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Research Article

CHANGES OF ELASTIC MODULUS OF MASONRY STRUCTURES DUE TO DIFFERENT DAMAGE RATIOS

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ABSTRACT

In masonry structures, it is challenging to determine the mechanical parameter values and to determine the structural behavior accordingly. For this purpose, a vaulted masonry structure resting on successive arches was built using solid clay brick and Khorasan mortar under laboratory conditions. Firstly, the Ambient Vibration Test was applied to the structure, and the natural frequency values and mode shapes of the structure were determined. Then, the displacement values due to the load were determined by using linear displacement transducer placed in different regions by applying force in the lateral direction with the incremental loading and unloading method. The structure was modeled with the Finite Element Method in the computer program by macro modeling technique, where mortar and brick were reduced to one element. The graph of change in elastic modulus due to damage ratios in the structure and the graph of change in natural frequency values due to variable elastic modulus were obtained by using the data of the Incremental Cyclic Loading Test in the Finite Element Model. Finally, Finite Element and Ambient Vibration Test analysis results were evaluated comparatively.
Keywords: Masonry structure, arch vault system, ambient vibration test, changes of elastic modulus of masonry structures.

1. INTRODUCTION

Far from today's technology, there are many examples of masonry structures consisting of stone/brick and, in general, mortar as the binding element. Although they generally have similar structural systems, they differ in material content and the way they're constructed. Furthermore, depending on the location, they are exposed to different external factors (earthquakes, wind, meteorological events, etc.) over the years. As a result of this, different structural damages and material degradations occur in the buildings. Therefore, each structure has its own characteristics and should be examined separately.

By using dynamic tests, dynamic parameters such as natural frequency values, mode shapes, and damping ratio can be determined. Based on these data, many studies have been carried out to determine the material properties of the buildings. Numerical analyses of the Lala Mustafa Pasha

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Mosque in Erzurum, Turkey, were carried out by using the material properties proposed in the literature in Finite Element (FE) model. Also, Operational Modal Analysis (OMA) was performed on the structure, and material prop erties were compared over the data obtained from experimental and numerical analyses. Then, the collapse mechanism of the structure under the influence of an earthquake was examined [1]. The effect of retrofitting and restoration of a masonry structure on the natural frequency values was determined experimentally by applying Ambient Vibration Test (AVT). Using the experimental data, the material properties of FE model were calibrated. Finally, the earthquake behavior of the structure was examined by numerical analysis [2]. The effects of reinforcement on the structure were examined by applying OMA before and after the restoration work in the damaged vault area of a temple built in the 15th century [3]. By applying AVT to a masonry minaret structure, dynamic parameter data of the structure were determined. Then, the earthquake behavior of the structure was investigated by performing linear and nonlinear time history analyses [4]. The dynamic properties of an existing masonry structure in Ankara, Turkey, were determined by experimental and numerical studies. Mechanical parameter data used in the model created with Finite Elements were calibrated with the dynamic data obtained by applying OMA to the structure [5]. A 38.3 meters high industrial chimney in Spain was modeled by FE method. Then, OMA test was conducted on the chimney and FE model of the structure was updated. [6]. Historical arch bridge was modeled by FE method. Then, FE model of the structure was updated according to AVT results. Earthquake effects were investigated in the updated FE model depending on distance between fault and ground [7]. Historical mosque called Hafsa Sultan in Manisa, Turkey was investigated by numerical and experimental analysis. The FE model of the mosque was calibrated by the use of the results obtained from AVT of the structure [8]. Dynamic data were obtained by applying OMA to two historic stone bridges. These data were compared with the results of numerical analysis performed in FE model. Improvements to be made in FE model were mentioned, according to experimental data [9]. Experimental and Operational Modal Analysis methods were applied to the masonry structure model built in the laboratory, and the dynamic data of the structure were obtained by different methods. At the same time, the structure is modeled with FE method in the computer. The results of the different experiments were compared both with each other and with numerical analysis results [10]. In addition to dynamic tests, studies were carried out to have an idea about the lateral displacement capacities, and crack formation zones and shapes under the effect of lateral load of masonry structures. The behavior of repetitive lateral loading effects of solid wall and arch structures constructed as masonry was examined. The models were also finite element modeled and numerical analyses were performed. As a result, experimental and numerical data were compared [11]. Repeated lateral loading was applied to the two existing masonry structures, then, the shifting of the floors and the forms and regions of formation were examined [12]. The behavior of the reinforced and non-reinforced masonry walls with lateral loading was investigated by experimental and numerical analysis. The data obtained were compared, comparatively [13]. A Lateral Load Test was performed on the same size masonry structure model, which was created in the laboratory. At the same time, numerical analyses were performed in the Finite Element Models, which were formed using different element modeling methods, and the results were compared with experimental data [14].

