belt and has been repeatedly affected by destructive earthquakes throughout its history [25]. Consequently, seismic hazard represents a critical consideration for the preservation and structural assessment of historic buildings. The North Anatolian Fault Zone, one of the most significant active fault systems in the country, passes approximately 55 km south of Karabük city center. The fault extends from the Bolu-Gerede segment toward the east through the İsmetpaşa area of Eskipazar and the Tosya district of Kastamonu. In addition, regional tectonic activity is influenced by the Amasra-Abdipaşa-Safranbolu-Karabük-Eskipazar fault system [24,26].

A further tectonic feature affecting the region is the Karabük Fault, located to the north of the city and extending in a northeast-southwest direction. Although this structure is presently regarded as inactive, the proximity of Safranbolu to active fault systems indicates that the area remains exposed to seismic effects. Historical records suggest that the district has not been subjected to a major destructive earthquake; nevertheless, earthquakes originating from neighboring regions have been felt within the settlement and its surroundings. Therefore, the traditional building stock cannot be considered free from future seismic risk.

The survival of a large number of traditional houses despite this tectonic setting has created a unique opportunity for structural investigation. Many of these buildings retain their original architectural and construction characteristics, allowing the evaluation of their behavior under earthquake actions. Because seismic forces generate time-dependent dynamic effects [26], the response of a structure is governed by its stiffness, mass distribution, and vibration characteristics in addition to its strength. For this reason, the dynamic assessment of traditional timber-masonry houses is essential for understanding their potential performance under future earthquake scenarios.

3. Methodology

3.1. Typological Analysis and Selection of Representative Plan Configurations

In order to develop representative structural models for the numerical analyses, a preliminary typological investigation of traditional Safranbolu houses was conducted. Architectural survey drawings, restoration project documentation, and previously published academic studies were examined to identify the dominant architectural and structural characteristics of the historic housing stock. Within the scope of this assessment, a total of 105 traditional houses documented in the literature were analyzed. Among these examples, 67 houses are located in the Çarşı district, 32 in the Bağlar district, and 6 in the Kıranköy district of Safranbolu. These districts represent the areas where the traditional urban fabric has been largely preserved and therefore provide reliable data regarding the architectural characteristics of the settlement. The examination of the selected buildings indicates that a large portion of the traditional houses are located on sloped terrain, reflecting the topographical structure of the region.

From a spatial perspective, the internal layout of Safranbolu houses is generally organized around a central circulation space known as the sofa. This space functions as the main common living area and establishes the spatial relationship between rooms. The location and configuration of the sofa within the floor plan create different typological arrangements. Based on the spatial relationship between the sofa and surrounding rooms, Safranbolu houses can generally be classified into three principal plan typologies: inner sofa, outer sofa, and corner sofa layouts [18]. The typological evaluation also revealed several recurring architectural features that characterize the traditional houses of Safranbolu. Among these, centrally located façade projections represent one of the most frequently observed elements in the elevation composition. In addition, many buildings exhibit irregular distributions of openings in the masonry ground-floor walls, which may influence the structural behavior of the building under lateral loading conditions (Figure 3).

