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Structural assessment of traditional stone-timber houses in Turkey

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Subject review

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This study mainly focuses on the performance of historical stone-timber structures. The finite element method (FEM) is used to analyse structural performance of such buildings in order to predict possible damage mechanisms and seismic vulnerability. Traditional Şirince houses in İzmir (Turkey) were selected for the analysis. Results obtained show that the critical section of such combined structures is the transition zone between the ground level and upper floors. Furthermore, the results indicate that the "rubble stone masonry and timber frame" of these combined structures is highly vulnerable to seismic action.

Key words:
historical structures, stone-timber structures, architectural heritage, finite element method

Pregledni rad

Fahriye H. Halicioglu, Ferit Cakir, Sevilay Demirkesen

Analiza konstrukcijskih svojstava povijesnih kameno-drvenih građevina

Rad je usmjeren na ponašanje povijesnih građevina izvedenih u kombinaciji kamenih zidova i drvenih okvira. Metodom konačnih elemenata analizirana je izvedba takvih građevina s ciljem predviđanja mogućih mehanizama razaranja i osjetljivosti na potres. Radi se o tradicionalnim kućama u naselju Sirince u Izmiru (Turska). Rezultati analize pokazali su da je kritični presjek takve kombinirane građevine prijelazna zona, između prizemlja i kata. Također je ustanovljeno da su kameni zidovi i drveni okviri u takvim konstrukcijama vrlo osjetljivi na potres.

Ključne riječi:
kombinirane povijesne građevine, kameni zid, drveni okvir, graditeljska baština, metoda konačnih elemenata

Übersichtsarbeit

Fahriye H. Halicioglu, Ferit Cakir, Sevilay Demirkesen

Tragwerksbewertung traditioneller Häuser aus Stein und Holz in der Türkei

Die vorliegende Arbeit befasst sich mit dem Verhalten historischer Bauten, die durch die Verknüpfung von Steinmauerwerk und Rahmenkonstruktionen aus Holz entstanden sind. Die Ausführung solcher Bauten ist mittels der Finite-Elemente-Methode analysiert, um mögliche Beschädigungsmechanismen und die seismische Vulnerabilität zu ermitteln. Dazu sind ausgewählte traditionelle Fachwerkhäuser in der Siedlung Sirince in Izmir (Türkei) analysiert worden. Die gegebenen Resultate zeigen, dass kritische Querschnitte dieser kombinierten Bauwerke sich in der Übergangszone zwischen dem Erdgeschoss und dem Stockwerk befinden. Außerdem ist eine hohe Empfindlichkeit dieser Konstruktionen gegenüber Erdbebeneinwirkungen festgestellt worden.

Schlüsselwörter:
historische Bauten, Bauten aus Mauerwerk und Holz, Architekturerbe, Finite-Elemente-Methode

1. Introduction

Historical structures showing aspects of high architectural interest are identified as cultural assets that should be preserved for posterity. Over time, some of these structures have disappeared while some have been preserved to this day. However, they have been subjected to structural deterioration during their lifetime for several reasons. It is a well-known fact that seismic forces may cause considerable damage to architectural heritage, but may also inflict losses in terms of historical, cultural, and architectural values. Seismic effects are the most important risk factors that threaten structural safety of structures. In fact, the seismic resistance of a structure depends on its geometrical configuration, structural materials and properties, interaction between structural elements, workmanship, and dynamic performance [1, 2]. On the other hand, inadequate or poor-quality interventions may result in significant structural irregularities. As a result of this, non-uniform structural behaviour might negatively affect structural integrity and cause severe damage to the entire structure. Therefore, this is considered to be another crucial threat to which architectural heritage is exposed. Architects and structural engineers involved in the rehabilitation and maintenance issues need to adequately recognize structural performance of historical structures so as to be able to generate compatible solutions in terms of original structural properties. Architects and engineers are mainly faced with the lack of significant information about structural analyses of historical structures, such as load bearing limitations and structural behaviour under seismic load. Hence, if seismic performance analyses are not made during the rehabilitation and maintenance of historical structures, this may lead to partial or complete collapse of these heritage structures, even under a moderate seismic activity. Therefore, the main focus of this study is the structural performance of historical combined "stone masonry and timber frame" structures in earthquake-prone areas of Turkey.

Masonry and timber frames are predominant forms of historical structural systems. Moreover, they are regarded as the earliest examples of historical heritage because of the use of natural materials and primitive construction techniques. Thus, their structural properties play an important role in the determination of their structural performance. There are different types of masonry and timber frame structures in the world. In addition, it has been observed that these structures have similar structural characteristics even though they were built under different conditions, both regionally and culturally. For example, timber framed with masonry infill (also generally known as half-timbered) is called "hımış" in Turkey, "pombaline" in Portugal, "half-timbered" in England, "fachwerk" in Germany, "colombage" in France, "dhajji-dewari" in India, "casa baraccata" in Italy, "telar de medianería" in Spain, and "bahareque" in parts of Central and South America [3, 4]. According to past studies, structural performance of traditional structures was mostly analysed by focusing on either solid masonry structures or timber frame with masonry infill structures [5-16]. This study focuses on a different type of traditional structures, i.e. on combined structures that are mostly encountered in traditional Turkish houses. It should be noted here that Turkey is located in an earthquake prone region. One of the most distinctive features of such combined structures is that the entire structure is built using a combination of two-different structural systems with two different materials. In this type of combined structures, the stone and wood are used as structural materials and the entire structure consists of the ground floor, which is made of stone masonry, and the upper floors, which are timber framed. Moreover, timber framed walls are constructed without infill and are mostly coated with laths and lime plaster. This covering technique used in timber framed wall construction is called "bağdadi" in Turkish. This is another distinctive feature of the combined structure analysed in this study. However, it should be noted that different structural systems may reveal different structural behaviour when they are built together. Therefore, the main questions considered in this paper are the determination of structural performance of a combined structure, and identification of structural behaviour of combined structures under seismic load. These questions cannot be answered directly due to lack of necessary results that need to be obtained through examination of load bearing mechanisms and present condition, and through numerical analyses. In order to answer the above mentioned questions, the study aims to analyse structural performance of historical combined "stone masonry and timber frame" structures by considering seismic forces. In this scope, a two-phased study is conducted. In the first phase, structural features and structural deterioration of such combined structures are examined through in-situ observations in form of a case study, which is conducted in a historical locality situated in an earthquake prone zone in Turkey. In the second phase, a three dimensional (3D) numerical model is made to visualize behaviour of the entire structure under seismic effects. The most common original structural properties of the existing historical combined structures are used as direct references in this numerical modelling. The structure is then analysed by the FEM in order to detect damage mechanisms for the entire structure and its vulnerability to seismic forces.