In this study, natural frequency values and mode shapes of a masonry structure that constructed in laboratory were determined by applying AVT. Using the natural frequency values, the initial elastic modulus was determined to be used in the Finite Element Model of the structure. Then, a lateral force was applied to the experimental structure by means of incremental loading and unloading method. Lateral displacements in the structure due to loading effect were determined with the help of 8 linear displacement transducer (LDT) placed in different regions. Due to the loading force, regional separations and cracks started to occur in the structure and partial strength losses occurred as a result of this. To what extent this loss of strength changes the elastic modulus was determined by using the experimental data in the analysis of the Finite

Element Model. In addition, the effect of elastic modulus, which can take different values depending on the damage, on natural frequency values was also examined.

2. EXPERIMENTAL MODEL

The masonry structure model was inspired by the structural system form in the Courtyard of the Ulu Mosque in Manisa, Turkey [15], and was scaled 1:6 considering laboratory conditions. Real structure and experimental model are shown in Figure 1 and 3. The building was 234 cm high with a housing space of 391x196 cm in the plan (Figure 2). Solid clay bricks were used in construction, and brick materials were held together using Khorasan mortar. The structure consists of consecutive arch structures resting on the body walls on the right and left sides of the long direction and on the caps of the columns carried by the marble columns in the middle sections. The structure, which has arch form in both directions, is covered with a single-line vault system. As the foundation, concrete cube specimens with 50 cm edge were used. The total weight of the building is 5460 kg (excluding the foundation elements). When modeling the structure, the tensioning elements were arranged to be removable. Since the system was first tested without a tension element for lateral loading, the change in the elastic modulus due to damage was determined by the analyses performed considering these test results [16].

Figure 1. Real structure.