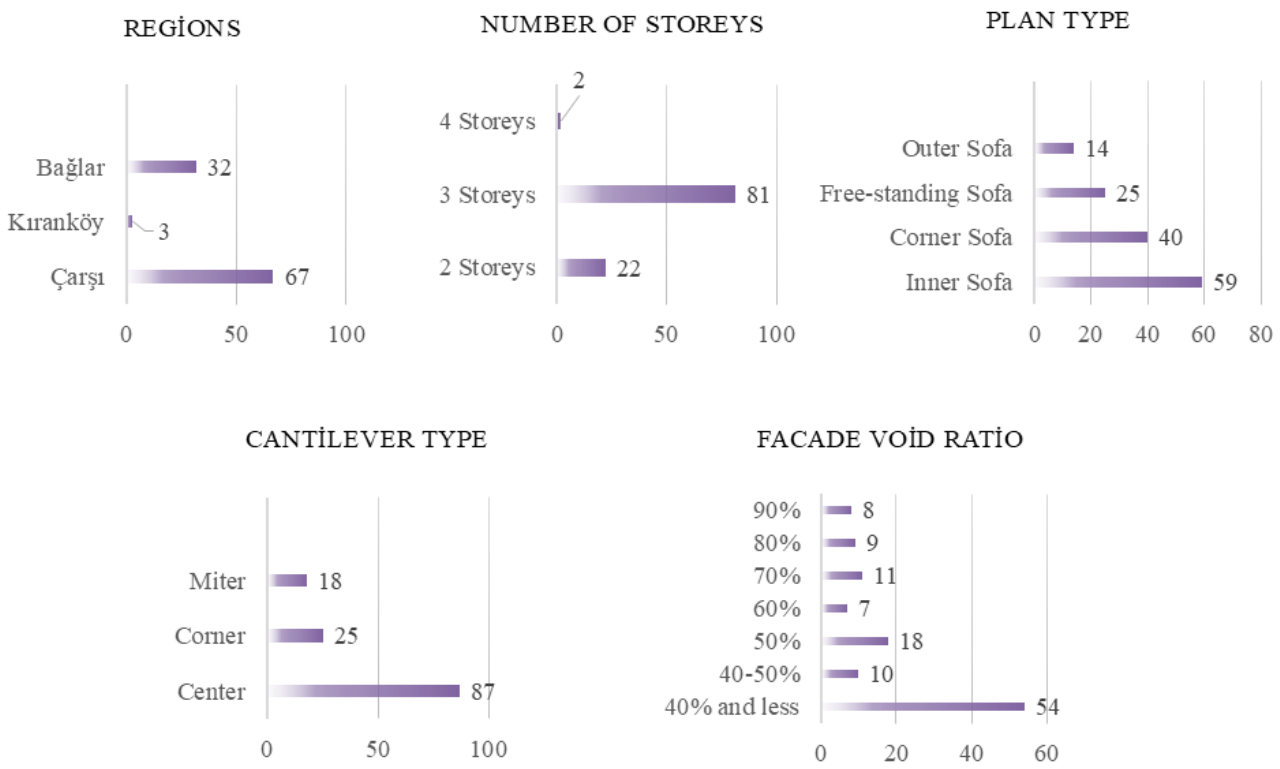


Figure 3. Typological distribution of traditional houses in Safranbolu

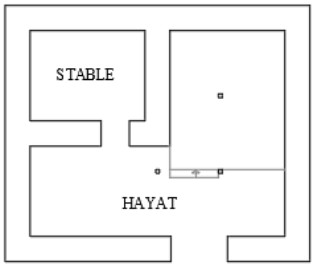
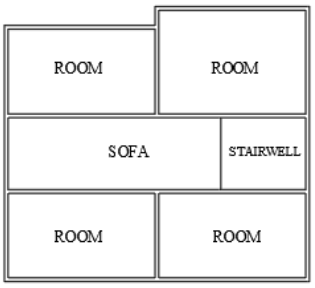
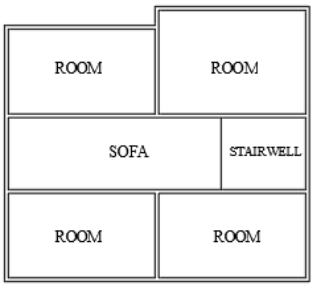
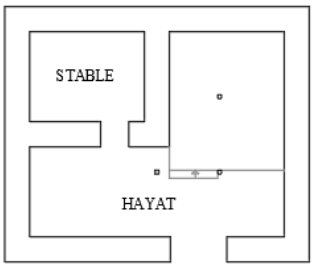
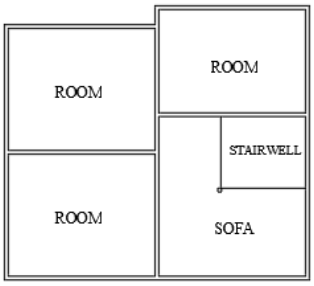
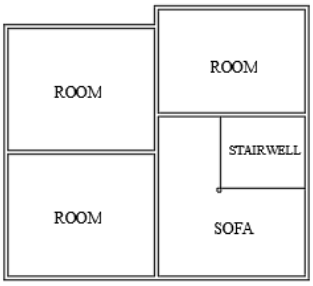
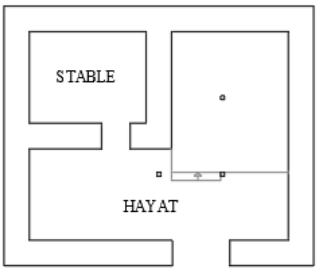
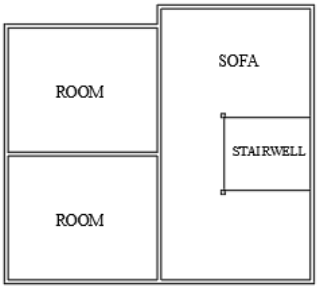
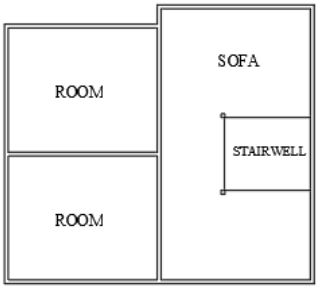
Considering the architectural and spatial characteristics identified during the typological analysis, three representative plan configurations were selected for the structural modeling process. These configurations correspond to the most common sofa-based plan organizations observed in traditional Safranbolu houses:

- Inner sofa plan configuration
- Corner sofa plan configuration
- Outer sofa plan configuration

Although free-sofa layouts were identified during the typological survey, they were not included in the numerical analyses because their occurrence within the investigated housing stock was limited and therefore did not provide a sufficiently representative basis for comparative modelling. The present study was limited to the inner sofa, corner sofa, and outer sofa configurations in order to establish a consistent comparative framework and to evaluate the influence of the most representative plan organizations on the seismic response of traditional Safranbolu houses.

Instead of analyzing a single existing building, the present study adopts a typology-based modeling approach in which representative prototype models are developed. This approach enables the investigation of the influence of plan configuration on structural behavior by eliminating irregularities associated with individual buildings. To ensure a consistent comparison between the models, the principal structural characteristics of the buildings-including structural system configuration, building height, geometric proportions, and material properties-were kept constant. Accordingly, plan typology was considered the only variable parameter in the comparative seismic analyses (Table 1).

Table 1. Floor plans of house models

Plan Type	Ground-floor plan	First-floor plan	Second-floor plan
Inner sofa			
Corner sofa			
Outer sofa			

3.2. Structural Modelling and Analysis Procedure

The structural behavior of the representative house models was investigated using the finite element method. Numerical models were developed in a three-dimensional environment using the SAP2000 structural analysis software. Traditional Safranbolu houses exhibit a hybrid structural system composed of stone masonry walls at the ground floor and timber frame construction in the upper stories. In order to accurately represent this plan configuration, the masonry and timber components were defined using different material properties in the numerical model. The modeling process was carried out in two stages. First, the structural behavior of the timber frame system forming the upper stories was defined. Subsequently, the stone masonry ground-floor walls were incorporated into the model in order to represent the interaction between the two structural systems. Through this procedure, the transfer of loads from the upper timber structure to the masonry walls was simulated, allowing the overall structural response of the hybrid system to be evaluated.

To investigate the influence of plan typology on structural performance, the numerical results were evaluated from several complementary perspectives. The dynamic characteristics of the models were examined through their vibration periods and mode shapes. Seismic deformation demand was assessed by considering floor displacements and interstory drift responses. The behavior of the timber structural system was evaluated by examining stress and serviceability criteria in beams and vertical members, including bending, shear, compression, and deflection responses. In addition, the mechanical performance of the masonry wall system was assessed through the distribution of compressive and shear stresses. The results obtained from the inner sofa, corner sofa, and outer sofa configurations were then compared to identify the extent to which spatial organization influences the overall seismic response of traditional Safranbolu houses.

3.3. Material Properties

Traditional Safranbolu houses are generally constructed using a hybrid structural system that combines stone masonry walls at the ground floor with timber frame construction in the upper stories. The masonry walls at the ground level typically have an average thickness of approximately 80 cm and are constructed using limestone blocks bonded with mud mortar [22,28]. The stone used in these structures belongs to the limestone group and is locally known as Yazıköy stone, which has historically been obtained from nearby quarries in the region [29]. In the

timber frame systems used in the upper floors, coniferous wood species such as fir and pine are commonly utilized [22]. The cross-sectional dimensions of the timber structural members generally range between 10 and 12 cm, while the spacing between vertical posts typically varies between 20 and 40 cm [21]. In older buildings, these distances may increase up to 45-70 cm [18]. In the present study, pine timber was selected as the representative material for the numerical modeling of the timber frame system. The primary vertical posts were modeled with cross-sections of 12 × 12 cm, while intermediate studs were defined with cross-sections of 6 × 12 cm. Beam elements were modeled using cross-sections of 12 × 15 cm, which correspond to commonly reported dimensions in the literature. The spacing between beams and vertical posts was assumed to be approximately 40 cm.

Because the investigated structural typologies represent protected cultural heritage assets, destructive material sampling and laboratory testing could not be performed. Consequently, direct determination of the mechanical properties of timber, masonry, and adobe materials was not feasible. Instead, the material parameters adopted in the numerical models were selected from experimentally validated values reported in previous studies dealing with traditional timber-masonry buildings constructed using comparable materials and construction techniques. Therefore, the mechanical properties used in the numerical models were adopted from widely accepted values reported in the literature. For pine timber, the modulus of elasticity parallel to the grain was taken as 10,000 MPa, while the modulus of elasticity perpendicular to the grain was assumed to be 300 MPa. The shear modulus was defined as 500 MPa, and the Poisson's ratio was taken as 0.30 [12,27]. This modelling strategy is widely adopted in the structural assessment of historic buildings where conservation regulations restrict invasive investigations. Consequently, the adopted material properties should be regarded as representative engineering values rather than building-specific measurements. Although direct experimental validation of the developed numerical models was beyond the scope of the present study, the modelling strategy follows previously published experimental and numerical investigations on comparable timber-masonry buildings. Therefore, the numerical results should primarily be interpreted in terms of comparative structural behavior rather than absolute predictions of the seismic performance of individual historic buildings [10,13].

The adobe infill material used within the timber frame system was modeled based on mechanical properties reported in previous experimental studies. Accordingly, the compressive strength of adobe was taken as 1.5 MPa, the modulus of elasticity as 880 MPa, the shear modulus as 180 MPa, and the unit weight as 20 kN/m³ [31]. Because the mechanical properties of stone masonry walls are generally difficult to determine separately for stone and mortar components, these materials were considered together as a homogenized composite material in the numerical model. Based on values commonly used in similar studies, the modulus of elasticity of the masonry walls was assumed to be 450 MPa, the unit weight was taken as 24 kN/m³, and the Poisson's ratio was defined as 0.20 [1,32]. In addition, according to the provisions of the Turkish Seismic Code for Buildings in Seismic Regions, the allowable compressive stress for stone masonry walls with unknown compressive strength is recommended as 0.3 MPa, while the cracking safety stress is defined as 0.1 MPa [33].

This modelling strategy is also consistent with recent studies on historic timber–masonry buildings, where representative material properties derived from previous experimental investigations have been adopted when direct material characterization was not feasible because of conservation restrictions [34].

