Hindawi
Shock and Vibration
Volume 2018, Article ID 3257434, 11 pages
https://doi.org/10.1155/2018/3257434

Research Article

The Dynamic Properties of Historic Timber-Framed Masonry Structures in Bursa, Turkey

M. Bilal Bağbancı and Özlem Köprülü Bağbancı

Uludağ University, Architecture Faculty, 16059 Bursa, Turkey

Correspondence should be addressed to M. Bilal Bağbancı; bilalbagbanci@yahoo.com

Received 25 May 2018; Revised 11 September 2018; Accepted 16 September 2018; Published 9 October 2018

Guest Editor: Emanuele Reccia

Timber-framed masonry structures are known as an effective earthquake load resisting system in high seismicity regions such as Bursa, Turkey. Intense earthquakes have occurred throughout history; however, many of the traditional timber structures have been able to survive without significant damage until the present day. In this study, six historic two-storied timber-framed masonry structures dating from the nineteenth century in Bursa City are investigated by using laboratory and in situ structural health monitoring tests. Although the houses have the same construction techniques, different masonry infill materials are used inside the timber frames. Stone, adobe, and brick are used as infill materials. Mud and lime mortars are used as binding materials. Mud mortar is used with stone and adobe materials. Lime mortar is used with brick material. The physical, mechanical, and dynamic parameters such as density, specific gravity, porosity, elastic modulus, frequencies, mode shapes, and damping ratios of the studied structures were investigated and the results were comparatively discussed. It is understood that the use of different infill materials affects the dynamic behaviors of these structures.

1. Introduction

Located in the northwest of Anatolia, the city of Bursa, has been a settlement and a cultural centre since ancient times. Bursa has survived until the present day by adapting to the changes resulting from Roman, Byzantine, Seljuk, and Ottoman domination [1–3].

Traditional Bursa houses display a very specialized style and use of materials that are characteristic of the area. The oldest houses have a timber framework, which is filled in with bricks, stones, and adobe materials.

Timber-framed masonry structures are known as an effective lateral load resisting system. The selection of rational solutions in the design of the timber structural system has helped the structures reach the present day without having suffered any important damage. In this context, structural analysis of timber-framed walls and structural health monitoring of these structures are important for understanding the behaviour of them.

In the last decades, dynamic monitoring of the architectural heritage and output-only modal identification techniques ensure that the modal parameters of the structures can be obtained. For this aim, operational modal analysis (OMA) is an effective way of providing the dynamic properties such as mode shapes, natural frequencies, and damping ratios [4]. Dynamic tests are performed considering ambient forces such as traffic, wind load, etc. The data are recorded by means of a series of accelerometers installed in specific points of the structure. The recorded data will be then used to evaluate the real values of the model parameters of the structures [5].

The most commonly researched topics on historical timber structures are the structural analysis of timber-framed masonry walls [6, 7] and the long-term monitoring of historical timber buildings [8, 9]. Few investigations on the structural health monitoring of real in situ full-scale historic timber structures exist in the literature. Among these, Diaferio et al. [10] analysed the Saint James Theatre in the city of Corfu (Greece) used as the Municipality House. The study deals with the structural identification of the structure through the analysis of its ambient vibrations recorded with accelerometers. The results of the dynamic tests are compared with the modal analysis of the finite element simulation of the structure. Due to the presence of wooden floors, the evaluation of the structural modal parameters presents some difficulties. Takahashi et al. [11] conducted a field survey with a microtremor measurement for Japanese traditional timber dwelling houses on a part of the Tokai district. The researchers were able to propose an effective seismic retrofit based on a microtremor measurement of the timber structure. Toshikazu et al. [12] studied the seismic and wind performance of a five-storied Pagoda structure. They aimed to interpret the monitoring records for understanding the seismic and wind performance of heritage timber pagodas that have survived for many centuries and to show the long-term monitoring records of the horizontal displacement of the heritage structure. Min et al. [13] studied the dynamic characteristics of a historic wooden structure by ambient vibration testing, presenting a novel estimation methodology of story stiffness for the purpose of vibration-based structural health monitoring. Zhang et al. [14] used a prediction method in the frequency domain for predicting the vibrations in the Buddhist sutra depositary at Yangzhou Zhunti Temple by using a double-confirmation analysis method based on the autospectrum.

In this study; infill materials of six timber-framed masonry houses are investigated in the laboratory and insitu structural health monitoring tests are conducted on full scale of the houses. The physical and mechanical properties such as density, specific gravity, porosity, mass of water absorption, volumetric water absorption, and elastic modulus of masonry infill materials are determined using standard test methods. Structural health monitoring of real in situ full-scale tests is performed in order to find out the dynamic characteristics such as natural frequencies, mode shapes, and damping ratios of houses. The researchers aim to understand the effects of the different infill materials used on the dynamic behaviours of these structures.

2. The Construction Techniques, Materials, and Failures of the Traditional Timber Structures

The construction type of the studied timber structures is called as "*hımış*" (a Turkish term used to describe the timber-framed system) in Turkey. The construction is a timber frame with masonry infill, such as bricks, adobe, or stones. This type of construction is a variation of a shared construction tradition that has existed throughout history in many parts of the world, from ancient Rome almost to the present day. In Britain, where this technique is identified with the Elizabethan Age, it is referred to as "*half-timbered*;" in Germany it is "*fachwerk*;" in France, "*colombage*;" in Kashmir, India, "*dhajji-dewari*;" and in parts of Central and South America, one variant is "*bahareque*" [15].

In these houses, the single or double-based timber structural system was used as shown in Figure 1 [16]. Floors were built on the stone walls. Stone walls were used for the foundation system. However, in structural timber system designs, sometimes a stone wall bonding beam or a clean-cut stone piece on tightened soil ground was used as the foundation. Through this foundation system, direct access between the timber and soil was obstructed.

