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Influence of modified intended use on the seismic behavior of historical himis structures

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Abstract. There are some modifications in the usage purpose of historical structures due to varying needs and changing conditions. However, those modifications can damage the structural system and the system stability. This study focuses on the investigation of the functional effects and usage modifications on the system stability. In this study, three different finite element models of the Hayati Teknecioğlu Mansion in Turkey are developed and the seismic responses of the models are investigated. Results of the analyses show that usage modifications might be considered as risky in terms of creating problems for seismic performance.

Keywords: himis structures; the modification of intended usage; seismic analyses; Finite Element Method (FEM)

1. Introduction

The protection of historical structures by the appropriate and convenient techniques is one of the most important challenges of today. Most of historical structures are damaged because of the natural disasters, time dependent deformations, and bad usage or conscious damage to the structure and thereby are exposed to the destruction. Several structures have different structural system properties in Turkey, where the historical structures are widespread. Especially, traditional buildings are characterized according to their historical structural properties. Moreover, they are treated to be the earliest examples of the historical heritage because of the use of natural materials and the primitive construction techniques. One of those structures is called as 'himis structure'. Himis construction is simply described as a timber frame with masonry infill such as bricks, adobes, or stones (Fig. 1). This type of construction is a variation on a shared construction

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tradition that has existed through history in many parts of the world, from ancient Rome almost to the present. In Britain, where it became one of the identity markers of the Elizabethan Age, it would be referred to as “half timbered.” In Germany, it was called “fancywork,” in France, “colombage,” in Kashmir, India as “dhajji-dewari” in parts of Central and South America, a variant was called “bahareque” (Gülkan and Langenbach 2004).

Himis structures are predominant among the historical structural systems in central Anatolia. In himis technique, main timber posts are placed at the corners. Then, the diagonal bracing elements are used to support the structural integrity of timber frames. Finally, the spaces of the timber supporting system are filled by the adobe elements in these structures. The examples of the adobe fills are applied to the examined zones in Turkey, which are shown on Fig. 2(a) and 2(b). Since Turkey is an earthquake country, the destructive earthquakes have damaged too many structures. In the most destructive earthquake that took place in the last century in Turkey, himis structures have shown better performance compared to the concrete structures (Fig. 3).

The most efficient way of protecting these structures and preventing their destruction is to ensure their continuous use. In the fifth item of Venice Charter (1964), it is stated “the protection of monuments becomes easier by their use for a public purpose” by making an emphasis on the importance of the continuous use of the historical structures for protection. However, it is difficult to protect all these structures with their original aspects. In the light of protection principle, many historical structures are exposed to the transformations and their purpose of usage is modified by adding new functions.

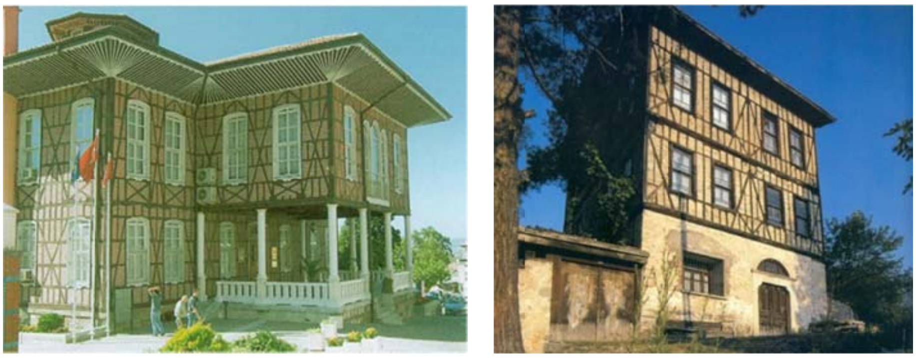


Fig. 1 Traditional himis structures in Turkey (Doğangün *et al*. 2006)

(a) (b)

Fig. 2 The use of smooth surfaced (a) moulded and (b) unmoulded adobe (Doğangün *et al*. 2004)

Fig. 3 View of traditional himis and reinforced concrete building after the 1999 Izmit earthquake in Turkey

There are many historical structures in Turkey of which the usage purpose has been modified and that have served for different purposes so far. The idea of making changes on historical structures has differently appeared in many historical buildings. Those changes are usually the add-ons to the structures inside and additional door and window openings outside. However, the modifications applied in the inner parts of the structures in order to promote their functions in accordance with present-day's needs are considered to be common applications (Gönül 2010). Therefore, the changes in the function and usage purpose are important issues in terms of causing changes in the structures' identity and originality. However, these changes are usually done in the form of non-engineering implements and these modifications may cause irreversible negative effects on historical structures. Fig. 4 illustrates some examples about non-standard and non-engineering applications below.

To better understand the structural behavior of himis structures, information about the effects of modifications and changes are very important. Although the structural behavior of masonry structures is a critical research area (Cakir and Uysal 2014, Soyluk and Tuna 2011, Akan 2010, Akan and Özen 2005, Toker and Ünay 2004), himis structures have been rarely investigated. Especially, the number of studies conducted about the performance analysis of structures where the adobe is used is quite rare. Some scientists have started to study the seismic performance of himis structures in the last decade. For example, the study conducted by Koçu and Korkmaz (2004) focused on the earthquake performances of the structures built with the adobe and it is found that the earthquake performance of the adobe structures which have deformed timber structure is lower compared to the other structures. Akan (2004) and Doğan (2010) conducted research on bagdadi and himis structures' behaviors under lateral loads and focused on the performance analyses, which have been made with the use of computer models by FEM. According to these studies, timber-framed structures are more ductile than reinforced concrete structures and the diagonal members of the timber-framed structures are the most important elements of the structural behavior. In addition, the studies also conclude that timber framed

Fig. 4 Non-engineering additions and changes (Photographs by the authors)

structures can be used as efficient lateral load resistance systems for seismic loads. Köylü (2008), in his study, examined the behaviors of himis and bagdadi structures under lateral loads and generated models by using different fill materials. In his study, he found that himis and bagdadi structures' ductility is higher than the concrete and masonry structural systems' ductility. Bakhteri *et al*. (2004) have conducted research on the finite element models of adobe structures, which have been prepared with clay materials under axial compression and focused on the most appropriate binding mortar, which is going to be used in adobe structures, by the numerical and experimental models. The study has demonstrated that the compressive strength of brick masonry should be revised with a magnification factor for the actual strength of the brickwork. Hardwick and Little (2010) evaluated the seismic performances of the structures built with the adobe that is a mixture of clay and mud and supported their experimental study by the computer-aided models. The results have shown that the mud brick walls might be considered as homogeneous units. Kauris and Kappos (2012) modelled a himis structure numerically and conducted research on the timber elements' connection details by the non-linear analyses. They suggested that the simplified model for the timber-framed structures could be taken into account for the seismic fragility assessment.