Şirince Village located in the western part of Turkey was chosen as the case study area. The first reason is that the village is located in the area of the highest seismic activity in Turkey. Secondly, its two-storey traditional houses, more than 150 years old, are original examples of historical combined "stone masonry and timber frame" structures. Thirdly, even though traditional Şirince houses figure on the list of historical heritage sites of Turkish Republic, they risk losing their historical, cultural, and architectural values due to poor quality interventions or the lack of proper rehabilitation and maintenance. Thus, there is an urgent need to detect damage mechanisms and seismic vulnerability of structural systems used in these heritage houses, in order to enable their accurate preservation and rehabilitation. Unfortunately, there is scarce information on traditional Şirince houses due to insufficiency of the past earthquake damage records and original records concerning intervention and restoration works conducted on such houses. The information about the present condition of these heritage houses, the type of deterioration that has affected their structures and individual elements, may provide further information about the historical combined structures. Roca et. al. (2010) [17] point out that the factors linked with the history of structures have a significant influences on their structural performance. These factors may occur due to natural disasters (earthquake, flooding, fire...), material and structural properties, geometrical characteristics, time-dependent ageing/long-term decay, biological degradation, poor quality structural interventions, architectural alterations, etc. Thus, structural deterioration might be considered as a source of knowledge about structural performance of the structure. For example, performance observed during past earthquakes may be helpful for deriving information about seismic resistance of the structure [17]. Therefore, an additional analysis was performed in the first phase of the structural performance analysis conducted in the scope of this study. As stated above, this first phase of the study is an in-situ investigation relying on the visual analysis carried out by the authors in Şirince Village. Hence, visual signs of deterioration to traditional Şirince houses were examined and presented. A detailed description of structural features and architectural characteristics of these heritage houses are also presented in the beginning of the study to ensure better interpretation of visual signs of deterioration, and to accurately perform the structural performance analysis.

2. Traditional Şirince houses

Şirince is a village located in Selçuk, which is a district of Izmir Province in the western part of Turkey (Figure 1.a). There are numerous historical remains in the area around Şirince. This village is well known for its locational proximity to the ancient city of Ephesus and the House of the Virgin Mary (Figure 1.b). Şirince (meaning "pleasant" in Turkish) is a lively place with rich culture and abundant architectural heritage. Even though the history of Şirince dates back to the fourteenth century, the houses in this historical settlement reflect features of the nineteenth century. In the early twentieth century, the number of houses varied between 1100 and 1800 [18]. Since these houses are of considerable historical and architectural value, the village was listed in 1984 as a "historical site" by the Council for Preservation of Cultural and Natural Property of the Republic of Turkey operating within the Ministry of Culture and Tourism [19]. The decrease in the number of houses over time indicates that the village has lost most of its historical houses (Figure 2.a).

Şirince Village is characterised by a compact traditional atmosphere. The typology of its houses has been significantly affected by topographic, climatic, and geologic conditions. This historical settlement is interspersed with streets in accordance with the slope of the terrain (Figure 2.a). In recent years, traditional Şirince houses have been subjected to architectural alterations such as functional changes, which stem from the need to gain additional space for new commercial activities such as restaurants, shops, boarding houses, etc. (Figure 2.b).

Figure 1. Şirince Village: a) Location on map; b) its immediate surroundings - the ancient city of Ephesus and the House of the Virgin Mary (Edited from Google Maps, 2013)

Şirince has a typical Mediterranean climate, varying from warm, hot and dry in summer, to mild, cool and rainy in winter. Most parts of Turkey are located in earthquake-prone areas where many structures are vulnerable to earthquake action. Şirince Village is located in the highest seismicity zone of Turkey (Figure 3.), where seismic activity has been frequent and intense.

It should be noted that architectural characteristics of traditional houses, such as geometrical configuration, mass dimensions, façades, window and door openings, etc. are significantly affected by structural properties and locally available materials, and also by user needs, culture, socio-economic conditions, environmental conditions, and so on. The form of the houses is typically rectangular or L-shaped (Figure 4.a). The ground floor of traditional Şirince houses is generally used for service spaces, such as kitchen and storage. The rooms are designed as living spaces on the upper floors. As a rule, the height of the ground floor is bigger than the height of the upper floors. Windows and

Figure 2. Overview of Şirince Village: a) the streets; b) the shops in traditional Şirince houses (August 2013)

doors are wooden. Upper floors have more window openings than ground floors (Figure 4.b).

Şirince Village is mostly composed of two-storey houses, while one-storey houses are rarely seen. These one-storey houses are generally built of the solid-stone masonry. The thickness of the load-bearing walls varies from 40 cm to 60 cm. In addition, wooden lintels (called "lento" in Turkish) are placed over the windows and door openings. The lime plaster and lime wash are commonly used on the interior surfaces of walls. Rubble stone masonry walls do not show plastered rubblework on the exterior surfaces of the walls. The rubble stone surface has kept its originality.