Turkey is frequently exposed to destructive earthquakes, approximately one every year. It is one of the few countries with the most rapid period for earthquake-based loss of lives [17]. Bursa city has experienced numerous earthquakes throughout history. Many of the historical monuments fully or partly collapsed in these earthquakes; however, traditional timber structures are able to survive without significant damage until present day. The severity of the earthquake caused this type of structure to crack, plaster to fall, mortar to fail, lost or failed connections, large lateral displacements, dislodgement of the masonry infill, and failed foundation connections [17, 18].

An important factor in the performance of the walls was the use of weak, rather than strong mortar. It is poor when field rubble is used and bonded with mud mortar, without quoins and with no through stones, etc. Different from reinforced and masonry buildings, for timber-framed buildings the shedding of the plaster and stucco in both the large and small earthquakes was similar. The only visible manifestation of earthquake excitation was the presence of cracks in the interior plaster along the walls and at the corners of the rooms. On the exterior, unless the masonry was covered with plaster, it is difficult to see damage with the naked eye. At the same time during the earthquake, the presence of a soft story results insignificantly increased deformation demands, and puts the burden of energy dissipation on the first-story framing elements. In the structural system for some traditional timber-framed buildings there are no strong and stiff elements such as bracing to attract the full lateral force of the earthquake. In these cases, it is difficult for such a traditional timber frame to survive during a strong earthquake. Thus, while these structures do not have much lateral strength, they do have lateral capacity. These buildings respond to seismic forces by swaying with them, rather than by attempting to resist them with a rigid frame like those that have bracing elements.

The connections of roof, floors, vertical framing elements, and bracing elements make the building a single solid structure unit and are important features for holding a building together during earthquakes. Thus, the connections between the members must be strong enough to hold together without loosening or worse, completely failing [18].

Resonance with earthquake vibrations is a principal factor in the cause of earthquake damage to buildings in general. The controlled sliding and cracking of the infill masonry reduces the infill frame structure's ability to resonate with the earthquake by providing damping, just as a shock absorber does for a car [19].

3. The Studied Traditional Timber Structural Houses

The studied houses are in Görükle and Ürünlü villages. They are 10 km from Bursa city centre. Bursa city is the second

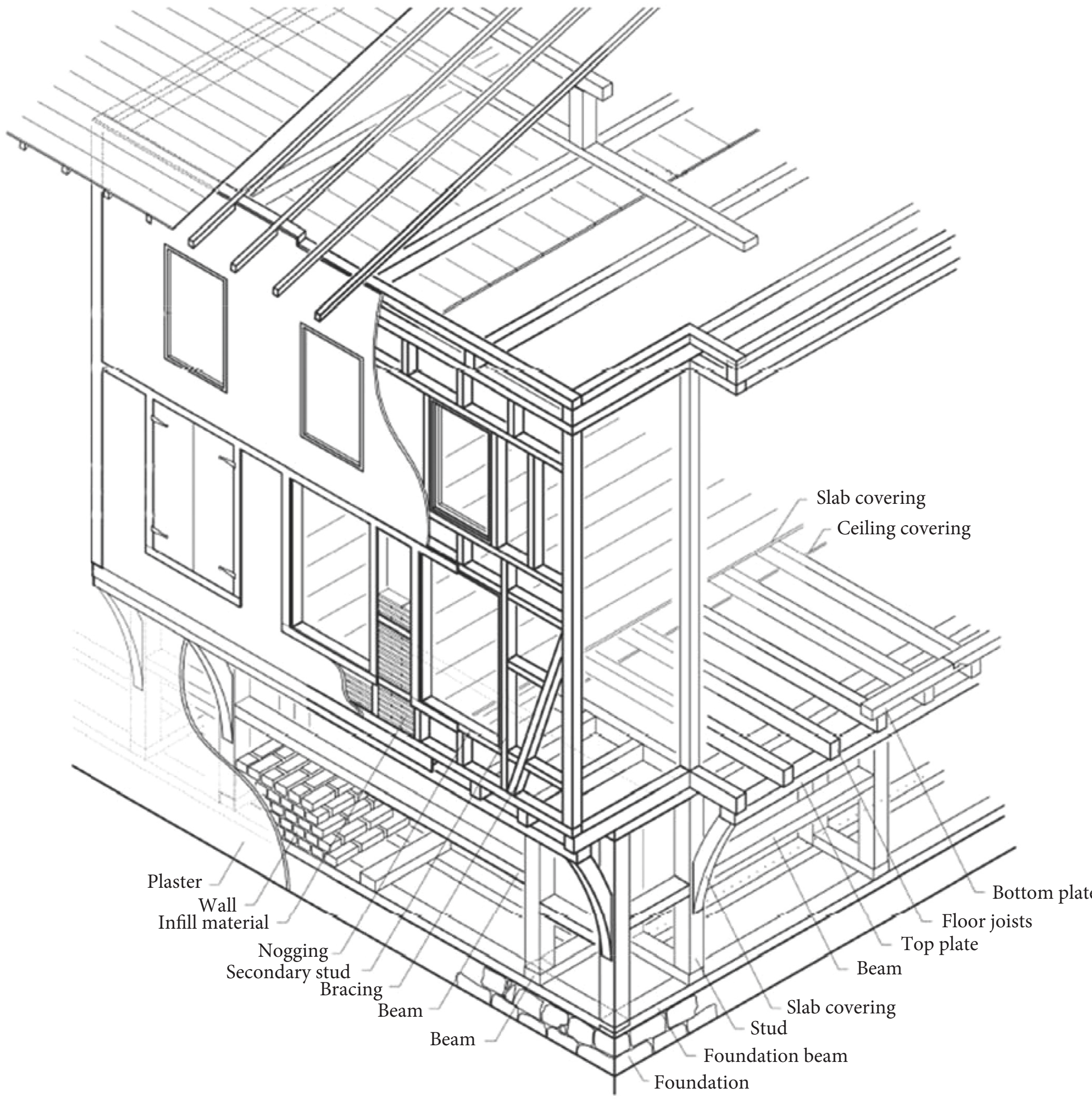


Figure 1: Double-based timber structural system [16].

largest metropolitan area after Istanbul and is located in the Marmara Region of Turkey. The Izmir-Bursa highway separates Görükle and Ürünlü villages. Görükle is to the north and Ürünlü is to the south of the highway (Figure 2). Ürünlü was also known as "Kitai/Kite or Kete" in history.