In this study, it is aimed to identify the effects on the structures' earthquake response caused by the functional modifications and modified usage purpose. Therefore, the historical proprietary Hayati Teknecioglu Mansion is examined. Since this structure is located in a touristic zone and the structural area is adaptive to the modifications, first functional modification is made by the transformation of the mansion into a hotel and the second modification is made by transforming the structure into a restaurant. In this scope, all those modifications towards the changes in the usage purpose are modelled numerically.

2. The historical Hayati Teknecioglu mansion

Tokat is an important city located in the middle of Black Sea Region with its historical and cultural background (Fig. 5(a)). In the Turkish earthquake map, it can be clearly seen that Tokat city center and most of its towns are located on the North Anatolia Fault Line (NAFL) and Tokat city center is located on the first-degree earthquake zone in which maximum ground acceleration is assumed as 0.4 g (Fig. 5(b)). North Anatolia Fault Line is a dangerous and active line where many earthquakes have taken places so far.

Hayati Teknecioğlu Mansion, the subject of this study, is located on the city center by occupying 9th map section, 73rd building lot, and 34th parcel. The structure that has 11.50×12.60 m living area is registered and protected as an immovable possession. The structure is a two-story building and is not currently in use. This first phase of the study is an in-situ investigation that relies on a visual analysis carried out by the authors in Teknecioğlu Mansion and Tokat. It is seen that timber, adobe, and stone materials are used in the building by the examination of structural materials. It is also observed that the structure's foundation and plint walls are built with the stone material and timber stable frame is made onto those stone walls.

The examined structure has gained its present appearance, which is composed of timber mainframe, adobe filled himis and fully plaster. Teknecioğlu Mansion is currently in the abandoned state and therefore, the owner of the structure has planned to change its intended usage. In this scope, an in-situ investigation was carried out by the authors in Teknicioğlu Mansion in order to detect deterioration in traditional himis structures (Figs. 6-8). The investigation mainly aimed to better understand the structural behaviour and deformation capacity of the structure. The visible signs of deterioration in the structure were visually examined in the light of the structural features and architectural characteristics. The majority of deteriorations in Teknecioğlu Mansion have been mainly caused by the damage on the structural elements and the decay of the structural materials. The main problems on the structure are the damage on the structural elements, the loss of material, and the decrease in the structural strength. One of the facades of the structure has been partly demolished on the timber frame and many irregular micro cracks have been observed on the plaster of timber-framed walls. In addition, during the structure's service life, construction materials have deteriorated and lost their qualities due to the environmental conditions, spalling or flaking. Potential failures because of material degradations should not be neglected because these degradations cause irreversible effects on the structure in a negative manner. Moreover, the drainage excavations on the side prove that the foundation soil was in good condition (Good Soil) and there is no significant damage on the structure.

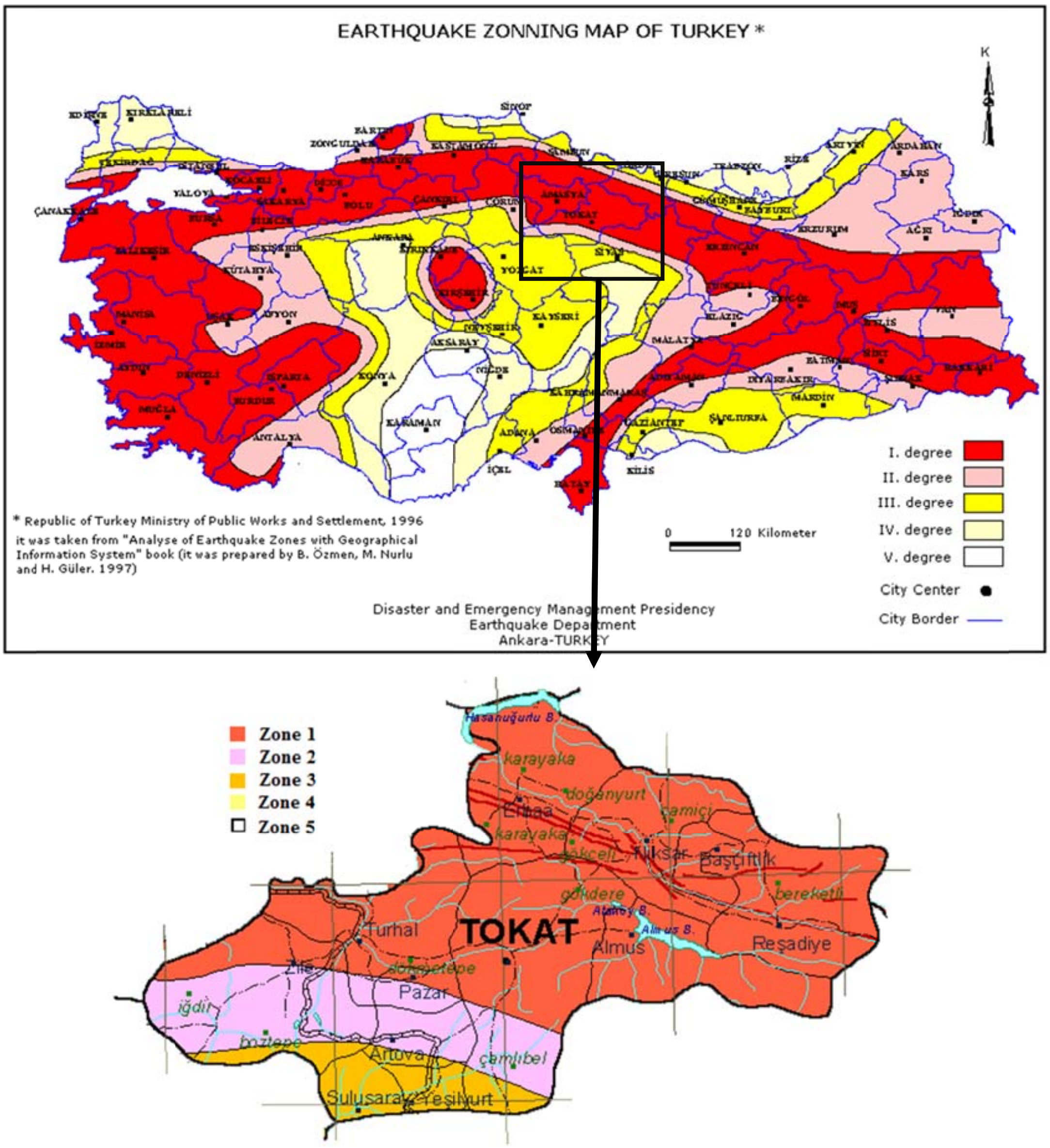
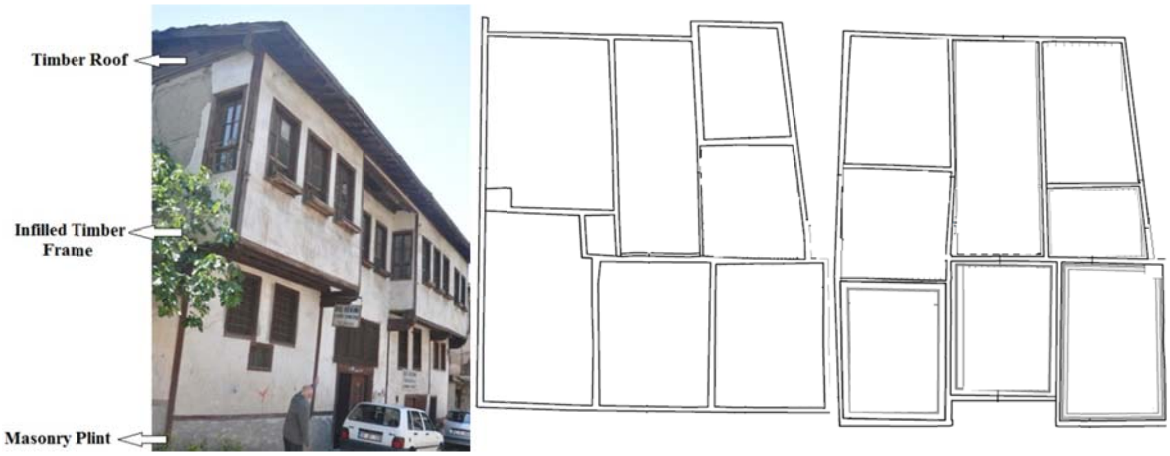


