Dynamic Identification of an Early 20th Century Civil Architectural Building

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Abstract

Historical structures are important in terms of both original construction techniques and cultural heritage. Therefore, material properties, construction techniques and dynamic behaviours of these structures must be identified in order to preserve them in the future by restoration studies. This study is aimed to serve as an example for similar buildings in the region whose walls were constructed using filled brick with lime mortar and constructed using both timber and reinforced concrete slabs. In this study, the plan layout, construction techniques and the material usage of the building were investigated in detail. The mechanical and dynamic properties such as compressive stress, elastic moduli, shear stress, natural frequencies and mode shapes of the building were determined in-situ by flat-jack, shear and vibration tests. The finite element model of the structure was prepared, and the modal analysis of the structure was performed. The calibration of the model was ensured according to the vibration test results. The results obtained from this study show us that in-situ tests are extremely important for the accuracy of finite element models. It has been determined that the mechanical test data can be used with over 80% success in finite element models.

Keywords: Timber; Masonry; Construction Technique; Operational Modal Analysis; Mechanical Tests.

1. Introduction

The studied building is situated in the centre of the Edremit district. It was constructed in the first quarter of the 20th century. The building is a modern architectural heritage in terms of its architectural features. The building has lots of values such as value of originality, value of rarity, economic value, social value, functional value and political value, as discussed by B. M. Feilden and J. Jokiletho [1]. The house, which gained its importance with the hosting of Mustafa Kemal Atatürk in 1934, is known as the Atatürk House in the collective memory of the district.

In terms of historical features, today's codes and standards are not sufficient for the restoration of the masonry structures. The complexity of the structure, the diversity in the use of materials, the different construction techniques, the absence of knowledge about the changes in time and causes of damage throughout its existence are the important problems. The mechanical properties and dynamic characteristics of the building should be identified by in-situ tests. The most effective methods for identifying the mechanical properties of masonry structures are flat-jack and shear tests. In these tests, a flatjack is inserted in a cut slot in the mortar and displacements are continuously read while hydraulic oil pressure is inflated into the metal plate. These test methods have been used over a long time by researchers [2-4]. The most common experimental study for identifying the dynamic properties of masonry structures is the Operational Modal Analysis (OMA) test method. In this test method, the dynamic parameters such as natural frequencies, mode shapes and damping ratios are estimated from output-only responses. There are many studies using

the OMA technique to identify the dynamic parameters of masonry constructions [5-13].

After performing the in-situ tests, the finite element model of the structure should be prepared in order to find out the structural behavior of the building. However, in many research studies, the finite element models did not accurately represent the real behavior of the structure. This was due to the estimation of the material properties without performing any in-situ tests. In some research studies, the material properties performed by test methods but vibration tests did not performed. For this reason, identifying the material properties and dynamic characteristics of the building gains importance before the finite element analysis of the building. The finite element model should be controlled and calibrated by comparing the modal analysis results and the in-situ vibration test results. After the calibration, the finite element model can represent the real behavior of the building. The mass participation factors, the mode shapes and the other structural analyses such as earthquake analysis, pushover analysis, etc. can be performed by using this model. In addition, the success of the flat-jack and shear test results is also investigated by the researchers.

In the first part of the paper, the methodology of the research is explained with a flowchart. This is followed by the expression of the plan, construction techniques and material usage of the building. After this, the mechanical properties and dynamic characteristic of the building are investigated by using in-situ tests. The modal analysis is performed using a finite element analysis program. After the calibration of the finite element model, the mode shapes, natural frequencies and mass participation factors are presented in tables and the results are discussed in the conclusion part.