The villages still maintain their authenticity and integrity. However, they require urgent intervention because they suffer from neglect and deterioration. The villages preserve their natural topography, authentic materials, and construction techniques through their traditional lifestyle. The houses form a tight fabric and are isolated from the public space by high stone walls, creating a private space inside.

The *taşlık* (courtyard) area is accessed directly after the main door, and is surrounded by the kitchen, storage area, toilet, and stable. The timber pillars that support the upper floor are seen from the *taşlık* space. The rooms on the upper floor open on to the hall called the *sofa* [20].

The studied houses have two floors and every floor has a separate function and identity. The entrance floor is a passage area that connects to the upper floor via the stairs. The stable, storage area, and toilet are on the ground floor. The upper floor hosts the "summer" spaces. This construction system uses a timber frame with masonry infill, such as bricks, adobe, or stones. The ground and upper floor plans of a sample house are shown in Figures 3 and 4.

The diagonal elements are formed as straight or curvilinear forms, and the timber elements are supported by timber beams. To fix the timber elements together, metal nails (*mıh*) were used. The timber edges are chamfered and nailed with wrought iron elements. The dimensions of the metal nails are 20, 15, 12, 8, and 6 cm. Timber from pine trees was used in the construction system.

The studied timber structures have similar timber frames but infill materials are different. Stone and mud mortar is used as an infill material in House 1 and House 2, while brick

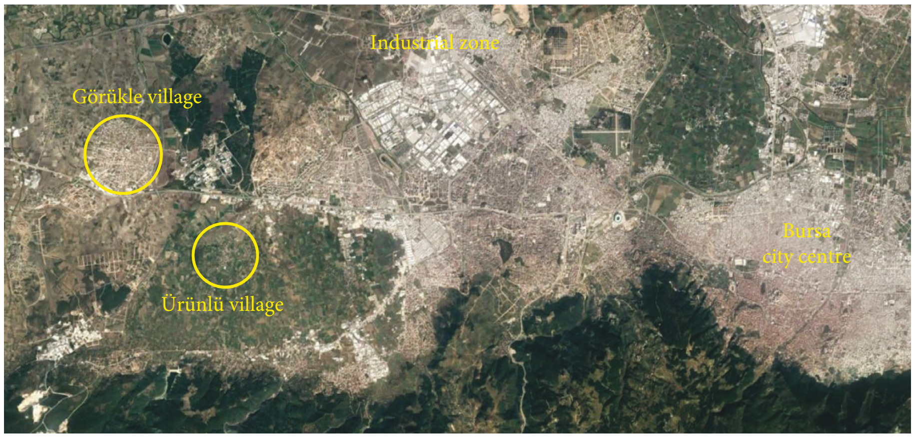


Figure 2: Location of Bursa Ürünlü and Görükle villages in Google Earth view.

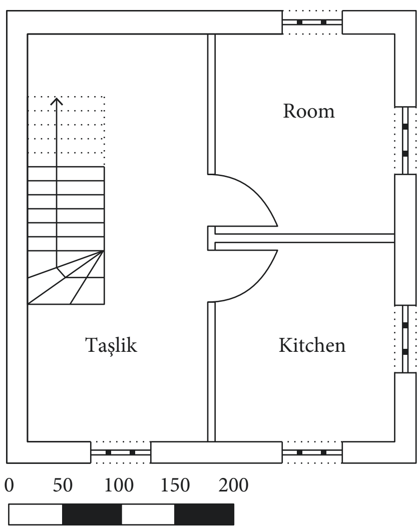


Figure 3: The ground floor plan.

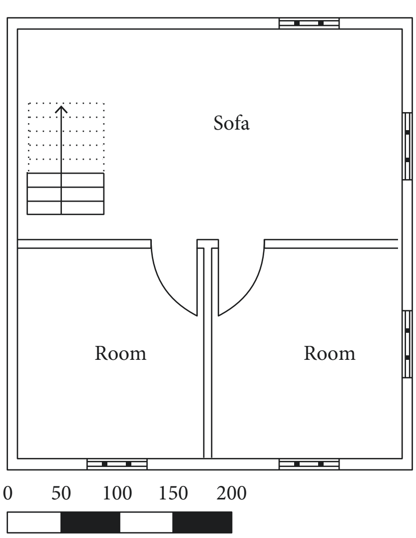


Figure 4: The upper floor plan.

and lime mortar is used as an infill material in House 3 in Görükle village. Adobe and mud mortar are used as an infill material in the houses of Ürünlü village. The houses dated from the nineteenth century. Three of them are in Görükle village and the other three are in Ürünlü village.

The geometrical and architectural features such as the dimensions of the 1st and 2nd floors, story heights and weights, and infill material types of the studied houses are shown in Table 1.

4. The Laboratory and Nondestructive Tests

The experimental characterization of the materials used as an infill material was based on physical and mechanical tests. The materials are stone, brick, and adobe as shown in Figure 5. Density (β, g·cm^{-3}), specific gravity (γ, g·cm^{-3}), porosity (p, %), mass of water absorption (Ks, %), volumetric water absorption (Hs, %), and elastic modulus (E, N·mm^{-2}) were determined using standard test methods [21, 22].