Fig. 5 (a) Earthquake Map of Turkey and Tokat (AFAD 2014)

Fig. 6 Overview of Teknecioğlu Mansion (Photographs by Elif Yaprak)

Fig. 7 Exterior views of Teknecioğlu Mansion (Photographs by Elif Yaprak)

Fig. 8 Interior views of Teknecioğlu Mansion (Photographs by Elif Yaprak)



(a) (b) (c)

Fig. 9 (a) The original shape of the Teknecioğlu Mansion, (b) Ground Floor, (c) First Floor

Teknecioğlu Mansion consists of three major parts. The first part is the masonry plint, the second part is the infilled timber frame, and the third part is the timber roof. The floors between stories consist of timber elements. Timber materials are easy to use and may be obtained from natural environmental and sustainable sources. Furthermore, timbers resist to tensile and compression forces. Therefore, it has been used as a horizontal bearing member to the structure. The mansion has differences in plan on ground and first floors. Additionally, the mansion rises towards front facade on the upper floor (Fig. 9). In the scope of the study, Hayati Teknecioğlu Mansion is firstly modelled as a current shape (mansion), after that, it is modelled as hotel and restaurant (the other two construction purposes) and it has gained new functions with those two models. The earthquake effects of the structure are examined by the dynamic analysis on the three models created. The appropriate analysis of the proprietary historical structures' and their reinforcement and maintenance are very important in order for the delivery of those to the future.

3. Numerical models

It is very difficult to analyze historical structures because of their complexity in forms and different material properties by the common engineering methods. Therefore, it is more convenient to create 3D models and analyze those structures by computer applications especially by the use of finite element method (FEM). The improvements in the computer technology have facilitated the numerical analysis and the examination of structural behavior in three-dimension (3D) models. Therefore, computer aided engineering plays an important role in the investigation of historical structures. In this study, 3D finite element models have been developed based on the structural state and the geometrical constraints of the structures.

The parameters used and assumptions made in the models are as follows;

• The plint walls of the structure and adobe fills between wooden windows are modelled with three-dimensional solid elements, timber floors between inter-stories are modelled with shell elements, and the timber frames are modelled with beam elements (Figure 10).

• In order to minimize the negative effects caused by the disordered architecture of the structure, the architectural plan that has nearly rectangle shape is assumed as a rectangle and middle floors and adjacent order which take part in a smaller part of the original structure are removed completely in the structural models.

• Himis structure that has timber supporting system is taken into consideration in this study. In the modeling phase, timber elements are used as supporting elements where adobe elements are used as fill materials.

• In this study, material sampling has not been considered because of the restrictions in the Turkish specifications. Therefore, the engineering properties of the materials are extracted from the proposed values in the literature by the careful consideration of the past examinations and studies because of the inability to take material samples and to conduct tests (Table 1).

• The cross sections of the timber, stone and adobe materials are chosen from the values proposed in the literature by the careful consideration of past studies and examinations since the structure is fully plastered (Table 2).

• All the numerical data used in the 3D models of the structure are created in accordance with the restitution and restoration projects of the historical structure.

The mansion form is taken into consideration in the first model and the present view of the structure is modelled. All the changes in the plans are made using ideCAD Architectural software similar to the hotel structure and 3D finite element model is generated through Sap2000 software. There are 6819 nodes, 481 beam, 4956 shell, and 632 solid elements in the mansion model (Fig. 10).