3.4. Finite Element Modelling

To evaluate the seismic behavior of traditional Safranbolu houses, three-dimensional structural models were developed using the finite element method. The numerical simulations were carried out using the structural analysis software SAP2000. In the modeling of masonry structures, three main approaches are commonly adopted in the literature: micro-modeling, simplified micro-modeling, and macro-modeling [35]. Micro-modeling techniques represent individual masonry units and mortar joints separately and therefore provide highly detailed results. However, this approach significantly increases the number of elements and nodes in the model, resulting in high computational demand and longer analysis times, particularly for large structural systems [2]. For this reason, macro-modeling approaches are frequently preferred in the structural analysis of complex masonry buildings because they allow the structural system to be represented using homogenized material properties while maintaining computational efficiency [32]. Within the scope of the present study, the macro-modeling approach was adopted. In this method, the stone units and mortar joints forming the masonry walls were represented as a homogenized composite material, and equivalent material properties reported in previous experimental and numerical studies were assigned to the masonry elements in SAP2000. This modelling strategy is widely employed in the structural assessment of historic masonry buildings, particularly when destructive material testing and detailed characterization of individual components are not feasible due to conservation constraints. Although the adopted approach cannot reproduce local cracking mechanisms or material heterogeneity, it provides a reliable representation of the global structural response and enables a consistent comparison between the investigated plan typologies.

Accordingly, the present numerical models were developed to evaluate the relative influence of plan typology under controlled modelling conditions rather than to reproduce the exact structural response of a particular historic building. Since identical modelling assumptions were adopted throughout the analyses, the comparative behavioral trends obtained from the investigated plan typologies are considered more reliable than the absolute numerical values.

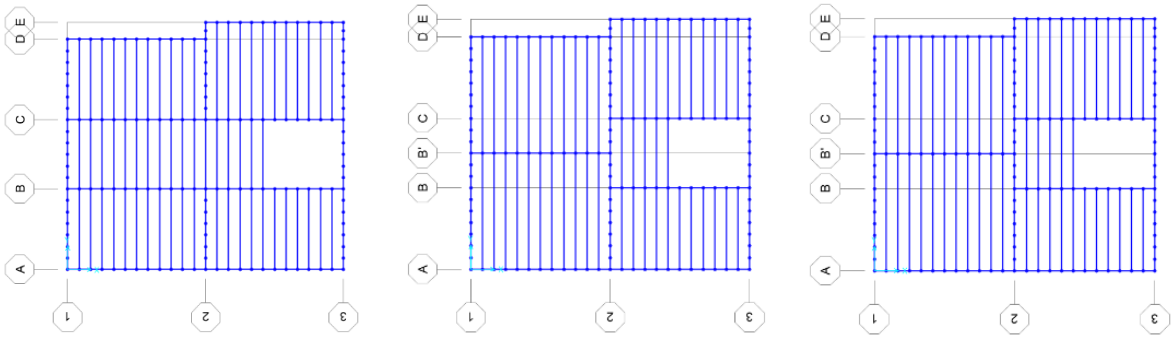
The finite element method allows complex structural systems to be represented by subdividing them into smaller and manageable elements connected at nodes. By defining the material properties, geometry, and boundary conditions of these elements, the structural response of the entire system

can be calculated under different loading conditions [36]. Owing to its capability to simulate complex structural behavior and interactions between different structural components, the finite element method has become one of the most widely adopted numerical techniques in structural engineering analyses [37]. In this study, the structural models were analysed using a linear elastic finite element approach. The primary objective of the numerical analyses was to compare the influence of different plan typologies under identical modelling conditions rather than to predict the exact damage state of a specific historic building. Therefore, a linear elastic framework was considered appropriate for evaluating the global structural response of the prototype models. Although this approach does not account for nonlinear phenomena such as masonry cracking, stiffness degradation, or connection slip, it allows meaningful comparison of the relative structural performance of the investigated configurations [38]. Nevertheless, it should be acknowledged that linear elastic analysis cannot represent nonlinear damage mechanisms such as progressive masonry cracking, stiffness degradation, or energy dissipation through timber connections. Therefore, the present analyses are intended to compare the relative structural response of different plan typologies rather than to predict actual earthquake-induced damage. Accordingly, the numerical results presented in this study should be interpreted as comparative indicators of structural behavior under elastic conditions rather than as predictions of the actual damage evolution or collapse mechanisms that may occur during strong earthquake events.

The use of a linear elastic analysis also ensured that the influence of nonlinear constitutive behavior did not introduce additional variables into the comparative assessment. Since the principal objective of this study was to isolate the effect of plan typology, adopting the same linear analysis procedure for all prototype models provided a consistent basis for evaluating the relative influence of spatial configuration on the global structural response.

The traditional houses were initially considered as two-dimensional load-bearing wall systems and subsequently developed into three-dimensional structural models within the SAP2000 environment in order to represent the spatial interaction between structural elements. The hybrid structural system consisting of timber frame upper stories and masonry ground-floor walls was modeled as an integrated structural system.

In the numerical model, timber structural components-including beams, vertical posts, braces, and horizontal ties-were represented using frame elements. In accordance with the variations in sofa-based plan configurations, the beam layouts differ among the three prototype models. The inner sofa configuration exhibits a completely distinct beam arrangement due to its central circulation scheme, whereas the corner sofa and outer sofa configurations present relatively similar beam layouts. However, despite these similarities in beam arrangement, the locations and distributions of the vertical load-bearing elements differ significantly between these two plan types. The first-floor beam layouts corresponding to the three plan configurations are illustrated in Figure 4.



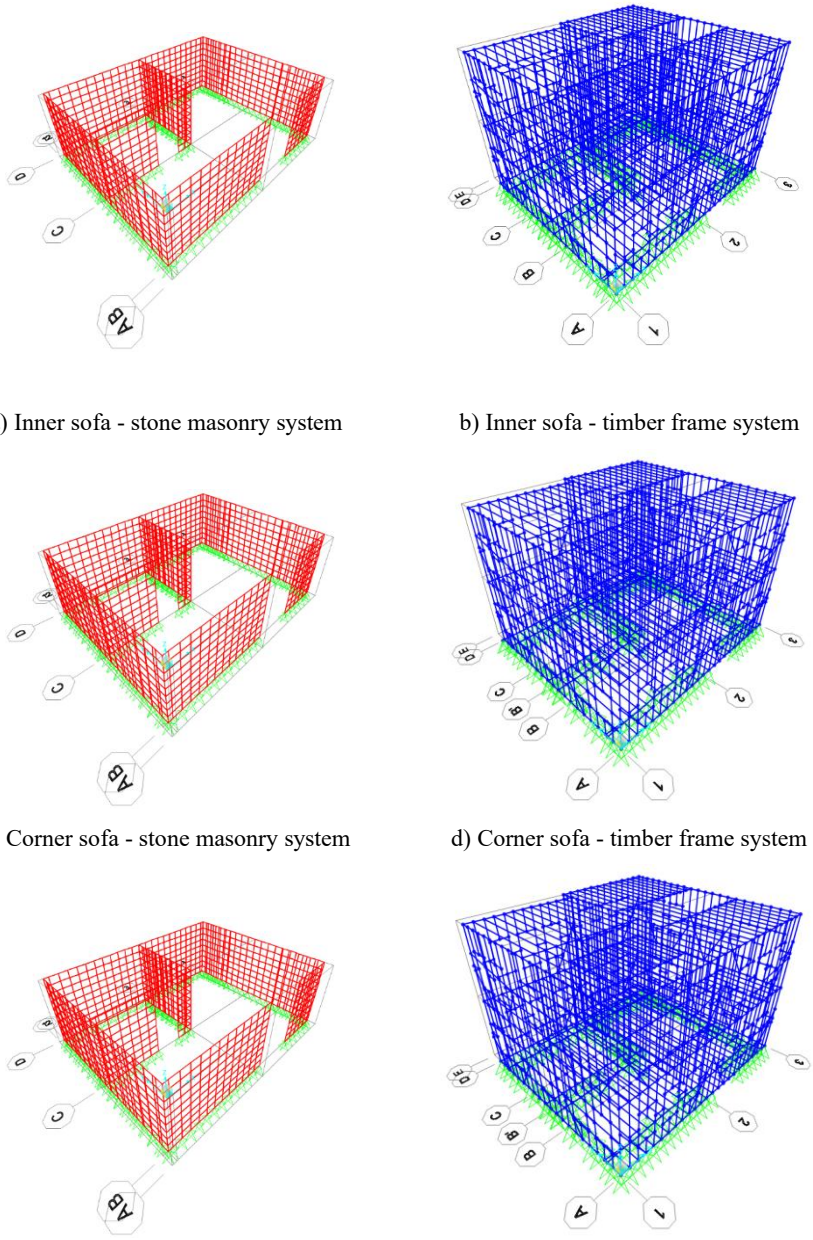
a) Inner sofa b) Corner sofa c) Outer sofa