The average results of the experimental tests are shown in Table 2.

The height of the stone material, the height of the brick material, and the thickness of the lime mortar varies between 7 and 15 cm, 5 and 7 cm, and 3 and 4 cm, respectively. The elastic modulus of lime mortar is calculated 1300 N·mm^{-2} in situ tests. The dynamic parameters such as fundamental frequency, mode shapes, and damping ratios of timber houses constructed by using different infill materials such as adobe, brick, and stone were investigated using nondestructive test methods. The technique utilized to obtain the dynamic parameters of the buildings is called operational modal analysis (OMA). The choice of using an operational modal analysis method derives from the necessity to know the modal parameters of a structure with a nondestructive testing method, because the structures have cultural historical value. The technique allows the possibility to extract the modal parameters (natural frequencies, mode shapes, and damping ratios) from output-only experimental data obtained by mean of ambient vibration testing [23]. In this technique, the loads are unknown and the modal identification has to be carried out based on responses only [24].

Table 1: The geometrical and architectural features of studied houses.

House in Görükle 1	1st floor	2nd floor	Photo
Dimensions (m)	8.10 × 5.50		
Weight (kN)	299.12	307.67	
Height (m)	2.80	2.60	
Material	Stone-filled timber frame		
House in Görükle 2	**1st floor**	**2nd floor**	**Photo**
Dimensions (m)	10.17 × 7.27		
Weight (kN)	421.48	429.24	
Height (m)	3.00	2.70	
Material	Stone-filled timber frame		
House in Görükle 3	**1st floor**	**2nd floor**	**Photo**
Dimensions (m)	13.30 × 10.20		
Weight (kN)	569.06	531.54	
Height (m)	3.20	2.60	
Material	Brick-filled timber frame		
House in Ürünlü 1	**1st floor**	**2nd floor**	**Photo**
Dimensions (m)	5.74 × 5.60		
Weight (kN)	189.17	207.16	
Height (m)	2.90	2.70	
Material	Adobe-filled timber frame		
House in Ürünlü 2	**1st floor**	**2nd floor**	**Photo**
Dimensions (m)	11.25 × 8.00		
Weight (kN)	269.72	320.31	
Height (m)	2.80	2.60	
Material	Adobe-filled timber frame		
House in Ürünlü 3	**1st floor**	**2nd floor**	**Photo**
Dimensions (m)	8.13 × 7.82		
Weight (kN)	261.56	304.31	
Height (m)	2.80	2.60	
Material	Adobe-filled timber frame		

(a) (b) (c)

Figure 5: The masonry infill materials of the studied houses. (a) Adobe. (b) Stone. (c) Brick.

Table 2: Physical and mechanical properties of infill materials.

Sample	β (g·cm^{-3})	γ (g·cm^{-3})	p (%)	Ks (%)	Hs (%)	E (N·mm^{-2})
Stone	2.30	2.65	13.21	7.50	11.40	12000
Brick	1.80	2.70	33.30	18.20	29.80	7000
Adobe	1.40	2.20	63.64	–	–	800

β = density; γ = specific gravity; p = porosity; Ks = mass of water absorption; Hs = volumetric water absorption; E = elastic modulus.

The modal parameters of the civil engineering structures such as bridges, dams, buildings, and towers can be obtained from the tests. Real case examples of some engineering structures can be found in Foti et al. [25], Wei-Xin and Zhou-Hong [26], Sevim et al. [27], and Peeters and Roeck [28].

The accelerometers used are very low-noise sensors and named Sensebox 7001/02/03 depending on the number of axes included. In this study, Sensebox 7001 monoaxial accelerometers are used. This series is an ideal solution for forced vibration dynamic identification, shake-table tests, machinery health monitoring, and structural health monitoring of relatively less rigid structures. They have wide selection options from ±2 g – 400 g measurement range and 0–4000 Hz bandwidth. The Testbox 2010 series data acquisition system was used for structural health monitoring of the houses. The product, which has signal amplifiers at channel inputs, is compatible with most of the frequently preferred sensors in civil engineering tests [29].

The modal analysis tests are performed on six timber houses in Görükle and Ürünlü villages in Bursa City. Studied houses have two stories and have the same plan types. Only the difference is the use of infill materials in the construction of the walls. The sensors were placed in the x and y directions at the corner walls inside the houses. They were placed at the top of the second floor and at the top of the first floor. The sensor placements and test equipment are shown in Figures 6 and 7.

Two measurements were made for at least 30 minutes for each. One of the sensors at the second-floor level was the reference sensor until the end of the measurements. In Figure 8, the sensor placement of the two tests, the placement of the reference sensor, and the whole set of tests are shown. In the first test, sensors are placed at the top of the upper floor corner walls, and in the second test, a reference sensor is left in the same position and the other sensors are placed at the top of the ground floor corner walls as shown in the figure. The sensor placements are the same for all houses. The sensor placements of the houses on plan views are shown in Figure 9.

The ambient vibration tests were performed under environmental conditions, such as traffic and wind. The measurement durations were 30 minutes, and the frequency span was chosen as 0–100 Hz. The singular values of the spectral densities of all the test setups belonging to House 3 in Görükle village are shown in Figure 10 as an example.

The orthogonality between the modes are checked by using modal assurance criteria (MAC). According to the MAC Values, the experimental modes are independent from one another and a good harmony obtained among natural frequencies and mode shapes. In Figure 11, the 2D and 3D presentation of MAC values belonging to House 3 in Görükle village can be seen. The numerical presentation of MAC values belonging to House 3 in Görükle village is presented in Table 3.

The calculated five modes were bending and torsion modes. The first two modes were bending modes, the third mode was torsion, and the fourth and fifth modes were bending as shown in Figure 12. The houses and the calculated first three frequencies and their damping ratios are shown in Table 4. The damping ratios of the first three modes ranging between 1~5%.