In the first modification of the usage purpose, the structure is transformed from the mansion to the hotel form. In the scope of transformation, additional windows are opened to the outside facades of the structure and there have been several changes inside to liken the structure to a hotel form (Fig. 11). In the finite element model of the structure, there are 6441 nodes, 453 beam, 4305 shell, and 632 solid elements in the hotel model (Fig. 12).

Table 1 Engineering properties of materials in the models

Material Type	**Elasticity Modulus (kN/m^2)**	**Poisson Ratio**	**Mass Density (kg/m^3)**
Stone	9E6	0.30	2550
Timber	14.5E6	-	800
Adobe fill	1.4E6	0.35	1750

Table 2 Dimensions of elements in the models

Material	**Width (cm)**	**Length (cm)**	**Height (cm)**
Plint Walls	20	50	30
Adobe Walls	20	30	20
Timber Columns	10	10	-
Timber Beams	10	-	10
Timber Braces	6	10	-
Timber Floor	300	300	12

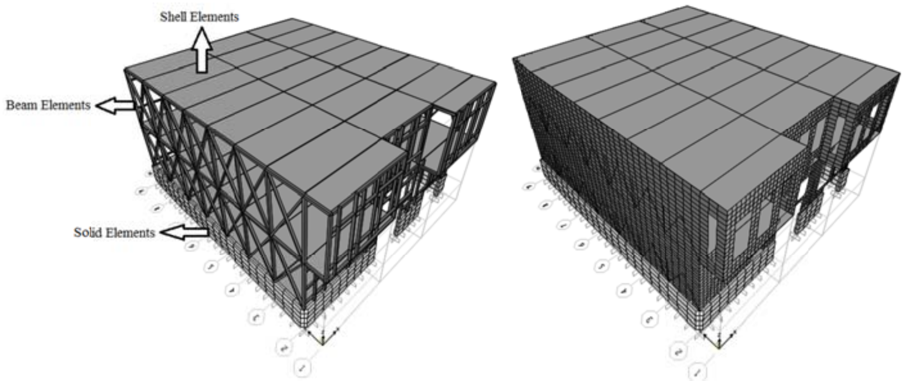
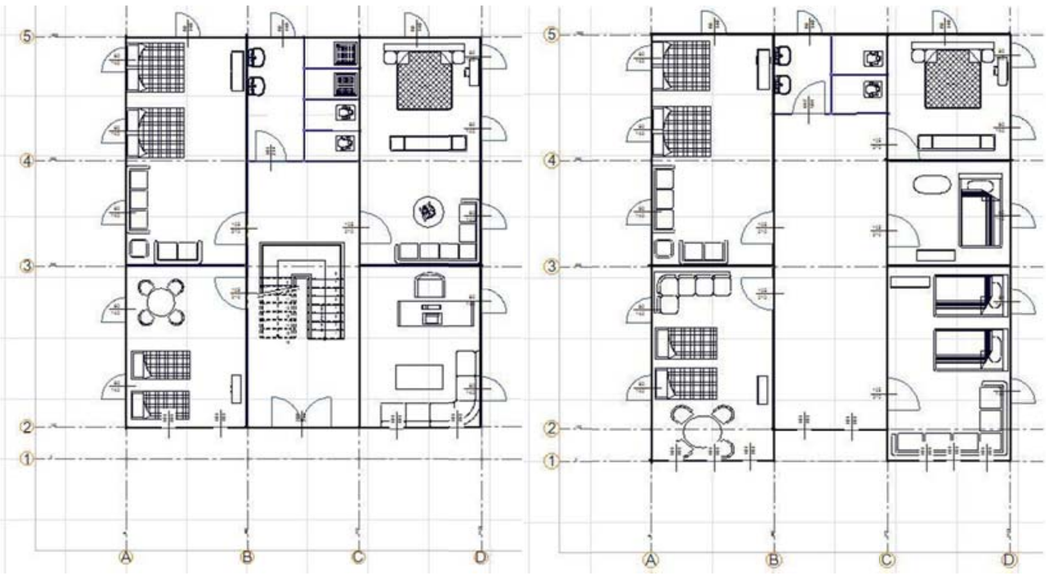


Fig. 10 Finite element model of the Mansion



(a) (b)

Fig. 11 Floor plans of the Hotel: (a) Ground floor (b) First floor

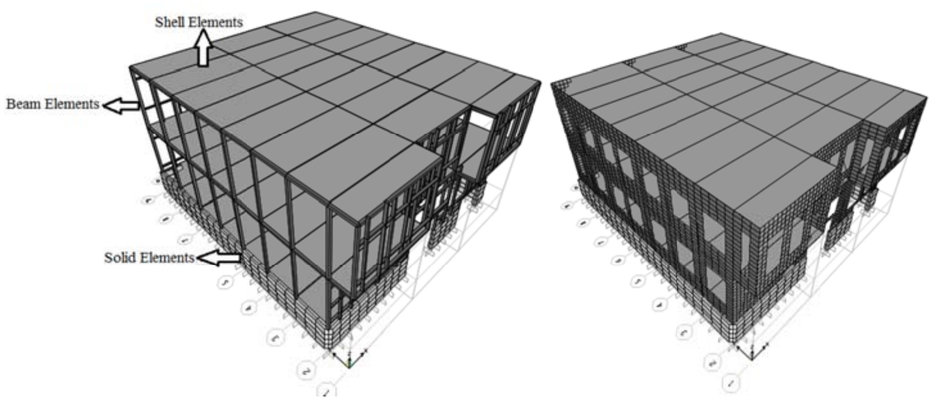
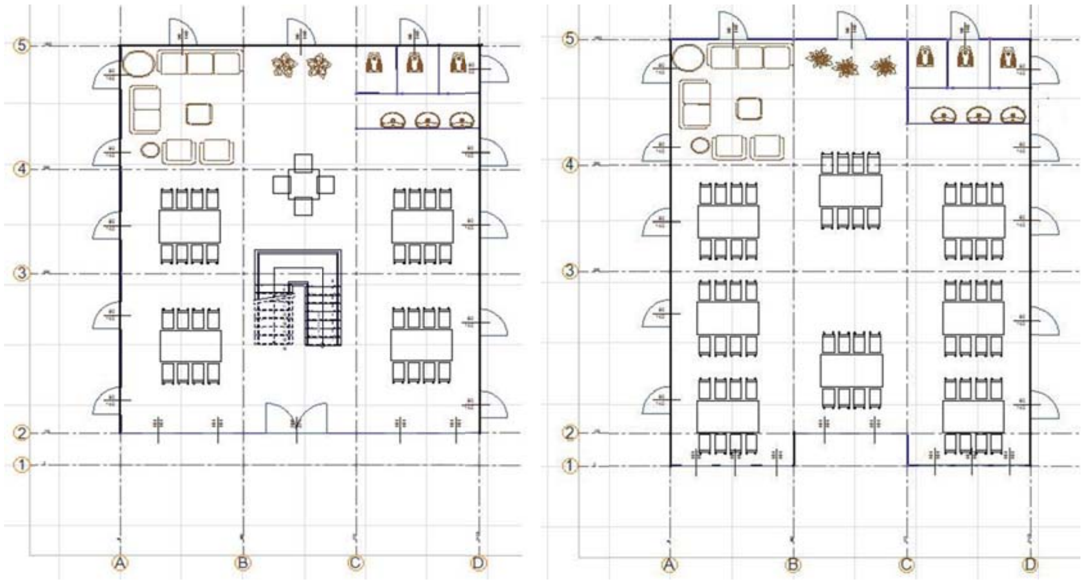