2. Research Methodology

In this study, the plan layout, construction techniques and material usage of the building were investigated on-site and the mechanical properties such as compressive stress, elastic moduli and shear stress of the masonry walls were investigated by using in-situ flat-jack and shear tests. The dynamic characteristics such as mode shapes and natural frequencies of the structure were analyzed by using in-situ vibration tests. The OMA test method was used for determining the dynamic characteristics of the structure. The finite element model of the structure was prepared, and the modal analysis of the structure was performed by using the ALGOR finite element program. The finite element model calibrations were done by comparing the frequencies obtained from the vibration tests and the finite element modal analysis. The process was repeated until the difference was under 10% and the finite element model was formed at the end. The flowchart of the study is presented in Figure 1.
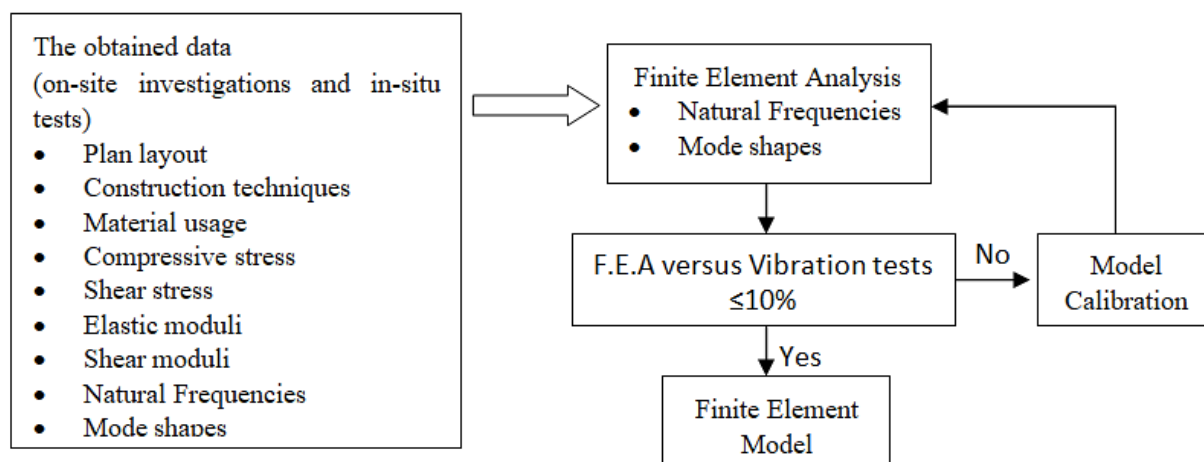

Figure 1. The flowchart of the study

3. Plan, Construction Techniques and Material Usage

The studied building, Edremit Atatürk House, is situated at the centre of the district. Edremit is a district of Balıkesir Province which is located in the north-west of Turkey and on the coast of the Aegean Sea. The building is situated on Çayiçi Street which is one of the most frequented streets in Edremit. The location of Edremit district and the studied house is presented in Figure 2.

Figure 2. Edremit district and the studied building (Google Earth)

The house gained its importance with the hosting of Mustafa Kemal Atatürk in 1934. The construction of the house began in the first quarter of the 20th century according to the architectural features. After it was exposed to a fire in 1991, the house was unavailable for use (Figure 3). Timber beams, timber slabs and the roof of the building collapsed after the fire.

Figure 3. The studied building a) Outside view of the building b) Inside view of the building

The house has three storeys; basement, ground floor and first floor. The house has a courtyard. The basement height is 2.10 m, while the ground and first floor heights are both 3.50 m. The basement floor plan can be seen in Figure 4.
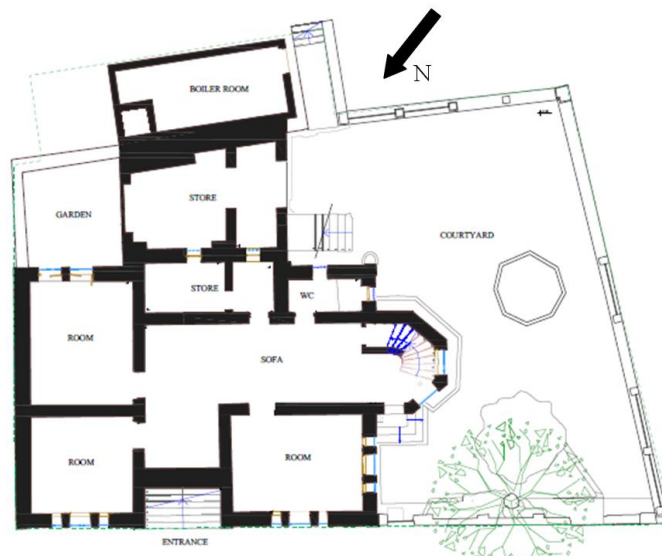