5. Effect of Different Infill Material Usage on the Dynamic Behaviors of the Studied Houses

The timber-framed construction techniques of the studied six buildings are similar but the infill materials used are different. Stone with mud mortar was used as an infill material in Houses 1 and 2, while brick with lime mortar was

Figure 6: The sensor placements.

Figure 7: The sensor placements and test equipment.

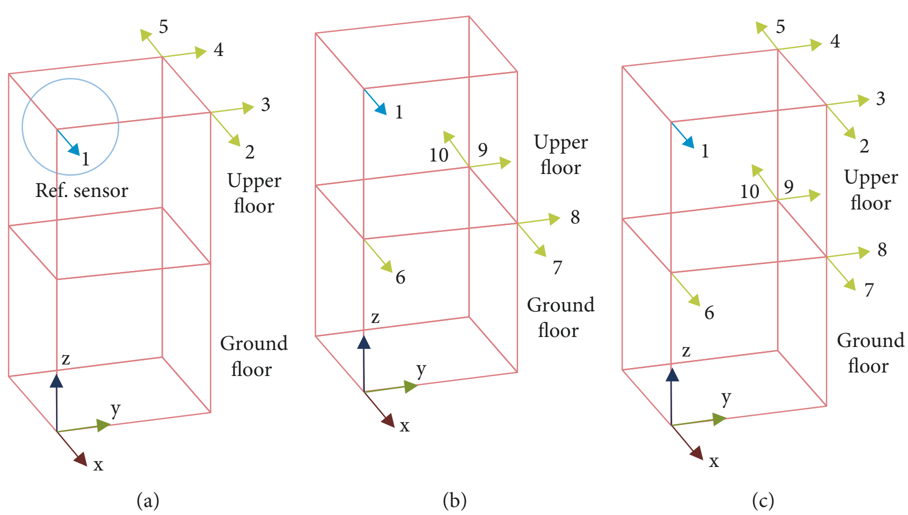


Figure 8: Sensor placements of two-story houses. (a) 1st test. (b) 2nd test. (c) All tests.

used in House 3 in Görükle village. Adobe with mud mortar was used as an infill material in the Ürünlü houses. In this case, timber-framed walls infilled with masonry units have different stiffness ratios and weights. It was observed that the studied houses in Görükle village are about 1.5 times as heavy as the buildings in Ürünlü village. To understand the effect of infill materials used on the dynamic behaviours of the studied houses, the stiffness ratios of the houses were investigated. The fundamental frequency of the houses is in x direction (short side of the houses) according to the test

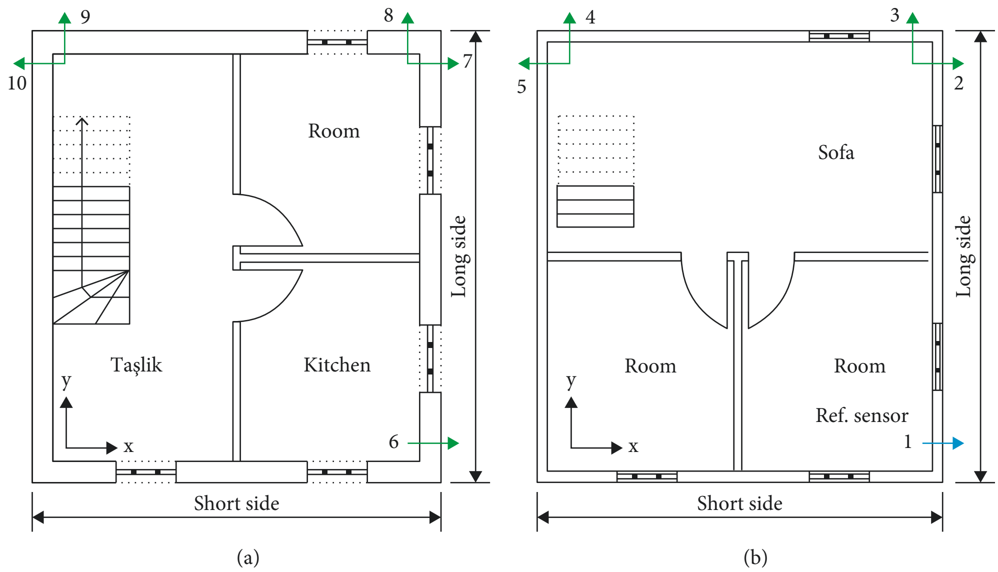


FIGURE 9: The sensor placements of the houses on plan views: (a) ground floor; (b) upper floor.