Fig. 12 Finite element model of the Hotel



(a) (b)

Fig. 13 Floor plans of the Restaurant: (a) Ground floor (b) First floor

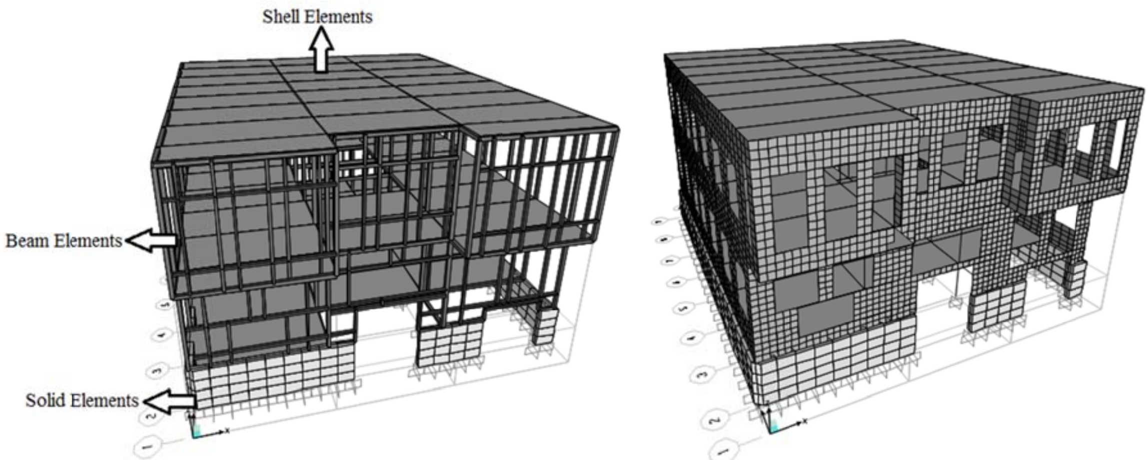


Fig. 14 Finite element model of the Restaurant

In the second modification of usage purpose, the mansion is transformed to the restaurant form. In the scope of this transformation, additional windows are opened to the outside facades of the structure and fully open spaces are created in the inner sections (Fig. 13). There are 6441 nodes, 425 beam, 4305 shell, and 632 solid elements in the restaurant model (Fig. 14).

4. Finite Element Analysis (FEA)

FEA is a widely used analysis technique in the identification of system behaviors of historical structures under static and dynamic loads and generation of the stress analyses of structural elements. For this purpose, all the numerical models used in this study are modelled with Sap2000 and the structural behaviors of all models are examined according to the earthquake conditions. The main objective of the linear-elastic analysis is to interpret the stresses and the damages that occur at beginning and at the elastic state of the models. The linear analysis provides an opportunity to solve small deformation and small displacement problems. Therefore, the analyses are conducted by the consideration that the elastic behavior and the timber floors are not modelled as rigid diaphragms. In addition, this paper takes into account the problems of very small deformations only where the deformation and the load have linear relationship. Hence, linear elastic material behavior is considered and the stiffness degradation is ignored in the study. The plint wall and the foundation of the structure are connected as fixed end. Moreover, the bonded assumption is applied to the all-structural elements and the elements are assumed to be fully bonded. In addition, Turkish Earthquake Code-2007 (TEC) is taken as basis in all analyses and it is assumed that Rayleigh damping ratio is 5%, the structural behavior factor (R) is 3 and importance factor (I) is 1.2.

4.1 Modal analysis

The modal analysis is primarily used for the dynamic analysis of the investigated structure. Sufficient numbers of vibration modes are determined considering TEC. With respect to TEC, sufficient number of vibration modes should be taken into consideration for the fact that the sum of effective mass participating ratios should be greater than 90% of the total mass of the building for each direction. The modal analyses are considered for the first 30 modes and the first five modes that have higher contributions to effective mass participating ratios. The first five mode shapes for the structures are presented in Fig. 15 and Fig. 16. As shown on the Fig. 16, the frequencies values of the mode shapes differ according to the modification in the usage and the most significant difference is observed on 2nd mode.