Figure 4. Beam plans of residential buildings in SAP2000

The masonry walls were modeled using shell elements to simulate their load-bearing behavior. Boundary conditions and connection assumptions were defined according to the structural details observed in architectural survey drawings and previous studies. The modelling of timber-timber connections was established considering the traditional construction techniques commonly observed in Safranbolu houses. Primary load-bearing members, including the main beams, main posts, and braces, were assumed to act as continuous structural components to ensure the continuity of the structural frame. In contrast, secondary beams, intermediate studs, and horizontal tie members were represented using pinned connections to simulate the behavior of traditional nailed joints, which primarily transfer axial and shear forces while exhibiting limited moment resistance [12,39]. The upper and lower plates of the timber frame walls, together with the primary beam members, were assumed to behave as continuous structural elements. At the intersections of orthogonal walls, one of the top plates was defined with hinged connections to represent the actual construction behavior. Secondary beams transferring vertical loads to the wall systems were modeled as simply supported elements. These beams were additionally supported by vertical studs, which allows vertical loads to be transferred eccentrically to the wall system in accordance with the traditional construction technique. The main vertical posts were defined as continuous elements between floors, while braces and intermediate studs were assigned pinned

boundary conditions at both ends. Tie beams connecting the timber frame elements were also modeled with pinned connections to the intermediate studs.

Consistent with the approach proposed by Meriç [30], fixed boundary conditions were assigned at the interface between the timber frame system and the masonry walls. Furthermore, the contribution of the adobe infill material to the structural behavior of the timber frame system was represented by applying equivalent distributed loads to the horizontal and diagonal timber members. The resulting three-dimensional structural models consist of frame elements representing timber members and shell elements representing masonry walls, as illustrated in Figure 5.



a) Inner sofa - stone masonry system

b) Inner sofa - timber frame system

c) Corner sofa - stone masonry system

d) Corner sofa - timber frame system

e) Outer sofa - stone masonry system

f) Outer sofa - timber frame system

Figure 5. 3D system modeling of residential buildings in SAP2000

Based on photographic documentation, architectural survey data, and previous modelling studies, the interface between the timber frame and the masonry ground floor was represented using simplified fixed boundary conditions to ensure modelling consistency among the prototype models. This idealization was adopted to represent the transfer of vertical and lateral loads between the masonry ground floor and the timber-framed upper stories within a simplified numerical framework. Although actual timber-masonry interfaces generally exhibit semi-rigid behavior owing to construction details, nailed connections, workmanship, and material deterioration, explicitly modelling this interaction requires detailed experimental characterization of connection stiffness and slip behavior, which was beyond the scope of the present comparative study [12,30]. Although the timber-masonry interface was idealized using fixed

boundary conditions, this assumption was adopted primarily to ensure modelling consistency among the prototype models. In actual historic buildings, the interaction between timber and masonry components is generally governed by semi-rigid connections, construction details, workmanship, and material degradation. Previous experimental and numerical investigations have also demonstrated that the mechanical behavior of traditional timber connections significantly influences the stiffness, load-transfer mechanism, and deformation capacity of timber structural systems [39]. However, explicitly modelling every traditional carpentry joint and timber-masonry interface requires detailed experimental characterization and substantially increases modelling complexity. Since the primary objective of the present study is to compare the influence of plan typology under identical modelling conditions, simplified connection assumptions were consistently adopted for all prototype models. Consequently, the adopted assumption may result in a slightly stiffer global structural response than that of the real structures. Accordingly, local deformation mechanisms associated with connection slip, partial rotational restraint, and local joint failures were not explicitly represented in the numerical models. Instead, the adopted connection idealizations were intended to provide a consistent representation of the global load-transfer mechanism among the prototype models. Nevertheless, because identical connection assumptions were consistently applied to all numerical models, this simplification does not affect the comparative evaluation of the influence of plan typology on seismic response [10,13,30].

3.5. Loading and Analysis Procedure

The seismic loading parameters used in the numerical analyses were obtained from the Turkey Seismic Hazard Maps provided by the Disaster and Emergency Management Authority (AFAD) [40]. The horizontal elastic design spectrum required for the structural analyses in SAP2000 was generated using the interactive web application based on the approximate geographical coordinates of a representative traditional house located in the historic Safranbolu Eski Çarşı district. According to the obtained data, the local soil class in the Eski Çarşı area is classified as ZC, which typically corresponds to dense sand and gravel deposits, stiff clay layers, and highly weathered rock formations. Based on these parameters, the horizontal elastic design spectrum used in the analyses was generated. Both static and dynamic loading conditions were considered in the structural analyses. Static loads consist of permanent loads and live loads acting on the building, while dynamic loads mainly correspond to seismic actions. The load definitions used in the numerical model were established in accordance with the provisions of the Turkish Building Earthquake Code [41].

In the structural models, permanent loads (G), live loads (Q), and horizontal loads (E) were considered. Permanent loads represent the self-weight of structural elements, whereas live loads correspond to variable loads associated with building occupancy and usage conditions. Seismic and wind actions were considered within the category of horizontal loads [30]. The live load values applied to the floor systems were determined according to the provisions of the TS 498 standard. Accordingly, the live load for residential spaces was taken as 2 kPa, while a value of 1.5 kPa was adopted for the roof floor [28,43]. In addition, the characteristic snow load corresponding to the Safranbolu region was taken as 0.75 kPa based on the same standard. To evaluate the dynamic behavior of the structural models, three-dimensional numerical analyses were performed in SAP2000. Modal analyses were conducted to determine the natural vibration periods and corresponding mode shapes of the structures. In addition, displacement responses and stress distributions within structural elements were obtained from the numerical simulations under seismic loading conditions.

The structural analyses were performed using the relevant load combinations by accounting for both seismic (horizontal) and gravity (vertical) effects. The resulting stresses in the timber structural elements were evaluated in accordance with the requirements of the TS 647 standard [44]. The shear stresses developed in the masonry walls were evaluated according to the relationships provided in the Turkish Earthquake Code [33].

4. Results

According to the provisions of the Turkish Building Earthquake Code [41], the modal response combination method must be applied in modal analysis to obtain reliable estimations of base shear forces and lateral displacement demands. Within this framework, the effective modal mass participation ratios contributing to the base shear were calculated for each vibration mode, and the cumulative modal mass was obtained by summing the contributions of individual modes. As specified in Article 4.8.1.2 of the code, the total effective modal mass participation ratio in each principal direction must be at least 95% of the total structural mass. The analysis results indicate that this requirement was satisfied for all three prototype models. The cumulative mass participation ratios reached 99.80% in both the X and Y directions for the inner sofa model, 99.40% and 99.79% for the corner sofa model, and 99.47% and 99.77% for the outer sofa model, respectively (Table 2).