Figure 4. The basement floor plan of the building

The walls of the building were constructed using brick material. Lime mortar was used as a binding material. Brick was used in the interior and exterior walls. The wall thicknesses are different for the exterior and interior walls. The exterior wall thicknesses are 50cm in the basement, and 40cm in the other storeys. The interior wall thicknesses are 45cm in the basement, 30cm in the ground floor and 25cm in the first floor. Two different techniques were used in the slab constructions. Timber slab was used in the living areas, while reinforced concrete slab was used in the wet areas and the entrance of the building. It is believed that these two types of slabs were constructed at the same time because there were no construction joints in the intersection of the walls, and the slab elevations are equal. Despite the fire, the reinforced concrete slabs are intact today (Figure 5).

Figure 5. The reinforced concrete slab in the entrance part of the building

The reinforced concrete slab and timber slab usage in the construction of the building is shown in Figure 6.
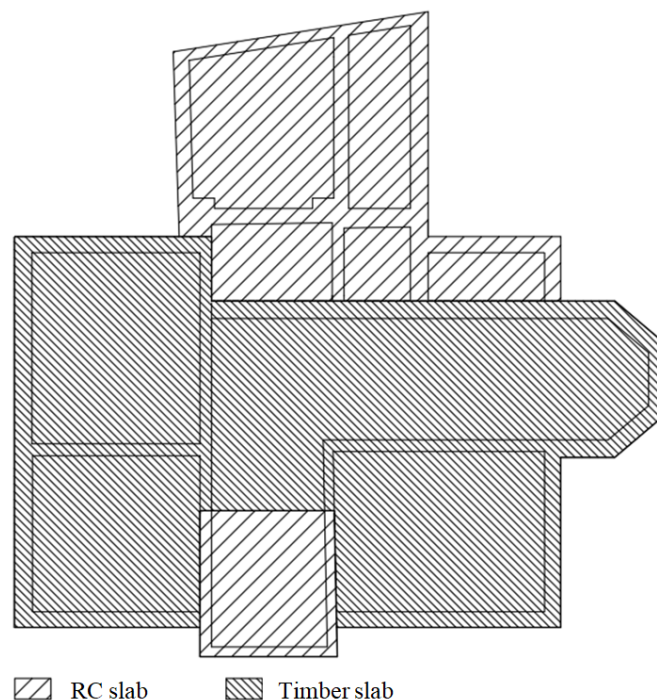

RC slab   Timber slab

Figure 6. The reinforced concrete and timber slabs of the building

4. The Mechanical Properties of the Brick Walls

The mechanical properties such as compressive stress, shear stress and elastic moduli of the walls were investigated by using in-situ flat-jack and shear tests. The single flat-jack method was used for determining the compressive stress and elastic moduli of the walls. In this method, a flatjack is inserted in a cut slot in the mortar and displacements are continuously read while hydraulic oil pressure is inflated into the flatjack (Figure 7). The tests were conducted according to ASTM C1197 and ASTM C1314 [14, 15].

Figure 7. The mechanical tests: Single flat-jack test

The method C was used in the shear test according to ASTM C1531-09 [16]. In this method, the flatjack is horizontally inserted at one end of the test unit (Figure 8). The oil pressure is applied until the slip of the mortar occurs.

Figure 8. The mechanical tests: Shear test

The average compressive stress, shear stress and elastic moduli of the walls are presented in Table 1.

Table 1. Mechanical properties of brick walls

Compressive stress	2.10 N/mm^2
Shear stress	0.50 N/mm^2
Elastic moduli	2750 N/mm^2

5. Vibration Tests

Vibration tests were conducted in-situ by placing sensitive accelerometers on the walls of the building. The Operational Modal Analysis test method was used to obtain the dynamic parameters of structure. Natural vibration frequencies and mode shapes were obtained by using this non-destructive test method.