The main structural system of traditional two-storey houses in Şirince consists of a combined system formed of rubble stone masonry and timber frame. According to structural configuration of this combined structural system, shown in Figure 5, these two-storey houses are generally composed of four main structural sections: stone masonry foundation, stone

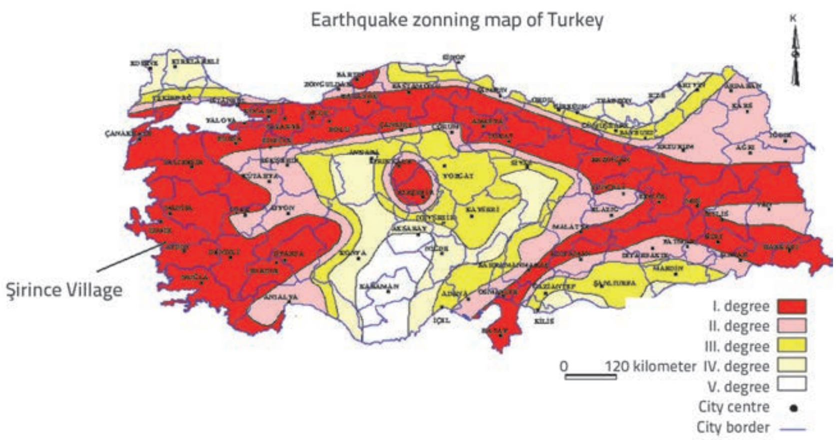

Figure 3. Seismic location of Şirince Village in accordance with the earthquake map of Turkey: 1st degree, the highest seismicity zone of Turkey, [20]

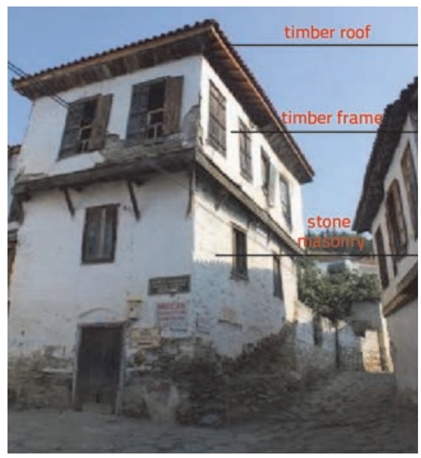

Figure 5. Structural configuration of a typical traditional two-storey Şirince house (August 2013)

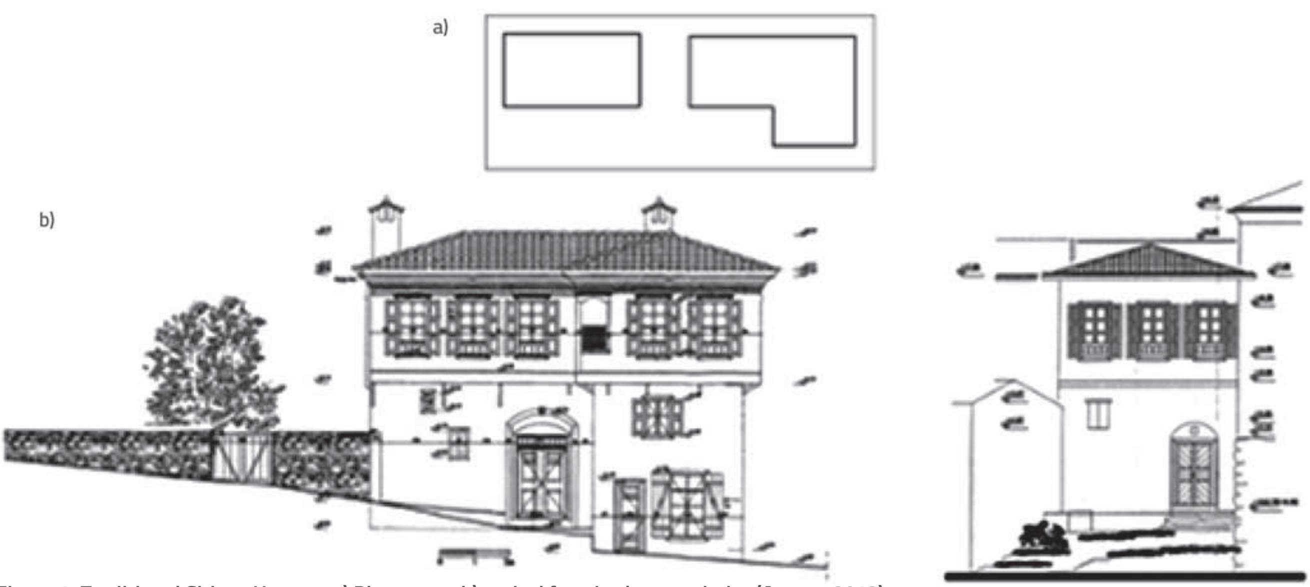

Figure 4. Traditional Şirince Houses: a) Plan types; b) typical façade characteristics (August 2013)

masonry ground floor, timber framed upper floor, and timber roof. Nevertheless, the houses with a basement floor may also be seen in Şirince. Foundations of these houses are generally made of rubble stone. However, it is not possible to provide a proper explanation of foundations of these houses because of the inadequacy of records concerning their construction details.
The timber-framed structure in the upper floor of traditional two-storey Şirince houses is typically composed of vertical structural timber elements (main posts and studs), horizontal timber beams, and diagonal bracing timber elements. Joints are significant structural elements of timber-framed structures.
All connections between timber elements are mostly made by nails at timber-framed upper floors of traditional Şirince houses. However, overlapping joints are also encountered in some cases. Main posts (nearly 10 cm x 10 cm in cross-section), located in corners, are simply joined by timber headings with nails. The span between these main posts is divided by studs (nearly 5 cm x 10 cm in cross-section) spaced at approximately 30 - 40 cm intervals. Diagonal bracing elements are also used for supporting the structural integrity of timber framed walls. In addition, these framed walls formed with structural timber elements are covered with wooden laths and lime plaster. This completes the wall structure for the upper floor. This kind of a traditional wall construction technique for timber-framed structures is called "bağdadi" in Turkish. The bağdadi (lath) is mainly used to cover walls, and for covering bottom sections of projections and eaves. The use of the original bağdadi technique is very common in Şirince. This is another distinctive structural feature of traditional Şirince houses. Wooden laths (nearly 2 cm x 4 cm in cross-section) are first horizontally nailed onto vertical structural timber elements (posts and studs) at very frequent intervals in order to cover empty spaces left between vertical and horizontal timber elements during the bağdadi procedure (Figure 6.). These timber laths are mostly placed at both the inner and outer wall surfaces. Generally, there is no infill between these surfaces. Nevertheless, the use of small rough pieces of rubble stones with lime or mud mortar may be observed, albeit rarely, as infill material. Finally, the lime plaster and lime wash are applied on these timber laths. These laths are therefore not visible from the outside.
Timber joists are placed on timber laced masonry walls of the ground floor at approximately 30 - 40 cm intervals for the timber framed upper floor construction. In addition, there is a projection, also known as cantilever (or "çıkma" in Turkish), at upper floors of traditional Şirince houses (Figure 7.). The projection braced with timber buttresses is more common than a simple projection without timber buttresses. The form of the projection is rectangular or triangular in shape because it is usually constructed according to the angle between the ground floor walls and the street. The projections are built by extending horizontal timber beams/timber sole plates and timber floor joists toward the outside of the walls.