Table 2. Modal mass participation ratios

Model	Load Case	Response Type	Direction	Mass Participation (%)
Inner sofa	Modal	Acceleration	X	99.80
Inner sofa	Modal	Acceleration	Y	99.80
Corner sofa	Modal	Acceleration	X	99.40
Corner sofa	Modal	Acceleration	Y	99.79
Outer sofa	Modal	Acceleration	X	99.47
Outer sofa	Modal	Acceleration	Y	99.77

The structural modes were evaluated based on the modal mass participation ratios, and the dominant vibration periods were identified in both the X and Y directions. In addition, the dynamic characteristics of the timber frame system, masonry ground-floor system, and the overall house models were examined separately. The results indicate that the timber frame systems exhibit longer vibration periods due to their relatively flexible structural behavior, whereas the masonry stone systems show considerably shorter periods owing to their higher stiffness. For the overall structural models, the dominant vibration periods were found to be 0.549 s and 0.556 s in the X and Y directions for the inner sofa model, 0.546 s and 0.570 s for the corner sofa model, and 0.552 s and 0.564 s for the outer sofa model, respectively. These values indicate that the dynamic characteristics of the house models vary slightly depending on the plan configuration (Table 3).

Table 3. Dominant vibration periods

Model	Dominant vibration period of timber frame system (s)		Dominant vibration period of masonry stone system (s)		Dominant vibration period of house models (s)	
	x direction	y direction	x direction	y direction	x direction	y direction
Inner sofa	0.765	0.805	0.228	0.185	0.549	0.556
Corner sofa	0.770	0.821	0.232	0.218	0.546	0.570
Outer sofa	0.786	0.817	0.242	0.227	0.552	0.564

As a result of the numerical analyses, the structural elements subjected to the highest stress levels in each house model were identified (Figure 6) and evaluated based on the calculated internal force demands. In this context, the main beams, secondary beams, and struts corresponding to the maximum moment, shear force, and axial force values at each floor level were determined for the three plan configurations. The stresses developed in these elements were subsequently calculated using the analytical formulations presented in this study, allowing a comparative evaluation of the structural response of the different plan typologies.

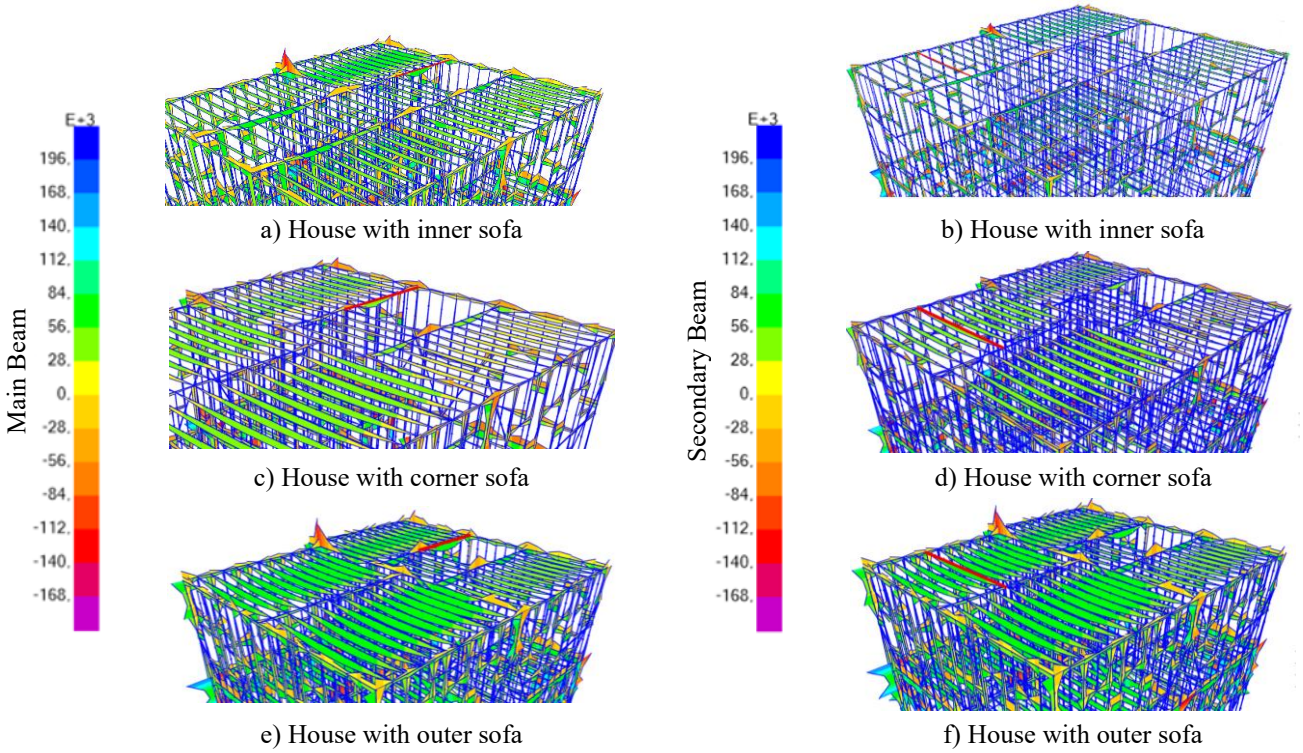


Figure 6. Beams with maximum bending moments

The strength and serviceability performance of the beam systems was evaluated for the inner sofa, corner sofa, and outer sofa plan configurations. The results indicate that plan typology influences both stress distribution and deformation behavior. For the main beams at the ground-floor level, all configurations exceed the allowable limits for bending stress, shear stress, and deflection. Among the models, the corner sofa configuration exhibits the highest structural demand, reaching a maximum deflection of 22.5 mm, a shear stress of 2.35 MPa, and a bending stress of 20.25 MPa. In contrast, the outer sofa configuration produces comparatively lower demand values at this level (15.5 mm, 1.55 MPa, and 13.97 MPa, respectively). At the upper floors,

bending and shear stresses generally remain within allowable limits; however, excessive deflections are still observed. The outer sofa model exhibits the highest bending stress on the second floor (15.87 MPa) and the largest main-beam deflection (17.6 mm). Similar trends are observed for the secondary beams. While the ground-floor beams fail to satisfy bending and deflection requirements, most upper-floor secondary beams remain within acceptable limits. Nevertheless, the corner and outer sofa configurations generate substantially greater deformations than the inner sofa model. For example, first-floor secondary beam deflections reach 21.8 mm in both the corner and outer sofa configurations, compared to only 5.2 mm in the inner sofa model. Overall, the findings demonstrate that sofa-based plan typology affects the load-transfer mechanism and stiffness distribution of the structural system. The corner sofa configuration generally results in higher stress concentrations, whereas the outer sofa configuration exhibits greater deformation demands. In contrast, the inner sofa model presents a more balanced structural response. The detailed results are summarized in Table 4. These observations are also consistent with recent numerical studies indicating that plan configuration plays an important role in the seismic behavior of historic timber-masonry and masonry buildings [3,34]. However, unlike previous investigations that primarily focused on the seismic assessment of individual historic buildings, the present study comparatively evaluates representative sofa-based plan typologies developed under identical modelling conditions, thereby enabling a direct comparison of the influence of plan configuration on structural response. The comparative trends identified in the present study are compatible with previously reported numerical investigations on traditional timber-masonry structures. Jiménez and Pelà [34] proposed a modelling methodology in which simplified numerical models were calibrated using benchmark experimental investigations before being applied to existing heritage buildings. Although the present study did not include direct experimental calibration, the adopted modelling philosophy similarly relies on representative material properties and established numerical modelling procedures reported in the literature. Within this framework, the observed differences among the investigated plan typologies should primarily be interpreted as comparative indicators of structural behavior rather than exact predictions of the seismic response of individual buildings. It should also be noted that these comparative trends were obtained within the framework of linear elastic analysis. Consequently, nonlinear phenomena such as masonry cracking, stiffness degradation, timber joint nonlinearity, and energy dissipation were beyond the scope of the present study and may influence the actual seismic behavior of historic timber-masonry buildings.