The dynamic parameters of the structure from output-only experimental data were found by this technique. The loads were environmental forces and the modal identification was based on responses only. The Dynamic Data

Acquisition/Structural Health Monitoring Device Testbox 2010 series data acquisition system was used in the study [17]. Six uniaxial accelerometers were used and for the accuracy of the tests, 20~30 minute test periods were applied. In the sensor placements, the perpendicular orientations were carefully checked for all walls. The sensors were placed on top of the first and second floor corners. Three sensors were placed on each floor. The orientations of the sensors on the plan view are shown in Figure 9.
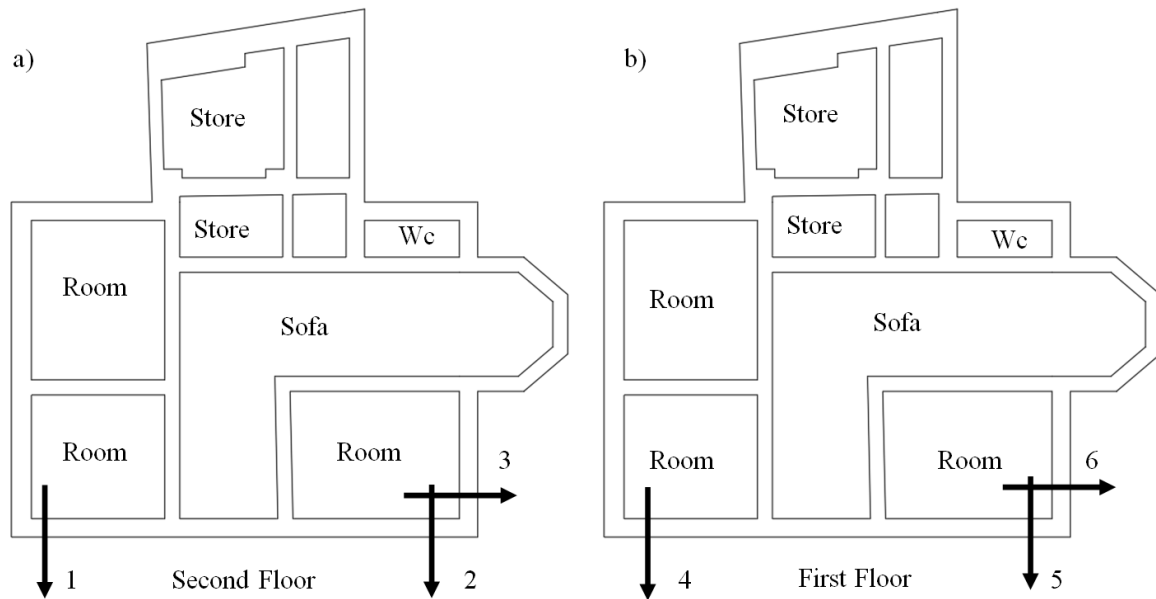

Figure 9. The sensor orientations on plan views a) Second floor b) First floor

The placements of sensor number 5 and sensor number 6 on the second floor and the test equipment can be seen in Figure 10.
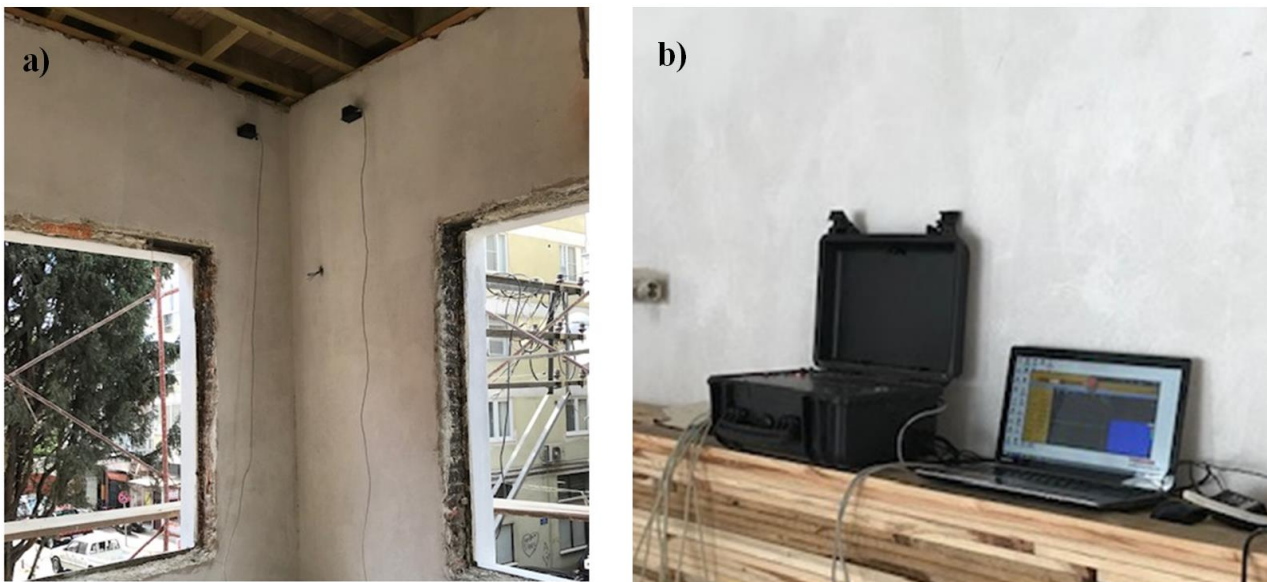