3. Causes of damage to traditional Şirince houses

The damage to traditional Şirince houses is mostly due to degradation of structural elements and decay of structural materials. The main forms of degradation are the damage to structural elements, loss of material, and decrease in structural strength [21]. The structural condition of external load-bearing rubble stone masonry walls on the ground floor of these houses is generally poor. Some significant cracks were also discovered at external surfaces of these walls. These cracks are considered to be visual signs of structural deformations. In fact, cracks may occur due to several factors such as the soil settlement, temperature variations, excessive loads, and seismic effects. It was observed at these heritage houses that the cracks are located close to corners of rubble stone masonry walls, and that their orientation is generally vertical (Figure 8.). These cracks often appear at the top of the rubble stone masonry wall (or under the timber floor beam) and they propagate vertically towards the bottom of the wall.
Rubble stone masonry walls at the ground floor have been extensively exposed to material degradation (Figure 9.). Moreover, as illustrated in Figure

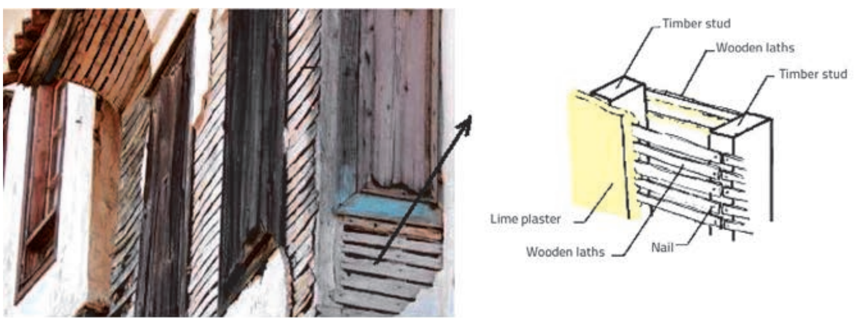

Figure 6. Bağdadi covering technique in timber framed structures of traditional Şirince houses: Wooden laths with lime plaster and lime wash (August 2013)

Figure 7. Examples of projections with timber buttresses in traditional Şirince houses (August 2013)

Figure 8. Vertical cracks at the corners and at external surfaces of the rubble stone masonry walls

Figure 9. Material degradation in rubble stone masonry walls of the ground floor of traditional Şirince houses

9., the flaking, powdering, swelling, dampness, and stains have been observed at external surfaces of these walls. The mortar between rubble stone units is partially eroded. The loss of this binding material caused the decrease of structural resistance of these walls. The greatest damage to these stone walls is concentrated near the bottom of the wall. In some cases, the effects of abrasion have also been observed on rubble stone units of these masonry walls.

One of façade walls of the timber-framed structure was partly demolished at the timber framed upper floor (Figure 10.). This partial collapse of the structure is not common and can only be seen in cases of the most severe damage to traditional Şirince houses (Figures 10.a and 10.b). This type of structural damage might stem from the out-of-plane behaviour of timber-framed walls, and from the sole use of nailed connections between timber elements of timber-framed walls at the upper floor. As shown in Figure 10.c, there are many irregular micro cracks in the plaster of timber-framed walls at the upper floor of these houses.

Figure 10. Examples of the most severe structural damage observed in the upper-floor timber framed structure of traditional Şirince houses: a) partial collapse at one of lateral timber framed walls; b) out-of-plane behaviour of timber framed walls; c) many irregular cracks on the surface of the plaster between openings in the upper floor; d) diagonal cracks under the bottom corner of a window opening; e) horizontal sliding damage at the floor level

Figure 11. Example of structural damage to a typical traditional Şirince house (August 2013)

Besides, diagonal cracks have also been observed (Figure 10.d). These diagonal cracks generally start at the bottom corners of the window openings and extend downward diagonally to the timber floor level. This type of cracking may result from shear stresses caused by lateral forces. Another important structural damage is the deterioration of horizontal timber beams (timber sole plates) placed on top of the rubble stone masonry walls. In some cases, structural damage in form of horizontal sliding has been registered, as illustrated in Figure 10.e.

The timber framed structure of the upper floor is connected to the stone masonry structure of the ground floor via horizontal timber

Figure 12. Distortion of horizontal timber element

Figure 13. Plaster damage on the surfaces of timber framed walls in the upper floors of traditional Şirince houses (August 2013)

Figure 14. Examples of roof deterioration in traditional Şirince houses

beams, which are placed along the top of stone masonry walls in traditional Şirince houses. In some cases, it causes disintegration of structural elements at the floor level even in case of very small displacements (Figure 11.). The detachment was observed between the horizontal timber element and the stone masonry wall. In addition, some cracks were observed along the entire length of stone masonry walls under horizontal timber beams. Also, distorted timber elements are rarely observed at the end of timber floor beams under the projections (Figure 12.).

After comparison of types of deterioration registered in these houses, it was established that the most common cause of deterioration is the loss of plaster (Figure 13.). Major plaster damage was mostly observed on the wooden laths in timber framed walls, and underneath the eaves. Lime plaster has partly detached from exterior surfaces of wooden laths.

Although biological decay of wood is not commonly seen in traditional Şirince houses, the discoloration and staining are extensively observed on wooden windows, door sills and wooden boards that are used for covering the bottom of eaves and projections. This type of decay in wooden boards is caused by the presence of rainwater

Figure 15. Typical examples of structural damage and material decay in traditional Şirince houses (August 2013)

on their surfaces and negative effects of sunlight. In fact, wooden boards underneath the eaves become wet mostly because of the lack of gutters on the roofs of these houses. The roof deterioration is also observed as the roof structure sagging, although it is not a deterioration commonly observed in these types of structures (Figure 14). In addition, the condition of the exterior lime wash is poor. The flaking and staining can be observed on wall surfaces. Most common instances of structural damage and material decay registered in traditional Şirince houses are shown in Figure 15.