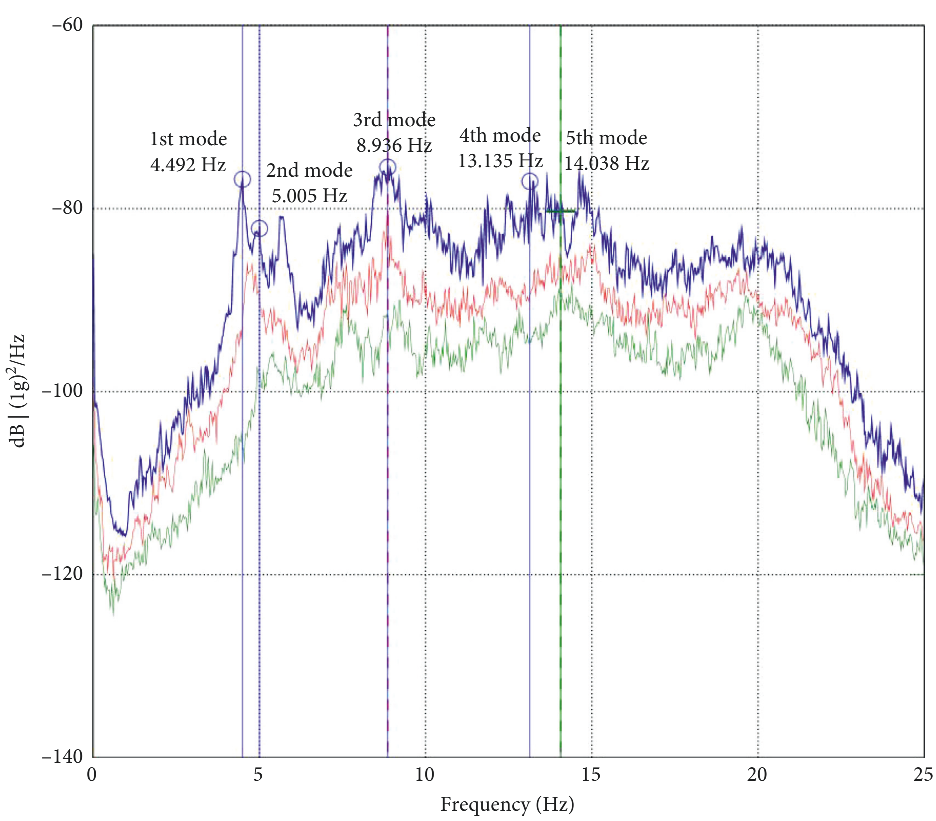
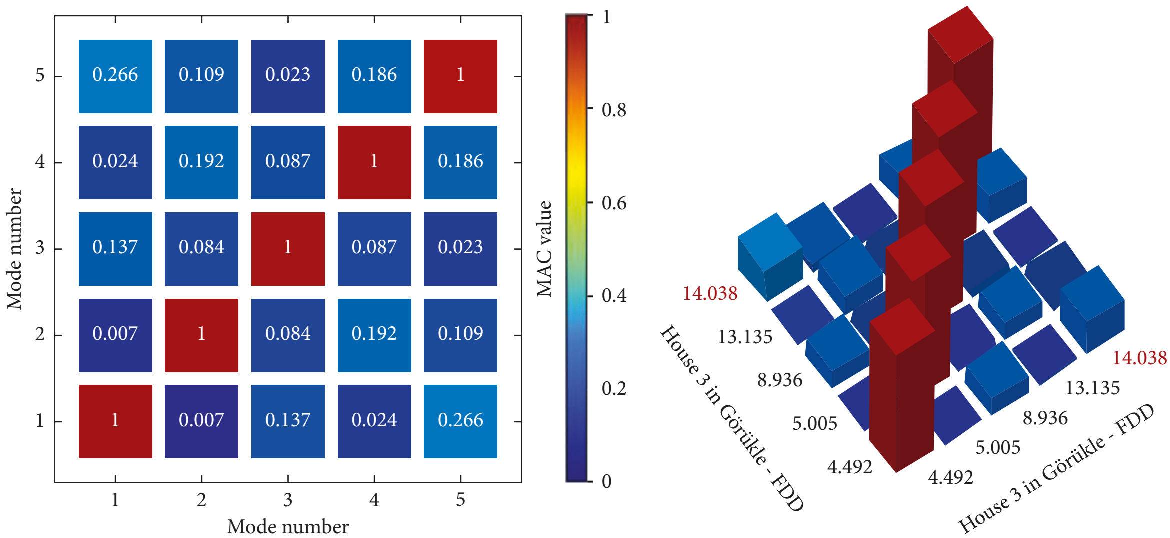


FIGURE 10: The singular values of the spectral densities of a selected house (House 3 in Görükle village).

results. Therefore, the normalized stiffness ratios of the masonry walls in x direction were determined with respect to maximum value with the formula $k = 3EI/L^3$, where k is the stiffness, E is the elastic modulus of masonry walls, I is the moment of inertia, and L is the height, respectively. Elastic modulus of masonry walls were calculated by equation $E = ((t_m + t_u)/((t_m/E_m) + (t_u/E_u))).\delta$ as described by Lourenço et al. [30]. Where, t_{m} and t_{u} represent the thickness of the mortar and the height of the masonry unit, respectively. Efficiency factor δ is taken 0.5 in this study.

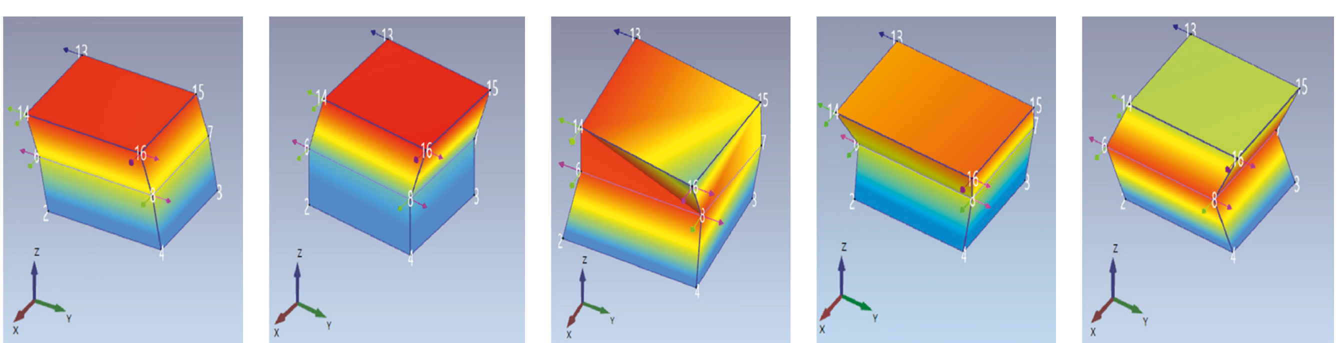


(a) (b)

Figure 11: (a) 2D and (b) 3D presentation of MAC values of House 3 in Görükle village.