Figure 10. The sensor placements and the test equipment

Frequency Domain Decomposition (FDD) was used in determination of the dynamic characteristics. The singular values of the spectral densities of the test setups are shown in Figure 11. The first mode frequencies can be seen in the figure.
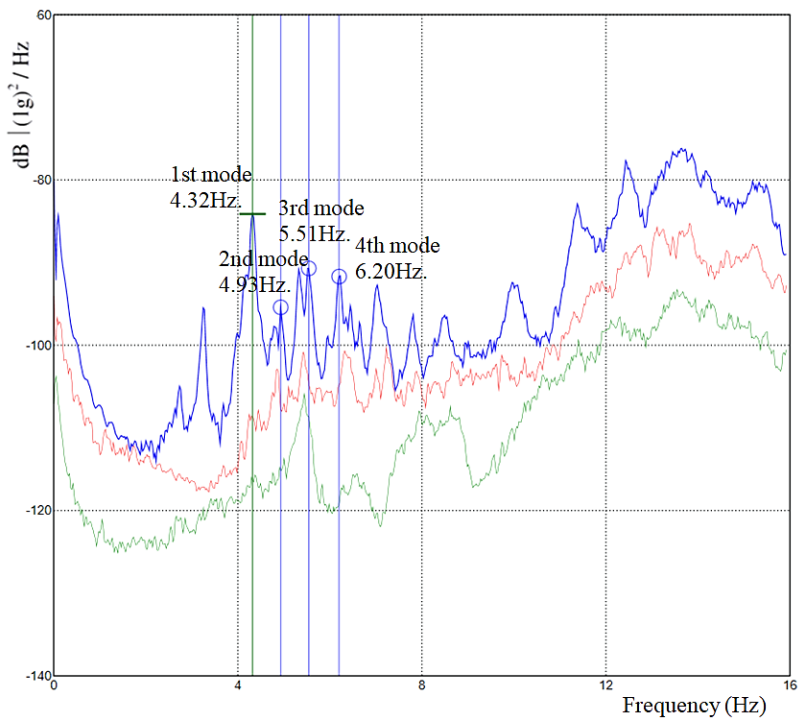
Figure 11. The singular values of the spectral densities

6. Finite Element Analysis

The three-dimensional finite element model of the studied building was prepared using the Algor finite element analysis program [18]. The building is modeled using brick elements having three degrees-of-freedom at every node. The material properties of the walls were obtained from the experimental studies. After the finite element models were prepared, the modal analysis of the building was performed. The mode shapes, natural frequencies and mass participation factors were obtained from numerical analyses. The material properties and the boundary conditions were updated in order to represent the real behavior of the building which was obtained from the experimental vibration tests.