4. Numerical model and finite element analysis

The structural conservation and restoration of historical structures has become increasingly important in recent years. The structural performance and load carrying mechanisms have to be evaluated effectively in order to determine structural protection requirements for these structures. It is very difficult to determine structural behaviour of such structures by means of common engineering methods. In this respect, masonry structures are especially complex and very difficult to analyse. Due to recent improvements in computer technology, FEM has become one of the most preferred methods for masonry structures. It is convenient for analysis of numerical models as these structures are highly complex namely because of their huge weight and the fact that they are made of several different engineering materials.

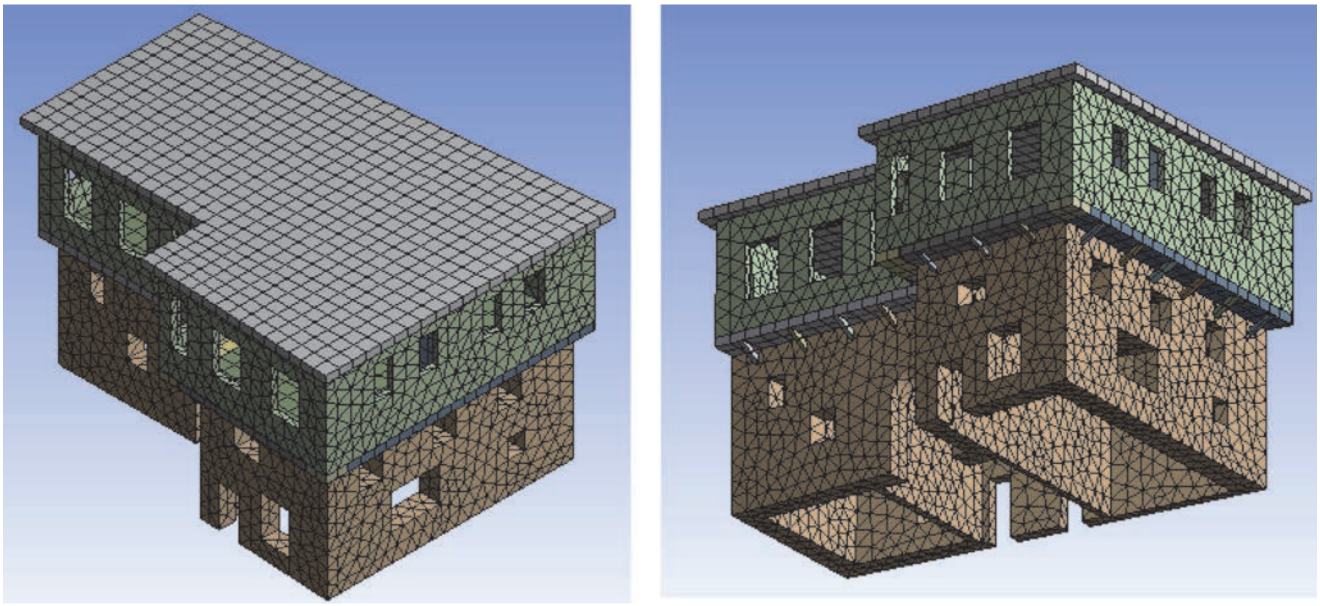

Figure 16. FEA of a typical traditional Şirince house

Table 1. Mechanical properties of materials [13, 23]

Material type	Elasticity modulus [kN/m^2]	Poisson ratio	Mass density [kg/m^3]
Stone	$4{,}0 \cdot 10^{-6}$	0,18	2500
Timber	$10{,}5 \cdot 10^{6}$	-	500

The FEM is a mathematical expression of physical structures. In other words, it is a method providing numerical solution to engineering problems. Therefore, this study essentially focuses on structural behaviour of a combined structure in Şirince with the use of FEA. For this purpose, a 3D model was developed based on the condition and geometrical constraints of the house. In this scope, a FEA program called ANSYS Workbench [22] was used to analyse the structure with SOLID186 elements, which have 20-noded quadratic hexahedrons, and three degrees of freedom (DOFs) per node. The 3D model consists of 42349 nodes and 13089 solid elements (Figure 16). Furthermore, the roof was neglected in order to enable easy interpretation of FEA results, but its mass was added to the model.

All numerical data used in the 3D model of the structure were generated in accordance with the restitution and restoration projects for historical structures. This paper deals mainly with solids and structures made of elastic materials. In addition, the paper considers only the problems of very small deformations, where the relationship between the deformation and load is linear. The purpose of the linear-elastic analysis is to correctly interpret the stresses and damage of the elastic phase and at initial levels. Hence, the linear elastic material behaviour is considered, and the stiffness degradation is ignored in this study. In addition, mechanical properties of materials are taken from values proposed in the literature, by careful consideration of past examinations and studies, because of the inability to take material samples and conduct tests (Table 1).

This study is specifically concerned with the static and dynamic analyses of the combined structure. The obtained analysis results are too complicated and therefore do not allow presentation of each node or element. For this reason, contour pictures and bars are used to present analyses results.

4.1. Static analysis

Masonry structures have large masses due to heavy construction materials. Dead loads consist of the fixed weight of structural members and the weight of any permanent fixtures attached to the structure (superimposed loads). Dead loads always remain on the structure and affect the structure throughout its lifetime. Furthermore, dead loads are static loads and these loads contribute to the stability of masonry structures [24, 16]. Thus, it is necessary to determine whether the structure is able to withstand the dead loads. Therefore, traditional Şirince houses were primarily analysed to define their load carrying capacity. Minimum principal stresses amount to about 7.373 MPa at the buttress timbers and they occur in the transition zone between the ground floor and the upper floor (Figure 17.). Maximum principal stresses amount to about 3.564 MPa and they occur above the top of the ground floor and at the upper floor façades. The maximum principal stresses also occur at the roof and at the edges of the windows (Figure 18.). Maximum displacements occur at the roof of the structure and amount to about 12.80 mm (Figure 19.).