Table 3: Numerical presentation of MAC values of House 3 in Görükle village.

Modes	Mode 1 4.492	Mode 2 5.005	Mode 3 8.936	Mode 4 13.135	Mode 5 14.038
Mode 1 4.492	**1**	0.007	0.137	0.024	0.266
Mode 2 5.005	0.007	**1**	0.084	0.192	0.109
Mode 3 8.936	0.137	0.084	**1**	0.087	0.023
Mode 4 13.135	0.024	0.192	0.087	**1**	0.186
Mode 5 14.038	0.266	0.109	0.023	0.186	**1**



(a) (b) (c) (d) (e)

Figure 12: The first five mode shapes of the houses. (a) 1st mode bending. (b) 2nd mode bending. (c) 3rd mode torsion. (d) 4th mode bending. (e) 5th mode bending.

In Figure 13, it is seen that the stiffness ratios of the masonry walls of the studied houses in Görükle village are higher than those of the houses in Ürünlü village. The use of stone and brick as an infill material results in higher stiffness ratios than the use of adobe infill. Also, according to the test results, the first frequency damping ratios of the Görükle houses were higher than those of the Ürünlü houses. Adobe material is composed of mud, clay, and straw. After being

Table 4: The first three modes and damping ratios of the studied houses.

Studied houses	1^{st} mode (Hz)	Damping factor (%)	2^{nd} mode (Hz)	Damping factor (%)	3^{rd} mode (Hz)	Damping factor (%)
House in Görükle 1	3.711	3.515	4.59	2.577	9.375	1.485
House in Görükle 2	4.858	4.354	5.784	2.252	9.931	1.092
House in Görükle 3	4.492	3.004	5.005	2.264	8.936	1.052
House in Ürünlü 1	3.546	2.176	4.465	2.133	5.693	1.622
House in Ürünlü 2	4.11	2.566	5.095	2.360	8.906	1.071
House in Ürünlü 3	4.773	1.611	6.146	2.218	7.584	1.834

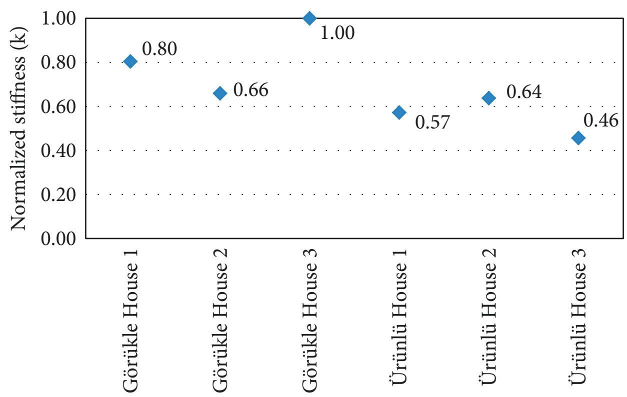


Figure 13: The normalized stiffness ratios of the masonry walls according to the fundamental frequencies in x direction.

compressed into the mould, the adobe blocks are sun-baked in the open air. Because of its earth content, adobe blocks have very weak mechanical behaviours under lateral loads and cannot generate more damping with friction like stone or brick infill materials.

On the other hand, the highest stiffness ratio belongs to House 3 in Görükle. It is believed that the highest stiffness ratio is due to use of brick with lime mortar as an infill material.

6. Conclusions and Recommendations

In this study, the physical, mechanical, and dynamic properties of six timber-framed masonry structures in Görükle and Ürünlü villages were investigated by using laboratory and structural health monitoring tests. The selected timber-framed houses have the same construction techniques, but different infill materials are used.

Considering all the investigations in situ, in the laboratory and by nondestructive structural health monitoring tests, the following results are obtained:

(i) The use of adobe and brick as an infill material ensures the lightness of the structural system unless it is exposed to water because of its high porosity characteristics.

(ii) Houses constructed by using stone and brick infill materials have 1.5~2 times higher first mode damping ratios than those resulting from adobe use.

(iii) Houses constructed by using stone and brick infill materials have higher stiffness ratios than those resulting from adobe use.

(vi) The use of brick with lime mortar as an infill material ensured a 30%–50% higher stiffness ratio than the houses constructed by stone and adobe with mud mortar as an infill material, respectively.

In conclusion, it is understood that the infill material used affects the dynamic behaviours of the timber-framed masonry structures. These structures were built with a holistic design understanding, and it is believed that they will survive for many years, subject to regular maintenance and repairs.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

In this paper, the results of a research project carried out by the authors are utilized, supported by Uludag University (no. OUAP(MM)-2015/32).

References

[1] K. Baykal, *Bursa and its Monuments*, Aysan Press, Bursa, Turkey, 1950, in Turkish.

[2] I. Tekeli, "Three conversion period in Bursa history," in *Proceedings of International Conference on Bursa and the*

Region in the Seven Hundredth Anniversary of the Establishment of the Ottoman Empire, Chamber of Architects, Bursa, Turkey, 1999, in Turkish.

[3] Z. Yenen, "The establishment and development of Turkish cities in Ottoman period with the context of complex system," Ph.D. dissertation, Istanbul Technical University, İstanbul, Turkey, 1987, in Turkish.

[4] M. Diaferio, D. Foti, and F. Potenza, "Prediction of the fundamental frequencies and modal shapes of historic masonry towers by empirical equations based on experimental data," *Engineering Structures*, vol. 156, pp. 433–442, 2018.

[5] D. Foti, "Non-destructive techniques and monitoring for the evolutive damage detection of an ancient masonry structure," *Key Engineering Materials*, vol. 628, pp. 168–177, 2015.

[6] A. M. Gonçalves, J. G. Ferreira, L. Guerreiro, and F. Branco, "Experimental characterization of timber framed masonry walls cyclic behaviour," *Structural Engineering and Mechanics*, vol. 53, no. 2, pp. 189–204, 2015.