Table 4. Strength and deflection checks on main and secondary beams

Beam Type	Model	Ground floor			First-floor			Second-floor		
		Deflection (f) (mm)	Shear stress (τ) (MPa)	Bending stress (σ) (MPa)	Deflection (f) (mm)	Shear stress (τ) (MPa)	Bending stress (σ) (MPa)	Deflection (f) (mm)	Shear stress (τ) (MPa)	Bending stress (σ) (MPa)
Main Beams	Inner sofa	21.7	2.28	19.58	16.5	1.55	14.85	13.0	0.76	11.74
	Corner sofa	22.5	2.35	20.25	16.8	1.65	15.12	13.2	0.83	11.89
	Outer sofa	15.5	1.55	13.97	20.7	0.94	18.64	17.6	1.04	15.87
Secondary Beams	Inner sofa	15.8	1.02	14.21	5.2	0.25	4.71	5.5	0.26	4.92
	Corner sofa	26.5	1.32	11.70	21.8	0.36	9.61	22.8	0.38	10.05
	Outer sofa	27.4	1.36	12.10	21.8	0.36	9.61	22.8	0.38	10.05

The compressive stresses obtained for the timber strut members were evaluated with respect to buckling-related stress demands. As presented in Table 5, the calculated compressive stresses at the first-floor level are relatively close for all sofa configurations, varying between 22.32 MPa and 22.99 MPa. The outer sofa model exhibits the highest compressive stress, followed by the corner sofa and inner sofa configurations. At the second-floor level, the stress values decrease significantly, ranging from 5.92 MPa to 6.47 MPa. Similar to the first-floor results, the outer sofa configuration produces the highest compressive stress, whereas the corner sofa model exhibits the lowest value. Overall, the results indicate that the compressive stress distribution in the strut members is only slightly affected by sofa-based plan typology, although the outer sofa configuration tends to generate marginally higher compression demands than the other models.

Table 5. Stress control in struts under buckling effect

Model	Compressive stress (σ) (MPa)	
	First-floor	Second-floor
Inner sofa	22.32	6.10
Corner sofa	22.76	5.92
Outer sofa	22.99	6.47

To provide a normalized engineering assessment of the structural performance, demand-to-capacity (D/C) ratios were additionally calculated for the critical timber structural members. The D/C ratios were obtained by comparing the calculated structural demands with the corresponding allowable stress and serviceability limits specified in TS 647 (Design and Construction Rules for Timber Structures). Since these ratios are dimensionless, they provide a consistent basis for comparing the structural performance of the investigated plan typologies irrespective of the units adopted in the structural analyses. The calculated D/C ratios are presented in Table 6.

Table 6. Demand-to-capacity (D/C) ratios of critical timber structural members based on TS 647 allowable design limits

Structural Member	Storey	Criterion	Inner Sofa	Corner Sofa	Outer Sofa
Main Beam	Ground floor	Deflection	2.33	2.42	1.67
		Shear	2.58	2.66	1.76
		Bending	1.54	1.59	1.10
	First floor	Deflection	1.77	1.81	2.23
		Shear	1.76	1.87	1.06
		Bending	1.16	1.19	1.46
	Second floor	Deflection	1.40	1.42	1.89
		Shear	0.86	0.94	1.18
		Bending	0.92	0.93	1.24
Secondary Beam	Ground floor	Deflection	1.70	2.85	2.95
		Shear	1.16	1.50	1.54
		Bending	1.11	0.92	0.95
	First floor	Deflection	0.56	2.34	2.34
		Shear	0.28	0.41	0.41
		Bending	0.37	0.75	0.75
	Second floor	Deflection	0.59	2.45	2.45
		Shear	0.29	0.43	0.43
		Bending	0.39	0.79	0.79
Timber Strut	First floor	Compression	2.07	2.11	2.13
	Second floor	Compression	0.57	0.55	0.60

The D/C ratios indicate that the ground-floor main beams experience the highest utilization levels among the investigated timber members, particularly with respect to bending, shear, and serviceability criteria. The first-floor timber struts also exhibit comparatively high compression utilization ratios, whereas most second-floor beam members remain closer to the allowable limits. These normalized indicators are consistent with the stress and displacement results and provide a clearer engineering comparison of the structural performance of the investigated plan typologies. Accordingly, the D/C ratios should be interpreted within the framework of allowable stress design and are intended to provide a normalized comparison of the investigated structural models rather than a prediction of actual structural safety.

The displacement values obtained for the inner sofa, corner sofa, and outer sofa configurations are presented in Table 7. The comparison indicates that the arrangement of the plan has a noticeable effect on the global deformation response of the buildings. At the ground-floor level, the highest displacement values are observed in the outer sofa model, reaching 0.880 cm in the X direction and 0.881 cm in the Y direction. The corner sofa configuration generally exhibits the lowest displacement demands. A comparable trend is evident at the upper floors, where the outer sofa model attains the maximum displacement values of 7.099 cm and 7.316 cm in the X and Y directions, respectively. These findings support the assumption that plan organization influences the global lateral stiffness of traditional timber-masonry buildings. Although the numerical models were developed using simplified material properties and idealized connection assumptions, the consistent modelling framework adopted for all prototype models provides a reliable basis for comparing the relative influence of different plan typologies.

Table 7. Displacement distribution and interstory drifts of the house models

Model	Ground floor displacement Δ_1 (cm)		First-floor displacement Δ_1 (cm)		First-floor interstory drift u_1 (cm)		Second-floor displacement $\Delta 2$ (cm)		Second-floor interstory drift u_2 (cm)	
	x direction $\Delta^{(x)}{}_1$	y direction $\Delta^{(y)}{}_1$	x direction $\Delta^{(x)}{}_1$	y direction $\Delta^{(y)}{}_1$	x direction $u^{(x)}{}_2$	y direction $u^{(y)}{}_2$	x direction $\Delta^{(x)}{}_2$	y direction $\Delta^{(y)}{}_2$	x direction $u^{(x)}{}_2$	y direction $u^{(y)}{}_2$
Inner sofa	0.783	0.368	5.579	5.345	4.796	4.626	6.705	7.075	1.909	2.449
Corner sofa	0.816	0.290	5.604	5.334	4.788	4.882	6.702	7.193	1.914	2.311
Outer sofa	0.880	0.881	5.829	5.501	4.949	4.866	7.099	7.316	2.150	2.450

Variations among the plan typologies are also reflected in the interstory drift responses. The largest drift demands at the first-floor level occur in the outer sofa and corner sofa configurations, whereas the drift values calculated for the second floor remain relatively close to each other. The results suggest that the outer sofa layout is associated with increased deformation demand under seismic loading, while the corner sofa configuration generally demonstrates a more restrained lateral response (Table 7).