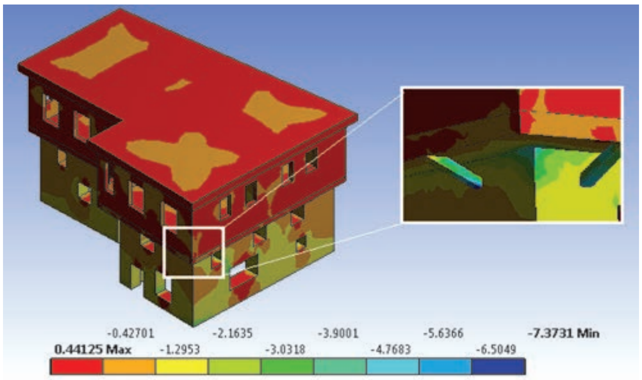

Figure 17. Minimum principal stress contours (MPa)

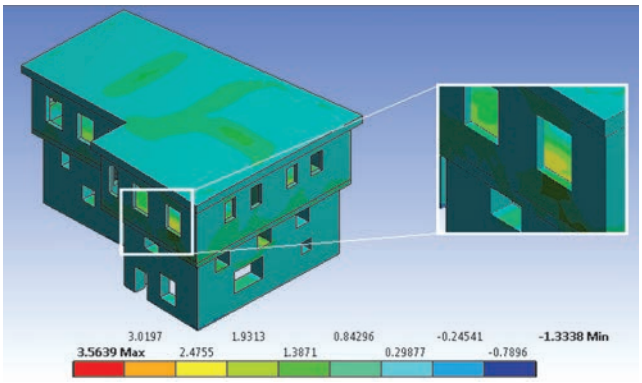

Figure 18. Maximum principal stres contours (MPa)

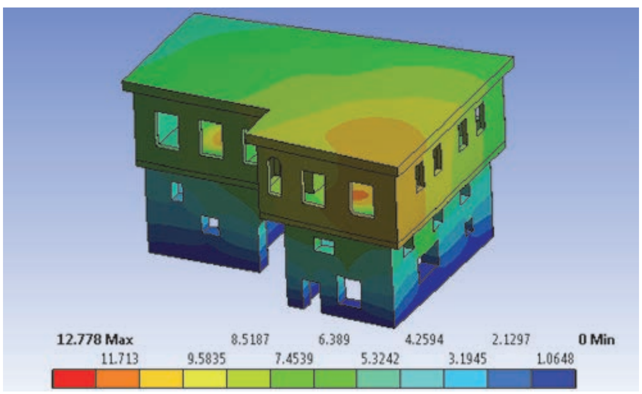

Figure 19. Maximum displacement contours (mm)

4.2. Modal analysis

Modal analysis was conducted in order to determine fundamental mode shapes and natural frequencies of the structure during free vibration [16]. The purpose of modal analysis is to obtain the maximum response of the structure in each of its important modes, which are then summed up in an appropriate manner [25]. Modal analysis of the structure included different modes of vibrations in combination. The Square-Root-of-Sum-of-Squares (SRSS) method was considered for 12 modes. Natural frequencies obtained through modal analysis are summarized in Figure 20. Figure 21 shows the mode shapes of the first four frequencies. According to modal analysis results, the first three modes occur as translational motions in x, z and y directions, respectively, and the fourth mode appears as the torsional motion only. Furthermore, all frequencies are below 5 Hz. The first frequency is close to 2.5 Hz which shows that the structure is adequately rigid in terms of seismic demand but, according to modal analysis results, the transition zone between the floors is the most precarious part of the structure.

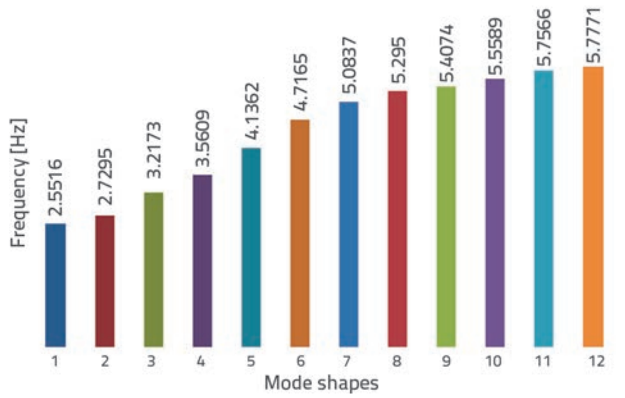

Figure 20. Frequencies obtained by modal analysis

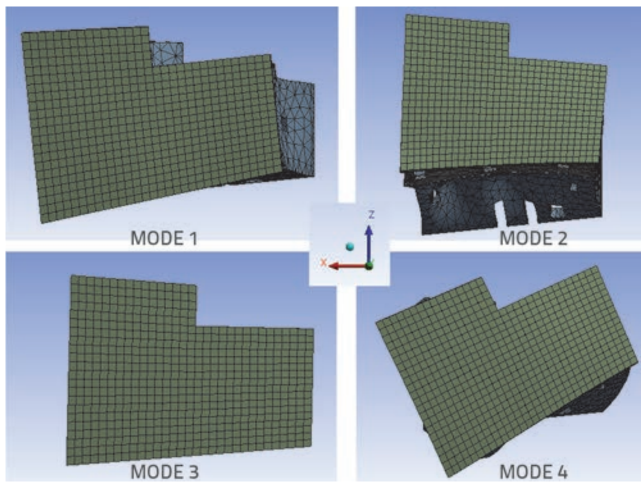

Figure 21. First four mode shapes and directions of the structure

4.3. Dynamic analysis

Masonry structures are vulnerable to earthquakes and seismic effects, which have been the most common reasons for collapse of masonry structures. Therefore, it is highly crucial to determine earthquake performance of masonry structures located in active seismic zones. According to Turkish Disaster and Emergency Management Presidency, Şirince is situated in a first-degree (the most dangerous) seismic zone in which the maximum ground acceleration is assumed to be 0.4 g [26]. Therefore, earthquakes constitute major problems for the Şirince houses. In dynamic analysis, the time history analyses were performed based on the East – West (E-W) component of Kocaeli earthquake that occurred on 17 August 1999 (Mw=7.4), [27]. The acceleration time history of Kocaeli earthquake is given in Figure 22.