The elastic moduli of the walls were taken with an average of 2250 N/mm^2 after the calibrations. There is only an 18% difference between the flat-jack test results. The first four mode shapes and the frequencies are presented in figure 12. The first mode is the displacement in the y direction, the second mode is the torsion, the third mode is the displacement in the x direction and the fourth mode is the torsion.
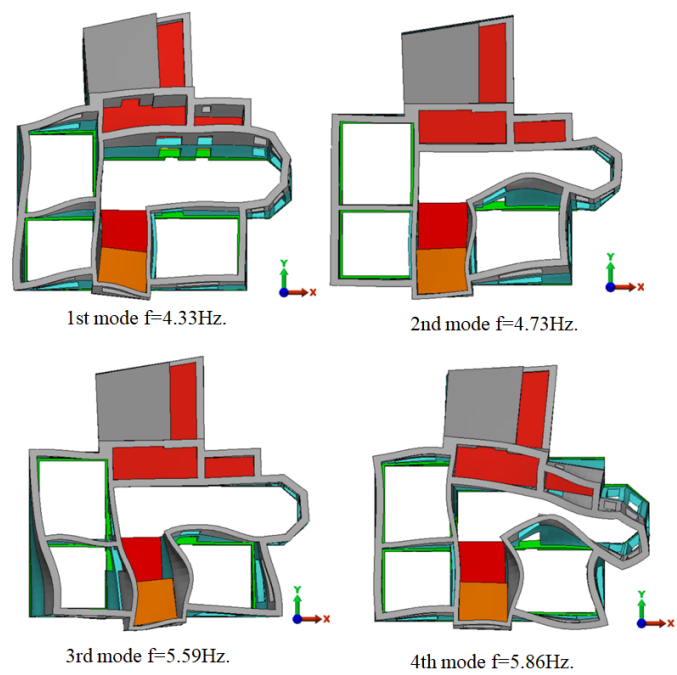

Figure 12. The first four mode shapes and frequencies

The comparisons of the first four mode frequencies of the studied building between the vibration test results and the finite element analysis results after calibrations are presented in Table 2. It was determined that there was a maximum 5% difference between the frequency values. It can be stated that the finite element model of the structure now represents the real behavior of the structure correctly. Earthquake analysis, pushover analysis, and etc. can be done by using this model.

Table 2. First four mode frequencies (experimental vibration test versus finite element analysis)

Mode Number	Vibration test	Finite element	Error
1	4.32	4.33	% 0.23
2	4.93	4.73	% 4
3	5.51	5.59	% 1.43
4	6.20	5.86	% 5.48

The mass participation factors of the first four modes in the x and y directions are presented in Table 3. Due to the lack of horizontal connections between the walls, the whole structure could not be completely included in the mass ratios. Therefore, the total mass participation ratios are low in the first four modes.

Table 3. The mass participation factors of the first four modes in the x and y directions

First mode		Second mode		Third mode		Fourth mode	
x	y	x	y	x	y	x	y
0.12	31.11	0.20	1.32	14.50	0.75	0.46	0.09

7. Conclusions

Understanding the current status of historical buildings will enable them to be restored in a healthy way. The construction techniques, the material usage, the mechanical properties of the walls and the dynamic characteristics of the structure must be determined precisely. The finite element models must represent the real behavior of the structure. Finally, the structural behavior of the building in all load cases should be performed by computer analysis.

Due to the unique construction techniques and material usages of each historical structure, the material properties obtained from the codes and standards are not sufficient for analysing a masonry structure. In some studies, the material properties of the structures were estimated by the researchers without any in-situ tests. Sometimes, the material properties were performed by test methods, but vibration tests were not performed. In all cases, the finite element models could not be sufficient for representing the real behavior of the structure. Only comprehensive on-site investigations and effective in-situ test methods can ensure the correct finite element models of the structure.

In this study, the dynamic identification of an early 20th century civil architectural building was investigated by using on-site investigations, in-situ experimental tests and finite element analysis.

The general conclusions of this study are outlined below.

- To understand the construction techniques and the material usage of the structure is important to ensure the correct finite element model.

- The flat-jack, shear and vibration tests were necessary to identify the mechanical and dynamic properties of the structure.

- The finite element model must be calibrated by comparing the vibration test results with the modal analysis results.

- There is only an 18% difference in elastic moduli values between the tests results and the calibrated finite element models. It can be stated that even if vibration tests are not performed, a close finite element model can be formed only with flat-jack and shear test data.

- After calibration of the material properties, the errors between the vibration test results and the modal analysis ranged from a minimum of 0.23% to a maximum of 5.48%. These results show us that there was very good harmony between the frequencies and the finite element models.

- Due to the lack of horizontal timber beams between the walls, about 20~30% of the whole structure could only be included in the mass ratios after the total of the first four mode frequencies.

- A full understanding from on-site investigations, in-situ tests and the finite element analysis has great importance for the success of the restoration works.

8. Funding and Acknowledgement

9. Conflicts of Interest

The authors declare no conflict of interest.

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