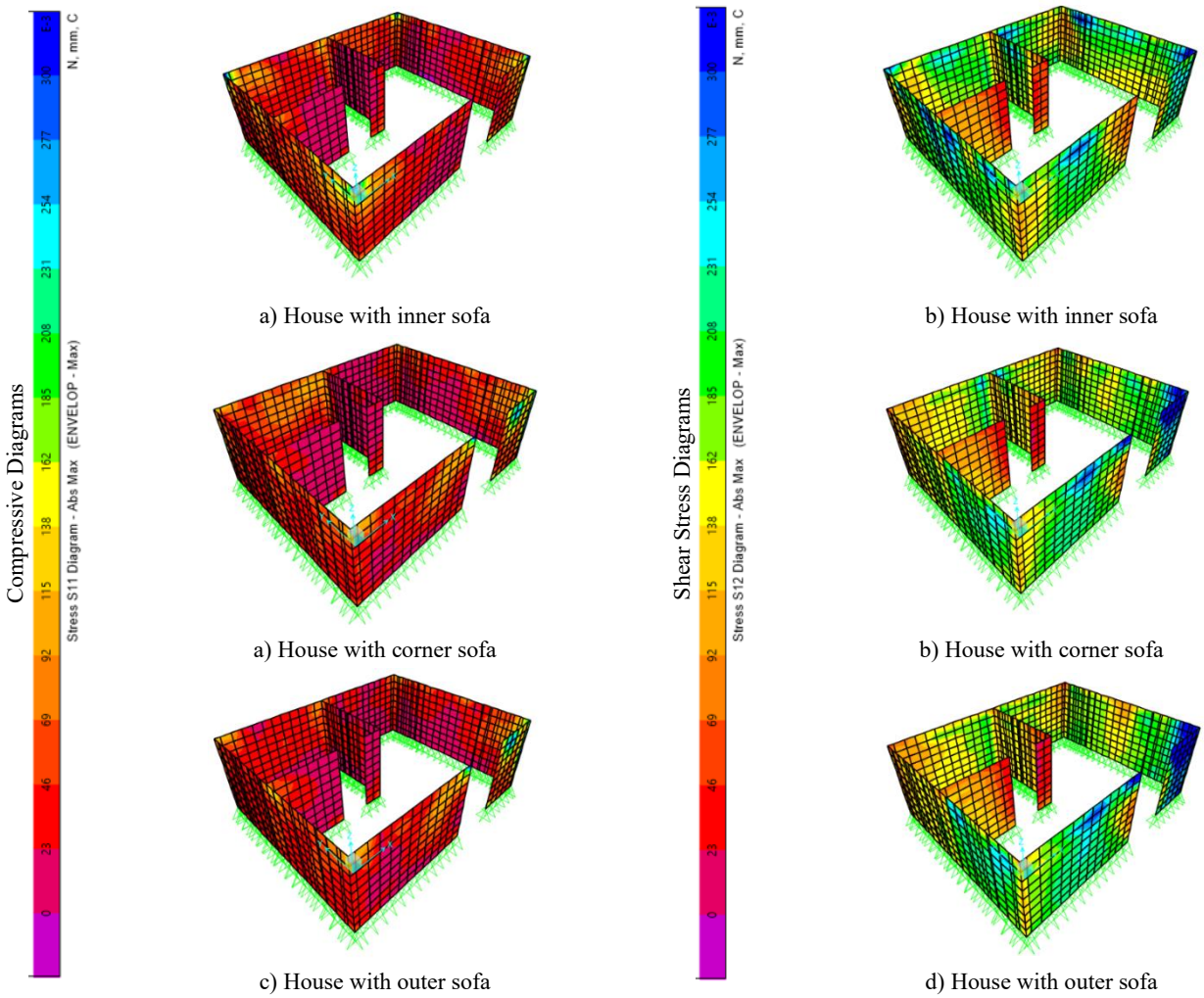


Figure 7. Compressive and shear stress diagrams of the house models

Following the modal analyses, the compressive and shear stresses developed in the masonry walls were evaluated and compared with the allowable limits specified by the Turkish Seismic Code. The stress distributions obtained from the numerical models are illustrated in Figure 7.

In all plan configurations, the highest stress concentrations occur along the exterior masonry walls and particularly near the corner regions, where seismic forces are transferred and accumulated. By contrast, the interior walls generally exhibit lower stress levels. Similar distribution patterns are observed in both the compressive and shear stress diagrams, indicating that the critical stress regions are primarily controlled by the overall geometry and load-transfer mechanism of the structural system.

The results presented in Table 8 demonstrate that the masonry wall stresses vary according to sofa-based plan typology. The outer sofa configuration produces the highest compressive stress (0.52 MPa), followed by the corner sofa (0.47 MPa) and inner sofa (0.37 MPa) models. In contrast, the maximum shear stress is obtained in the inner sofa model (0.30 MPa), while the corner and outer sofa configurations exhibit slightly lower values (0.27 MPa). The evaluation of the shear capacity utilization ratio reveals that all models exceed the allowable capacity, indicating inadequate shear resistance of the masonry wall system under the considered loading conditions. The highest utilization ratio is observed in the outer sofa model (189.07%), whereas the inner sofa model exhibits the lowest value (122.13%). These findings suggest that sofa-based plan organization significantly influences the stress demand imposed on masonry walls, with the outer sofa configuration representing the most critical case in terms of wall performance under seismic loading.

Table 8. Masonry wall stresses and shear capacity utilization ratios of the house models

Model	Compressive stress (σ) (MPa)	Shear stress (τ) (MPa)	Shear capacity utilization ratio (%)
Inner sofa	0.37	0.30	122.13
Corner sofa	0.47	0.27	174.86
Outer sofa	0.52	0.27	189.07

4. Discussion

The comparative analyses performed on the inner sofa, corner sofa, and outer sofa structural models demonstrate that plan typology influences the seismic response of traditional timber-masonry houses. Although the three models possess identical material properties, structural systems, and story configurations, differences in spatial organization result in variations in dynamic behavior, deformation demands, and stress distribution patterns. These general behavioral trends are consistent with previous numerical investigations on traditional timber-masonry buildings, which have shown that differences in plan configuration and stiffness distribution influence global seismic response [12,30]. It should also be emphasized that the observed differences among the investigated plan typologies were obtained within the framework of linear elastic analysis. Therefore, the identified trends represent differences in the elastic structural response of the prototype models. The actual seismic behavior of historic timber-masonry buildings may be influenced by nonlinear phenomena such as masonry cracking, stiffness degradation, local failure of timber joints, and energy dissipation mechanisms, which were beyond the scope of the present study.

The modal analysis results indicate that the dominant vibration periods of the models are relatively close to each other, varying between 0.546 s and 0.552 s in the X direction and between 0.556 s and 0.570 s in the Y direction. These findings suggest that plan typology has a limited influence on the global dynamic characteristics of the buildings. Nevertheless, the observed differences confirm that variations in spatial arrangement and load-bearing element distribution slightly modify the stiffness characteristics of the structural system.

The displacement analyses reveal a more pronounced influence of plan configuration on structural response. Among the investigated models, the outer sofa configuration exhibits the highest lateral displacement values at both floor levels, reaching 7.099 cm in the X direction and 7.316 cm in the Y direction at the second floor. Similarly, the largest interstory drift values are generally observed in the outer sofa model. These results indicate that the outer sofa configuration possesses comparatively lower lateral stiffness and is therefore more susceptible to seismic deformation demands. In contrast, the corner sofa model generally demonstrates lower displacement demands and a more favorable deformation performance. Despite the observed differences among the plan configurations, the calculated interstory drift values remain within the allowable range adopted for the structural assessment. A comparable trend has been reported in previous investigations of traditional timber and timber-masonry structures, where deformation demands increased without resulting in excessive drift ratios [12,45,46].

The stress analyses of the timber structural members further highlight the influence of plan typology. The corner sofa configuration produces the highest bending and shear stresses in the ground-floor main beams, whereas the outer sofa configuration exhibits greater deformation demands in the upper-floor beam systems. The secondary beams of the corner and outer sofa models also experience significantly larger deflections than those of the inner sofa model. These findings indicate that the distribution of timber structural elements associated with different sofa arrangements affects the transfer of seismic forces within the structural system.

The normalized D/C ratios further confirm that the observed differences among the investigated plan typologies are primarily associated with variations in load distribution and global stiffness rather than with changes in material properties or structural dimensions, which were kept identical in all numerical models.