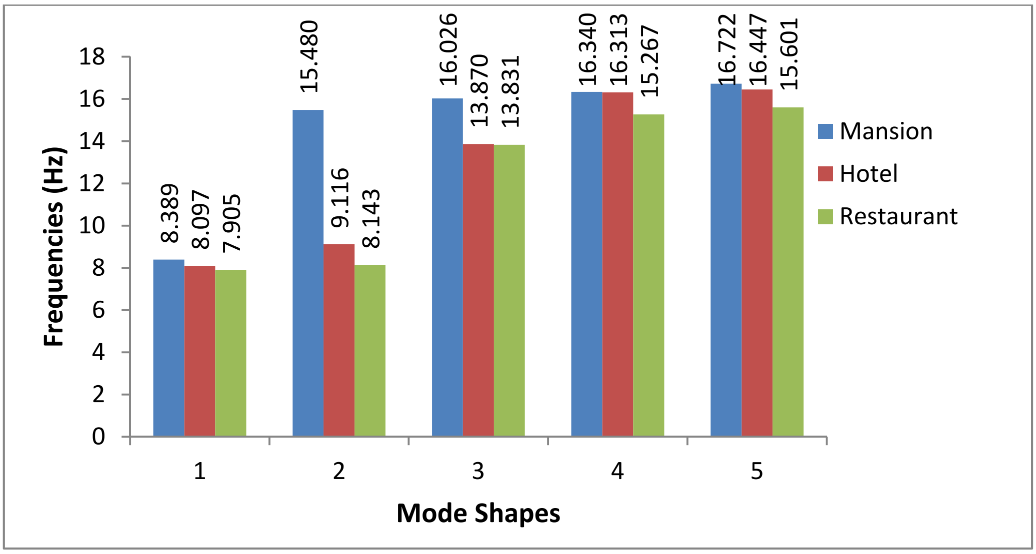


Fig. 15 Frequencies values for first five mode shapes

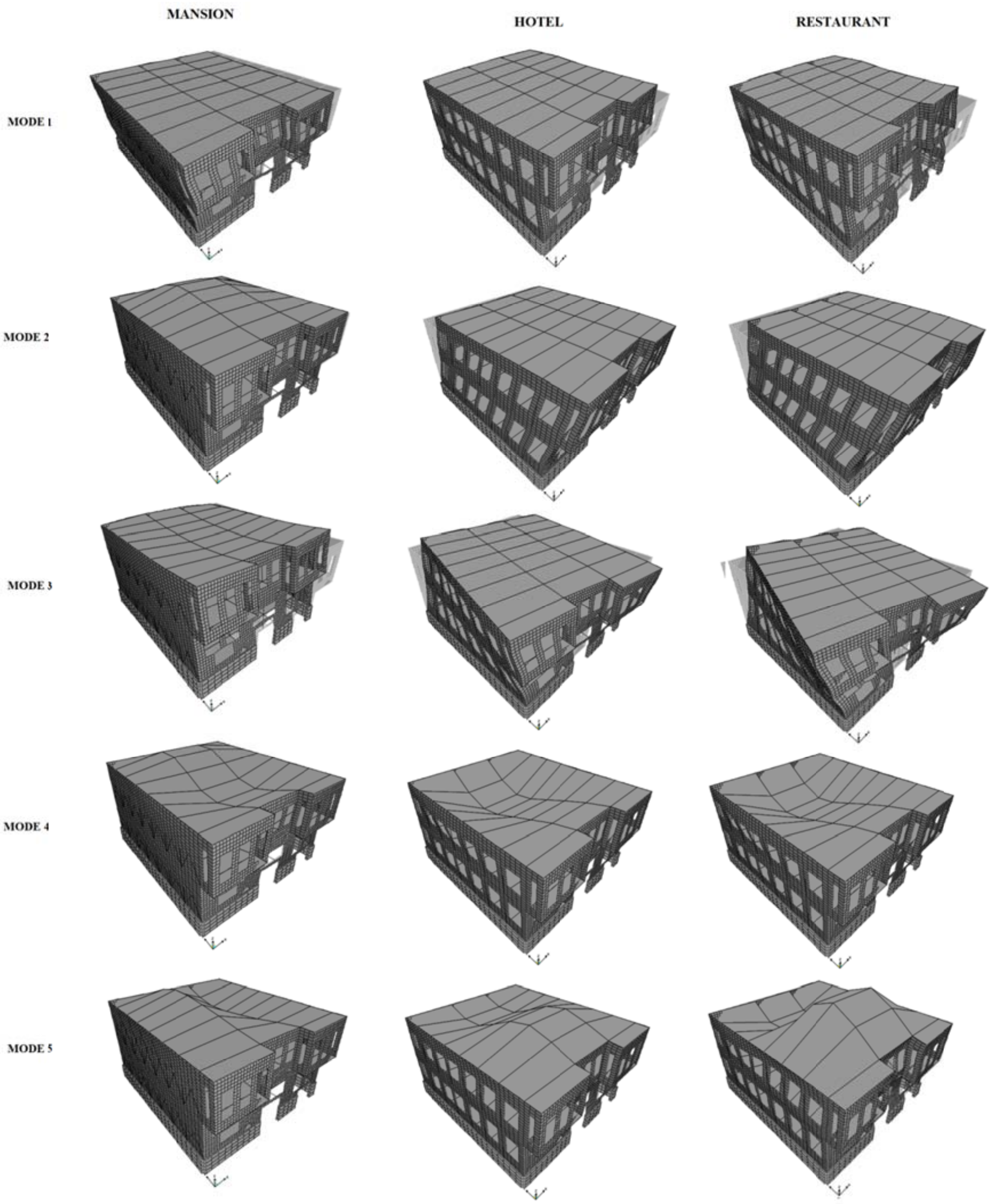


Fig. 16 The first five mode shapes for the structures

4.2 Dynamic analysis

In dynamic analysis, the loads are accounted with dynamic actions in different loading case combinations. In all models generated in the study, dynamic analyses according to the loading combinations (Table 3) are made by considering TS500 (2000) and TEC, which are current specifications in Turkey. The response spectrum analysis of each model is carried out using the design spectrum specified in the TEC as shown in Fig. 17. Moreover, design spectrum includes the effect of local soil conditions. Based on this approach, TEC has defined the spectrum curves for four different soil types. Good soil curve has been considered in this study (Fig. 17).

The generation of the analyses for each node and element is quite difficult. Therefore, coloured graphical representations and stress distributions are presented in this study. Figs. 18-20 represents tension/compression stresses (MPa) generated through 1 (S11), 2 (S22) and 3 (S33) directions according to their local axial group under G+Q+Ex+0.3Ey, G+Q+Ey+0.3Ex and 1.4G+1.6Q loading conditions for mansion, hotel and restaurant models. Furthermore, Fig. 21 presents the maximum displacements in X, Y and Z directions for the structures and the maximum base shear forces generated through X, Y directions for each load combination during the analyses are presented in Table 4.