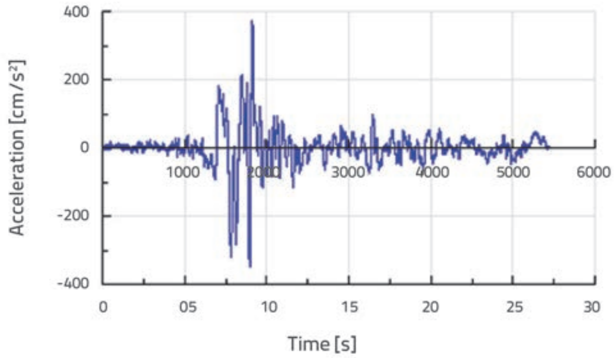

Figure 22. Surface accelerations recorded during Kocaeli earthquake [26]

The obtained maximum compression stresses are significantly more intense at lower parts of the structure during the earthquake. Maximum compression stress contours for the structure are shown in Figure 23. As can be seen in this figure, maximum compression stresses amount to about 9.78 MPa around and below of the entrance gates and buttress support. Minimum principal stress contours for the structure are shown in Figure 24.

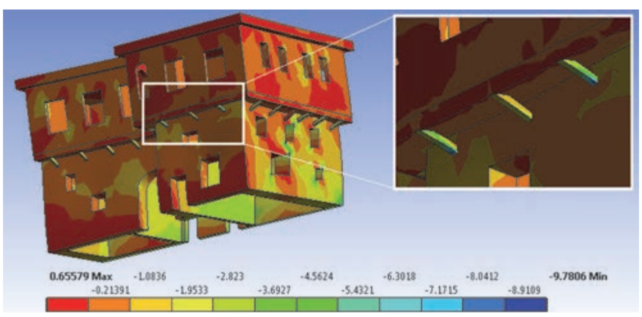

Figure 23. Minimum principal stress contours (MPa)

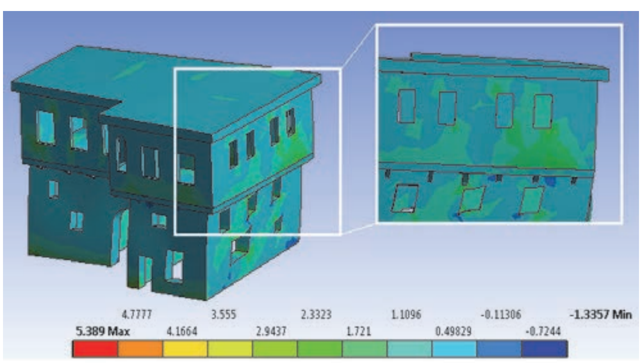

Figure 24. Maximum principal stress contours (MPa)

It was established that maximum principal stresses amount to about 5.389 MPa around the connection to the entrance gate, at window sides, and at upper parts of the entrance wall. Lateral displacement of about 28 mm was registered at the top of the roof (Figure 25.).

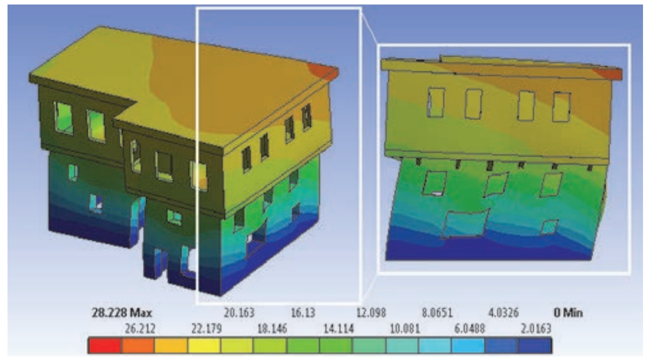

Figure 25. Maximum lateral displacement contours (mm)

5. Conclusion

This study focuses on historical combined "rubble stone masonry and timber frame" structures situated in Şirince Village, which is located in a seismically active zone of Turkey. The objective was to analyse damage mechanisms and seismic vulnerability of these houses. First a brief description of structural features and architectural characteristics of traditional Şirince houses is presented. This is followed by modelling one of the most typical traditional Şirince houses to visualize structural response of these houses to seismic forces. A 3D numerical model was prepared in order to show behaviour of the structure and its probable local and global weaknesses under seismic actions. The FEA is applied to predict possible damage mechanisms and seismic vulnerability in weak zones of the structure under expected seismic intensity.

The results indicate that the combined structure of traditional Şirince houses is highly vulnerable to seismic actions. The FEA results show good agreement with findings obtained during in-situ investigations. Thus, the FEA results have revealed that the critical section for the Şirince structure is the transition zone between the ground floor and upper floors. The most critical stresses calculated during the static analysis occurred at the timber buttress supports and slabs. Results of the analyses show that the dynamic interaction between the buttress supports and walls plays an important role in the dynamic behaviour of the structure. It may be considered as risky in terms of creating structural stability problems. The results also show that structural problems and damage to Şirince houses generally occur in the critical stress parts, and these results prove accuracy of the numerical approach.

This study has also resulted in some recommendations for the preservation and rehabilitation of traditional Şirince houses. In fact, some major issues requiring further analyses have been revealed. The following recommendations and issues provide further research opportunities. In these heritage houses, visual signs of crack damage are observed at different levels ranging from micro cracks in the plaster to partial collapse of the structure. These types of structural damage and material decay may considerably affect seismic resistance of the entire structure. For this reason, the structural damage and material decay must be examined in greater detail by means of non-destructive diagnostic techniques. Furthermore, the connections present in combined structural system of traditional Şirince houses need to be analysed in more detail. The timber-framed part of this type of combined structure helps to reduce the weight of the entire structure and provide more flexibility, Findings obtained from in-situ investigations show that the timber framed structure of the upper floor has suffered greater structural damage than the rubble stone masonry of the ground floor. This might be caused by the exclusive use of nailed connections between timber elements and the absence of adequate connections at the junction of the rubble stone masonry structural system of the ground floor with the timber frame structural system of the upper floor. Therefore, special care must be paid to structural rehabilitation of connections in the combined structural system of these houses. Finally, more efficient and less invasive rehabilitation and maintenance techniques are required in order to keep architectural values of these houses, make them fit for habitation, and preserve them as a precious heritage for future generations. It is not possible to make accurate structural interventions to historical structures in earthquake prone areas without considering the effect of seismic risk. In this context, the question can be put about proper determination of the most efficient and less invasive techniques for the preservation and rehabilitation of these heritage houses. Thus, further studies are encouraged to answer this significant question.