The compressive stresses calculated for the timber strut members show relatively small variations among the models. The maximum compressive stress is observed in the outer sofa configuration, while the inner sofa model exhibits the lowest values. This result suggests that plan typology has a limited influence on the axial force distribution of vertical timber members when compared with its effect on beam behavior and lateral deformation demands. A similar tendency has been reported in previous studies, where the axial stress distribution in vertical timber members was found to be less sensitive to plan configuration than the deformation and stress demands observed in beam and wall systems [12,30].

The masonry wall analyses reveal more significant differences between the plan configurations. The outer sofa model produces the highest compressive stress (0.52 MPa) and the highest shear capacity utilization ratio (189.07%), indicating the most critical wall performance among the investigated models. Although the inner sofa model exhibits the highest shear stress value (0.30 MPa), its overall wall demand remains lower than those of the corner and outer sofa configurations. The concentration of stresses along exterior wall regions observed in all models confirms the important role of wall geometry and load-transfer mechanisms in the seismic behavior of traditional timber-masonry houses.

Overall, the results demonstrate that sofa-based plan typology affects the seismic performance of traditional Safranbolu houses by modifying stiffness distribution, deformation characteristics, and internal force transfer mechanisms. Among the investigated configurations, the outer sofa model generally represents the most critical structural case, whereas the inner sofa model exhibits a comparatively more balanced structural response.

The comparative findings obtained in the present study are consistent with recent numerical investigations on traditional timber-masonry buildings. Previous studies have demonstrated that reliable numerical models for historic timber-masonry structures can be established by adopting representative material properties and modelling assumptions supported by experimental evidence available in the literature, particularly when direct testing of protected heritage buildings is not feasible [34]. Likewise, recent research has emphasized that numerical modelling has become an effective approach for evaluating the seismic behavior of historic structures under conservation constraints, provided that the modelling assumptions are appropriately justified [3]. Within this context, the present study adopts the same general modelling philosophy and focuses on the comparative influence of plan typology rather than the exact prediction of the behavior of a specific historic building. Accordingly, the adopted modelling assumptions should be interpreted within the framework of comparative structural assessment. Rather than reproducing the exact seismic behavior of a specific historic building, the numerical models were developed to evaluate the relative influence of plan typology under identical modelling conditions, an approach commonly adopted in recent studies on historic timber-masonry structures.

One of the limitations of the present study is the absence of direct experimental validation of the numerical models. Owing to the conservation status of traditional Safranbolu houses, destructive material testing and in-situ structural investigations could not be performed. Consequently, the numerical models were established using representative material properties and modelling assumptions derived from previously published experimental and numerical investigations on comparable timber-masonry structures, an approach that has been widely adopted in the structural assessment of protected historic buildings where destructive testing is not feasible [12,44,45]. Recent studies have also demonstrated that combining experimental observations with numerical simulations provides a more reliable basis for validating structural models developed for historic masonry and timber-masonry buildings [47]. In addition, timber-timber and timber-masonry connections were represented using simplified connection idealizations intended to reproduce the global structural behavior rather than the detailed mechanical response of individual joints. Consequently, local connection slip, semi-rigid interaction effects, and localized joint failures were not explicitly simulated, which should be considered when interpreting the numerical results. Although this approach does not eliminate all sources of uncertainty, it represents a widely accepted methodology in the structural assessment of heritage buildings where intervention is restricted. Recent experimental studies have further demonstrated the importance of validating numerical models through comparison with laboratory observations in order to improve confidence in the predicted structural response. Although such validation was beyond the scope of the present study because of conservation restrictions, it represents an important direction for future investigations on traditional timber-masonry structures [47]. Furthermore, because all prototype models were developed using identical material properties, plan configurations, loading conditions, and modelling assumptions, the observed differences in seismic response can reasonably be attributed to plan typology rather than inconsistencies in the modelling strategy.

The present findings should therefore be interpreted as comparative indicators of structural behavior rather than exact predictions of the seismic performance of individual historic buildings. Within this framework, the objective of the study is to identify the relative influence of plan typology under controlled modelling conditions. Future studies integrating ambient vibration measurements, material characterization, and nonlinear numerical calibration would further improve the reliability of the proposed modelling approach and provide additional validation for the observed behavioral trends.

These findings are consistent with the numerical modelling approach reported by Meriç [30], who emphasized that modelling assumptions governing the timber-masonry interaction significantly influence the global structural response. Similarly, Kaplan [12] reported that the spatial arrangement of load-bearing members affects stiffness distribution and deformation behavior in traditional timber houses. The present study extends these observations by demonstrating that sofa-based plan typology alone can produce noticeable differences in displacement and stress distribution even when all other structural parameters remain unchanged.

5. Conclusions

This study investigated the influence of plan typology on the seismic behavior of traditional timber-masonry house models derived from Safranbolu residential architecture. Three representative structural models corresponding to inner sofa, corner sofa, and outer sofa plan configurations were developed and analyzed using the finite element method. To isolate the effect of plan typology, all models were defined with identical material properties, structural systems, and geometric characteristics.

Based on the analytical results, the following conclusions can be drawn:

- The dominant vibration periods of the models are relatively similar, ranging between 0.546-0.552 s in the X direction and 0.556-0.570 s in the Y direction. These results indicate that plan typology has only a limited influence on the global dynamic characteristics of the structures.
- The outer sofa configuration exhibits the highest displacement and interstory drift values. The maximum lateral displacements reach 7.099 cm and 7.316 cm in the X and Y directions, respectively, indicating comparatively lower lateral stiffness and greater deformation demands.
- The corner sofa configuration generates the highest bending and shear stresses in the ground-floor main beams, while the outer sofa model produces larger deformation demands in the upper-floor beam systems. The inner sofa model generally exhibits a more balanced stress distribution and lower deformation levels.
- The compressive stresses in the timber strut members vary only slightly among the investigated plan configurations. This finding suggests that plan typology has a relatively limited effect on the axial behavior of vertical timber elements.
- The masonry wall analyses indicate that the outer sofa configuration produces the highest compressive stress (0.52 MPa) and the highest shear capacity utilization ratio (189.07%). All models exceed the allowable shear capacity, demonstrating that masonry wall performance represents one of the most critical aspects of the structural system under seismic loading.
- The stress distributions obtained from the numerical models reveal that critical stress concentrations occur primarily along the exterior masonry walls and corner regions, where seismic forces are transferred and accumulated.

The results demonstrate that plan typology plays an important role in the seismic performance of traditional timber-masonry houses. Variations in sofa organization influence the stiffness distribution, deformation demands, and stress concentrations within the structural system. Among the investigated configurations, the outer sofa model exhibits the most unfavorable seismic response, whereas the inner sofa model presents a comparatively more balanced structural behavior. These findings may contribute to future assessment, conservation, and strengthening studies concerning traditional Safranbolu houses and similar timber-masonry residential heritage structures.

Finally, the findings of this study should be interpreted within the limitations associated with comparative numerical modelling. Because the investigated buildings are protected cultural heritage assets, direct material characterization and experimental validation were not feasible. Similar limitations have been acknowledged in recent studies on historic timber-masonry structures, where direct experimental testing of existing buildings was not feasible and numerical models were developed using material properties and modelling assumptions derived from previous experimental investigations [34]. Consequently, representative material properties and modelling assumptions derived from previous experimental and numerical studies were adopted throughout the analyses. Although this approach is widely accepted for the structural assessment of historic buildings where destructive testing is not permitted, further validation would improve the reliability of the proposed modelling strategy. Future research should focus on experimental calibration and validation of representative timber-masonry structural models through laboratory testing, ambient vibration measurements, detailed material characterization, and nonlinear numerical simulations capable of representing cracking, stiffness degradation, connection nonlinearity, and energy dissipation mechanisms.

Conflict of Interest Statement

The authors declare no conflict of interest.

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