Table 3 Loading combinations on analyses

G+Q+Ex+0.3Ey	0.9G+Ex+0.3Ey	G+Q+Ey+0.3Ex	0.9G+Ey+0.3Ex	1.4G+1.6Q
G+Q+Ex-0.3Ey	0.9G+Ex-0.3Ey	G+Q+Ey-0.3Ex	0.9G+Ey-0.3Ex	
G+Q-Ex+0.3Ey	0.9G-Ex+0.3Ey	G+Q-Ey+0.3Ex	0.9G-Ey+0.3Ex	
G+Q-Ex-0.3Ey	0.9G-Ex-03Ey	G+Q-Ey-0.3Ex	0.9G-Ey-0.3Ex	

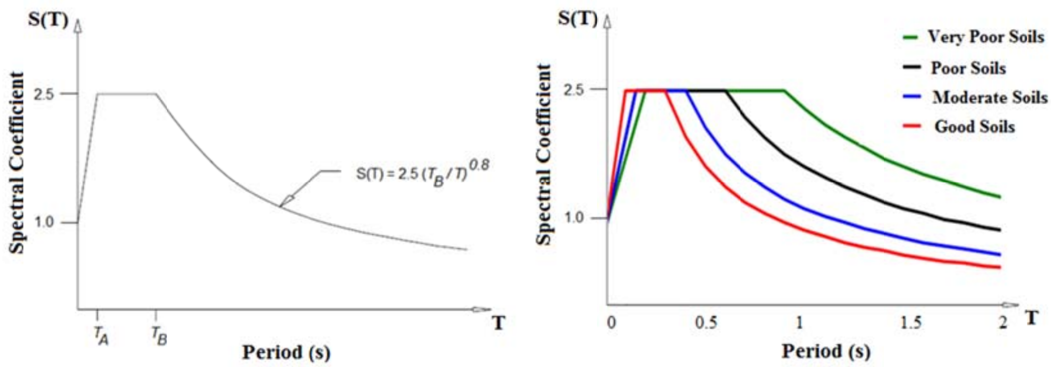


Fig. 17 Design spectrums recommended by TEC

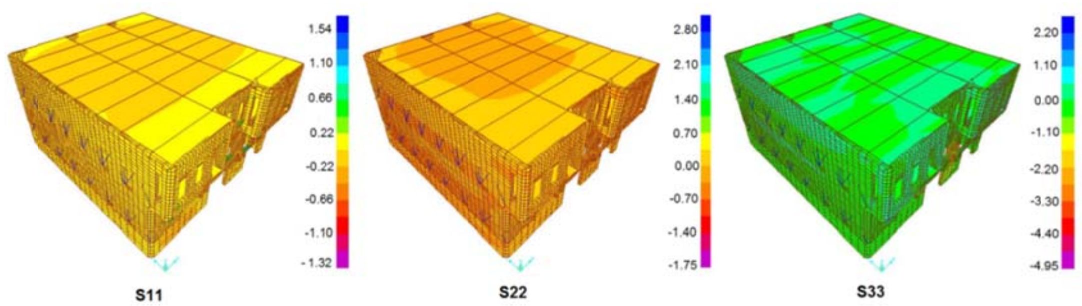


Fig. 18 The stresses along 1, 2 and 3 directions on model of the Mansion (MPa)

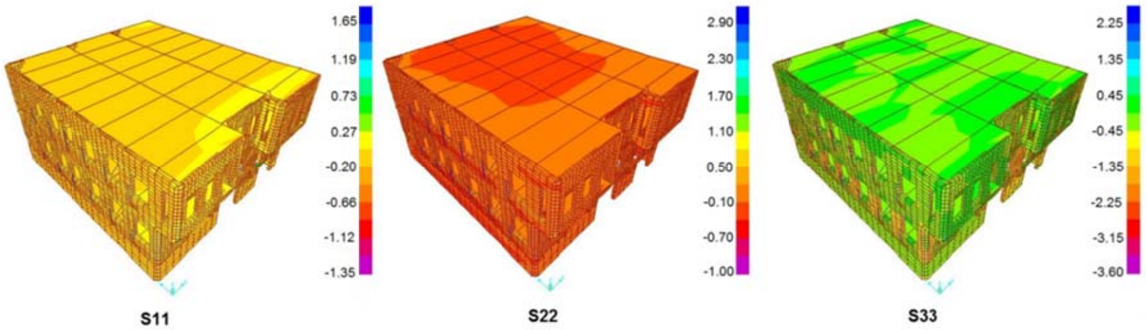


Fig. 19 The stresses along 1, 2 and 3 directions on model of the Hotel (MPa)

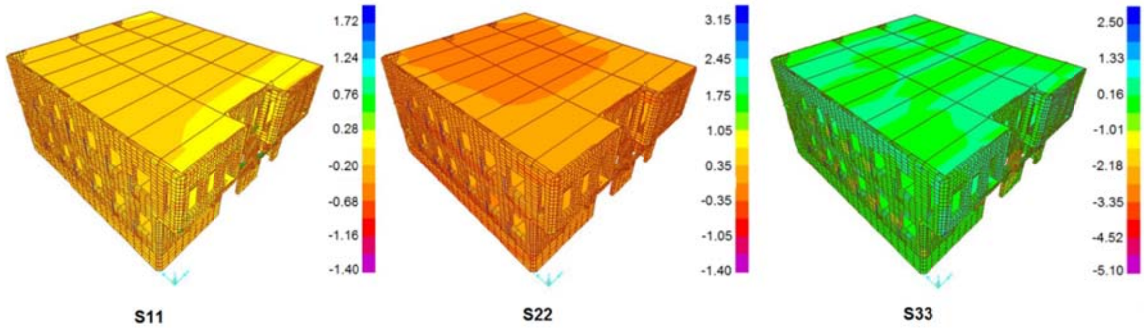


Fig. 20 The stresses along 1, 2 and 3 directions on model of the Restaurant (MPa)