[7] L. A. S. Kouris, H. Melreles, R. Bento, and A. J. Kappos, "Simple and complex modelling of timber framed masonry walls in Pombalino buildings," *Bulletin of Earthquake Engineering*, vol. 12, no. 4, pp. 1777–1803, 2014.

[8] F. Lanata, "Monitoring the long-term behaviour of timber structures," *Journal of Civil Structural Health Monitoring*, vol. 5, no. 2, pp. 167–182, 2015.

[9] G. Ting and Y. Na, "The analysis of the long-term structural health monitoring of a typical ancient Titetan Building," in *Proceedings of 4th International Conferences on Structural Health Assessment of Timber Structures*, pp. 361–368, İstanbul, Turkey, September 2017.

[10] M. Diaferio, D. Foti, N. I. Giannoccaro, and S. Ivorra, "Optimal model through identified frequencies of a masonry building structure with wooden floors," *International Journal of Mechanics*, vol. 8, no. 1, pp. 282–288, 2014.

[11] A. Takahashi, K. Kohara, and M. Fukumoto, "A study on vibration performances of Japanese traditional timber buildings based on microtremor measurements," in *Proceedings of 14th World Conference on Earthquake Engineering*, Beijing, China, October 2008.

[12] H. Toshikazu, M. Chikahiro, N. Yasushi et al., "Seismic and wind performance of five-storied Pagoda of timber heritage structure," *Advanced Materials Research*, vol. 133-134, pp. 79–95, 2010.

[13] K. W. Min, J. Kim, S. A. Park, and C. S. Park, "Ambient vibration testing for story stiffness estimation of a heritage timber building," *The Scientific World Journal*, vol. 2013, Article ID 198483, 2013.

[14] Y. Zhang, N. Zhang, Y. Cao, and H. Xia, "A prediction method of historical timber buildings' vibrations induced by traffic loads and its validation," *Shock and Vibration*, vol. 2017, Article ID 1451483, 12 pages, 2017.

[15] P. Gülkan and R. Langenbach, "The earthquake resistance of traditional timber and masonry dwellings in Turkey," in *Proceedings of 13th World Conference on Earthquake Engineering*, Vancouver, BC, Canada, August 2004.

[16] F. Aksoy, "The analyses of the traditional Bursa houses constructed 17th and 18th centuries," Master Thesis, Mimar Sinan University of Fine Arts, Natural Sciences Institute, İstanbul, Turkey, 2011.

[17] M. B. Bağbancı, "Examination of the failures and determination of intervention methods for historical Ottoman traditional timber houses in the Cumalıkızık Village, Bursa-Turkey," *Engineering Failure Analysis*, vol. 35, pp. 470–479, 2013.

[18] A. Doğangün, Ö. İ. Tuluk, R. Livaoğlu, and R. Acar, "Traditional wooden buildings and their damages during earthquakes in Turkey," *Engineering Failure Analysis*, vol. 13, no. 6, pp. 981–996, 2006.

[19] R. Langenbach, "Cross walls instead of shear walls; a proposed research project for the retrofit of vulnerable reinforced concrete buildings in earthquake areas based on traditional hımış construction," in *Proceedings of Fifth National Conference on Earthquake Engineering*, İstanbul, Turkey, May 2003.

[20] Ö. K. Bağbancı and M. B. Bağbancı, "Examination of the structural failures of traditional timber structures constructed by using different infill materials in Bursa, Turkey," in *Proceedings of 6th International Conference on Engineering Failure Analysis*, Leipzig, Germany, July 2016.

[21] TS 699, *Methods of Testing for Natural Building Stones*, Turkish Standards Institute, Ankara, Turkey, 1987.

[22] ASTM C50-00, *Standard Practice for Sampling, Sample Preparation, Packaging, and Marking of Lime and Limestone Products*, ASTM International, West Conshohocken, PA, USA, 2006.

[23] D. Foti, S. Ivorra, and M. F. Sabba, "Dynamic investigation of an ancient masonry bell tower with operational modal analysis," *Open Construction and Building Technology Journal*, vol. 6, pp. 384–391, 2012.

[24] R. Brincker, L. Zhang, and P. Andersen, "Modal identification of output-only systems using frequency domain decomposition," *Smart Materials and Structures*, vol. 10, no. 3, pp. 441–445, 2001.

[25] D. Foti, M. Diaferio, N. I. Giannoccaro, and S. Ivorra, "Structural identification and numerical models for slender historical structures," in *Handbook of Research on Seismic Assessment and Rehabilitation of Historic Structures*, P. Asteris and V. Plevris, Eds., pp. 674–703, IGI Global, Hershey, PA, USA, 2015.

[26] R. Wei-Xin and Z. Zhou-Hong, "Output-only modal parameters identification of civil engineering structures," *Structural Engineering and Mechanics*, vol. 17, no. 3-4, pp. 429–444, 2004.

[27] B. Sevim, A. C. Altunışık, and A. Bayraktar, "Earthquake behavior of Berke Arch Dam using ambient vibration test results," *Journal of Performance of Constructed Facilities*, vol. 26, no. 6, pp. 780–792, 2012.

[28] B. Peeters and G. D. Roeck, "Reference-based stochastic subspace identification for output-only modal analysis," *Mechanical Systems and Signal Processing*, vol. 13, no. 6, pp. 855–878, 1999.

[29] OMA, *Operational Modal Analysis, Release 4.5*, Structural Vibration Solution A/S, Denmark, 2016.

[30] P. B. Lourenço, G. Vasconcelos, and L. Ramos, "Assessment of the stability conditions of a cistercian cloister," in *Proceedings of the 2nd International Congress on Studies in Ancient Structures*, Istanbul, Turkey, July 2001.