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REFERENCES

[1] Feilden, B. M.: Earthquakes and historic buildings Proceedings of 7th World Conference on Earthquake Engineering, Istanbul, 9, pp. 213 -226, 1980.

[2] Gülkan, P., Wasti, S.T.: Seismic assessment and rehabilitation of historic structures, SL, 1 (2), pp. 111-134, 2009.

[3] Dogangun, A., Tuluk, Ö.İ., Livaoğlu, R., Acar, R.: Traditional wooden buildings and their damage during earthquakes in Turkey, Engineering Failure Analysis, Vol. 13, No. 6, pp. 981-996, 2006.

[4] Dutu, A., Gomes Ferreira, J., Guerreiro, L., Branco, F., Goncalves, A. M.: Technical note: Timbered masonry for earthquake resistance in Europe. Materiales de Construccion, 62 (308), pp. 615-628, 2012.

[5] Lourenco, P.B.: Computations on historic masonry structures, Structural Engineering and Materials, Volume 4 (3), pp. 301–319, 2002.

[6] Kiyono, J., Kalantari, A.: Collapse Mechanism of Adobe and Masonry Structures During the 2003 Iran Bam Earthquake, Bull. Earthq. Res. Inst. Univ. Tokyo, Vol. 79, pp. 157-161, 2004.

[7] Toker, S., Unay, A.İ.: Mathematical modeling and finite element analysis of masonry arch bridges, Gazi University Journal of Science, Vol. 17(2), pp. 129-139, 2004.

[8] Bayraktar, A., Coşkun, N., Yalcin, A.: Damage of masonry buildings during the July 2, 2004 Doğubayazıt (Ağrı) earthquake in Turkey, Engineering Failure Analysis, Volume 14(1), pp. 147–157, 2007.

[9] Dogangun, A., Acar, R., Sezen, H., Livaoğlu, R.: Investigation of Dynamic Response of Masonry Minaret Structure, Bull Earthquake Eng. 2008(6), pp. 505-517, 2008.

[10] Aras, F., Krstevska, L., Altay, G., Taskov, L.: Experimental and Numerical Modal Analyses of a Historical Masonry Palace, Construction and Building Materials, Volume 25(1), pp. 81-91, 2011.

[11] Votsis, R.A., Kyriakides, N., Chrysostomou, C.Z., Tantele, E., Demetriou, T.: Ambient vibration testing of two masonry monuments in Cyprus, Soil Dynamics and Earthquake Engineering, Vol. 43, pp. 58–68, 2012.

[12] Oliveira, C.S., Çaktı, E., Stengel, D., Branco, M.: Minaret behavior under earthquake loading: The case of historical Istanbul, Earthquake Eng. Struct. Dyn. Vol.41, pp. 19–39, 2012.

[13] Ural, A., Dogangun, A., Sezen, H., Angin, S.: Seismic Performance of Masonry Buildings during the 2007 Bala, Turkey Earthquakes, Natural Hazards, Vol. 60(3), pp. 1013-1026, 2012.

[14] Milani, G.: Lesson learned after the Emilia-Romagna, Italy, 20–29 May 2012 earthquakes: A limit analysis insight on three masonry churches, Engineering Failure Analysis, 2013.

[15] Uysal, H., Cakir, F.: Static and Dynamic Analyses of the Historical Erzurum Watchtower, TAC Foundation, Foundation for the Preservation of Turkish Monuments an Environmental, Issue 1, pp. 72-80, 2013.

[16] Seker, B.S., Dogangun, A., Cakir, F.: Structural Analysis and Assessment of Historical Kara Mustafa Pasha Mosque in Merzifon, Turkey, SDU International Technologic Science, Vol. 5, No 1, pp. 112-120, 2013.

[17] Roca, P., Cervera, M., Gariup, G., Pela, L.: Structural analysis of masonry historical constructions. Classical and advanced approaches. Arch. Comput. Methods Eng., 17: 299–325, 2010.

[18] Beker, O.: Research report: Şirince conservation plan. Ankara, Turkey, 2002.

[19] Akdogan, K.N.: Management plan of Sirince Village. Available from: http://www.hdm.lth.se/fileadmin/hdm/alumni/papers/CMHB_2007/Turkey__Kivilcim_Nese__Akdogan.pdf [Accessed on 20th August 2013].

[20] Earthquake map of Turkey, the Republic of Turkey Prime Ministry, Disaster and Emergency Management Presidency, Earthquake Department. Available from: http://www.deprem.gov.tr/SarbisEng/Shared/DepremHaritalari.aspx [Accessed on 20th August 2013].

[21] CIB Publication 335., Guide for the structural rehabilitation of heritage buildings. Prepared by CIB Commission W023 - Wall Structures. Available from: http://cibworld.xs4all.nl/dl/publications/pub335.pdf [Accessed on 25th August 2013].

[22] FEA program, ANSYS Workbench Release:14.0., USA

[23] Ural, A.: Finite Element Analysis of Historical Arch Bridges, International Earthquake Symposium, Kocaeli, Turkey, 2005.

[24] Cakir, F.: Assessment of Structural Integrity And Seismic Retrofit of Masonry Bridges Using Micropiles, Master's Thesis, Department of Civil, Architectural and Environmental Engineering, Graduate College of the Illinois Institute of Technology, Chicago, USA, 2011.

[25] Taranath, B.S.: Reinforced Concrete Design of Tall Buildings, CRC Press, USA, 2009.

[26] AFAD, The Republic of Turkey Prime Ministry, Disaster and Emergency Management Presidency, Earthquake Department, Available from: http://kyh.deprem.gov.tr/ftpt.htm [Accessed on 15th August 2013].

[27] Soyluk, A., İlerisoy, Z.Y.: Dynamic analysis of Dolmabahce masonary clock tower, GRAĐEVINAR 65 (2013) 4, pp. 345-352.