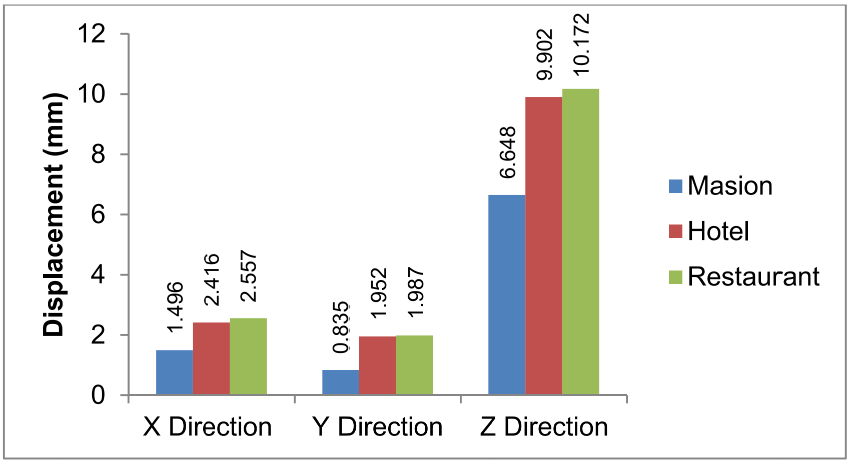


Fig. 21 Maximum displacements on X, Y and Z directions

5. Evaluation of results

In this study, the effects of modified usage purpose in a historical himis structure which is built with materials that have different rigidity and engineering properties are investigated. Firstly, the present condition of the structure is modelled numerically and in further steps, two different

Table 4 Base shear forces on X and Y directions

Load Combinations	Step	Mansion X Direction	Mansion Y Direction	Hotel X Direction	Hotel Y Direction	Restaurant X Direction	Restaurant Y Direction
		Base Shear Forces (kN)					
G+Q+Ex+0.3Ey	Max	118.54	30.19	110.34	41.95	110.53	46.99
G+Q+Ex-0.3Ey	Max						
G+Q-Ex+0.3Ey	Max						
G+Q-Ex-0.3Ey	Max						
0.9G+Ex+0.3Ey	Max						
0.9G+Ex-0.3Ey	Max						
0.9G-Ex+0.3Ey	Max						
0.9G-Ex-0.3Ey	Max						
G+Q+Ey+0.3Ex	Max	36.61	97.12	39.78	117.56	45.36	115.95
G+Q+Ey-0.3Ex	Max						
G+Q-Ey+0.3Ex	Max						
G+Q-Ey-0.3Ex	Max						
0.9G+Ey+0.3Ex	Max						
0.9G+Ey-0.3Ex	Max						
0.9G-Ey+0.3Ex	Max						
0.9G-Ey-0.3Ex	Max						

modified usage purposes are predicted and new usage plans are generated in the light of architectural requirements and constraints. The newly generated plans are modelled numerically and separately as in the first step and the dynamic analyses are conducted on three different models (mansion, hotel and restaurant). In this section, the results of the analyses conducted with FEM are evaluated and the differences among results are examined.

The period values generated through the evaluation of the analyses prove that the first condition of the structure is quite rigid. However, it is observed that the period values get higher and the structure's rigidity decreases due to structural system and loads after the transformation of the structure from the mansion into a hotel and restaurant.

The analyses of the displacements show that the maximum displacement in the X direction with G+Q+Ex+0.3Ey load combination, the maximum displacement in Y direction with G+Q+Ey+0.3Ex and the maximum displacement in the Z direction with 1.4G+1.6Q load combination are generated. The evaluation of the displacements generated through the structure because of the modified usage show that the least displacement is generated in the mansion form while the highest displacement is generated in the restaurant form among the three models analyzed. Additionally, the comparison between the mansion and restaurant form reflect that there are 70.9% change in the X direction, 137.8% change in the Y direction and 53% change in the Z direction in terms of displacements.

The stresses of shell elements used for the hotel and restaurant models which are generated in 1, 2 and 3 directions according to their local axial groups show that the minimum stresses are observed in the mansion form and the stresses are increased up to 50% when transformed from the hotel to the restaurant form. The evaluation of the maximum base shear forces prove that the changes in shear forces are similar for each model generated in parallel to the mass of the structure and the maximum base shear force is reached in the mansion form. The sum of all shear forces constitutes 15% percent of the mass of structure since the total mass of the structure is 982.463 kN.

When the displacement values are compared, the Turkish earthquake code specifies the following maximum relative displacement requirement for masonry structures (Cakir and Uysal 2014, Seker *et al*. 2014)

$$\Delta_{i\max} \leq \frac{0.02 \cdot h_i}{R} \quad (1)$$

where h_i is the story height, and R is the behavior factor related to the ductility of structure. If this requirement is applied to the Teknecioğlu Mansion (h_i=8 m, R=3), the corresponding maximum allowable top displacement is 0.05 m. The dynamic displacements achieved are lower than the values generated through the formula. In this respect, it is seen that the maximum displacement values are within the allowable limits.

6. Conclusions

The historical structures are past heritages and thereby should be delivered to the future safely. Therefore, it is very important to protect historical structures by allowing their use in convenient form and prevent them being disappeared. In the scope of this study, the effects of modified usage purpose on the structures and a himis structure which possess a timber structural system and an adobe fill system is analyzed. The changes in the purpose of usage are very common in Turkey to increase the service life of the historical structures. However, the changes in purpose of usage are out of engineering scope and unconscious applications in general. In this study, it is investigated that whether the structure is convenient with the purpose of usage. Thus, this study has more focused on the changes in the purpose of usage and thereby several analyses have been conducted. The models generated and the analyses conducted show that the modifications in the function and usage purpose affect the himis structure's behavior negatively. The most important reason of those negative effects is that the structural system is affected by the modified usage purpose in a negative manner. Since the timber frames do not allow lateral movement of the structure, the modifications in the structure increased the horizontal displacements. In addition, the modifications have affected the dynamic resistance of the structure. Thus, inappropriate modifications might cause fatal and destructive crashes and these negations might cause irreversible effects on the himis structure. Furthermore, these damages should be considered seriously and some precautions should be taken to avoid or to abate their effects. As a result, the modifications in the historical structures' usage purpose should be carefully made in order not to decrease the seismic performance of the structure and careful investigations should be conducted to better analyze seismic response behavior of the historical structures when modifications are realized on the structure. Moreover, the additional forces originated from the modified usage purpose create additional stresses and the stability of the system is deformed. Therefore, the modifications planned for the historical structures should be kept at minimum in order not to affect structural system in a negative manner. Especially, the convenient restoration projects should be prepared and the static and dynamic analyses should be conducted carefully in the studies towards the modifications in the function of the proprietary historical structures. Finally, it is expected that the analyses and the results of the analyses of this study will encourage similar studies in the subject of historical structures that possess different structural systems and different construction materials.

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