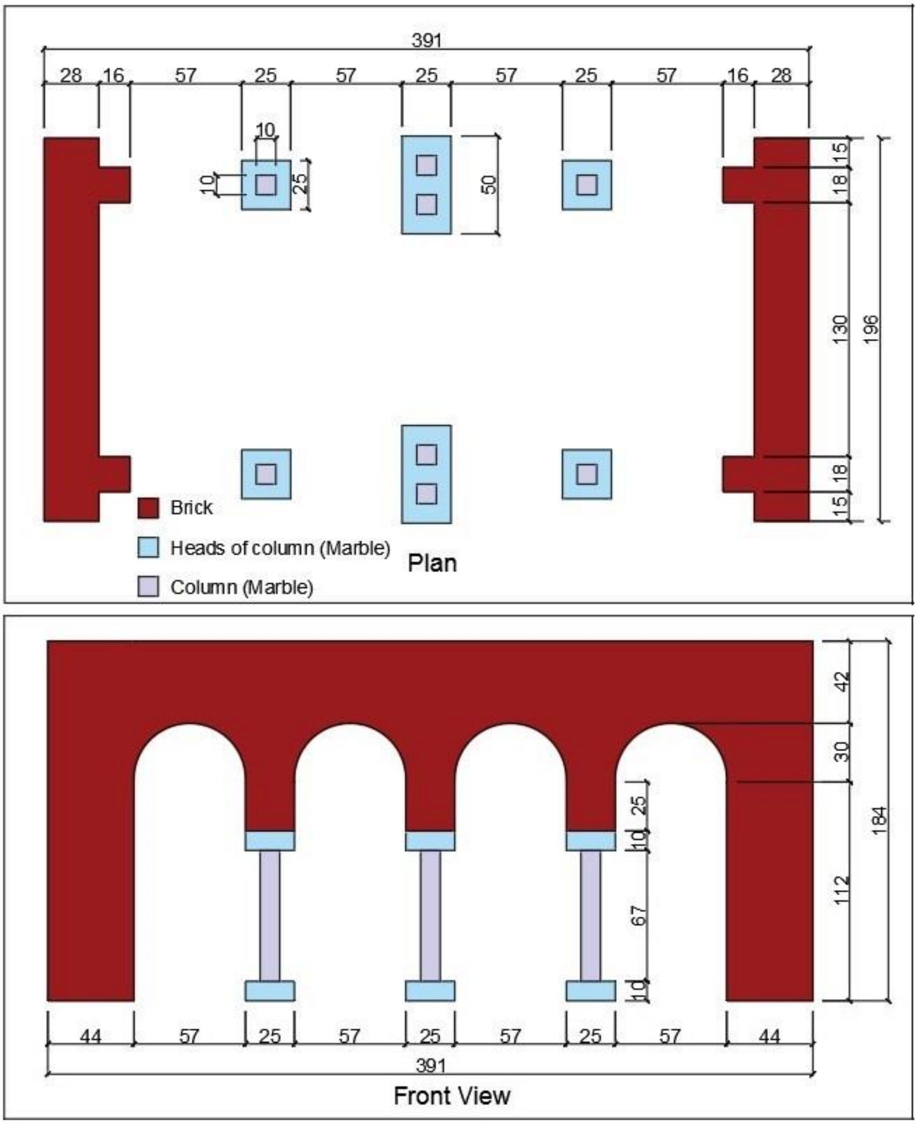

Figure 2. Technical drawing of experimental model (Units are cm).

3. EXPERIMENTAL STUDIES

3.1. Ambient Vibration Test

Ambient Vibration Test (AVT) is a commonly used method because it is a non-destructive test type for masonry structures. AVT is primarily used to extract the dynamic characteristics of the structure such as natural frequency values, mode shapes, and damping ratio. In the masonry structures where it is very difficult to determine the mechanical parameters, the initially accepted material properties are calibrated using these obtained dynamic data results and realistic models can be constituted.

In this test, in order to determine the natural frequency values and mode shapes of the masonry, accelerometers were placed on the peaks where the maximum oscillation was present in the structure (Figure 3). The acceleration data were recorded with the help of a 16 channel dynamic data acquisition device and were processed with ARTeMIS Modal Pro [17] software to extract the natural frequency values and mode shapes of the structure. A total of 16 uniaxial accelerometers were used in this experiment. Since it is not possible to obtain data from all points with a single experiment, two experiments were made and the two data were combined in the ARTeMIS Modal Pro software.

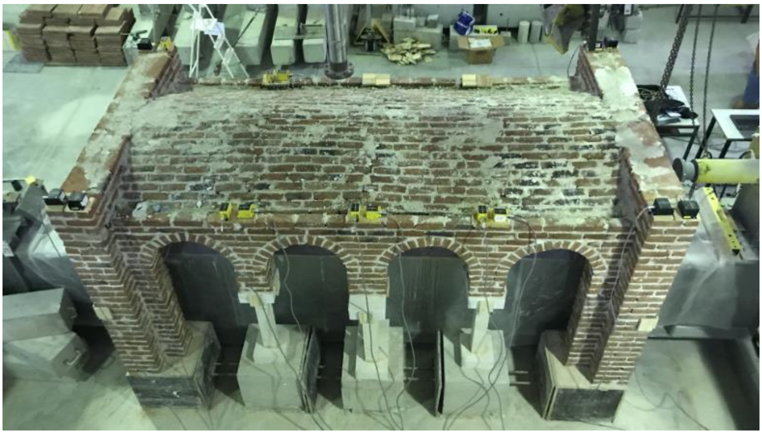

Figure 3. Application of the Ambient Vibration Test on experimental modal.

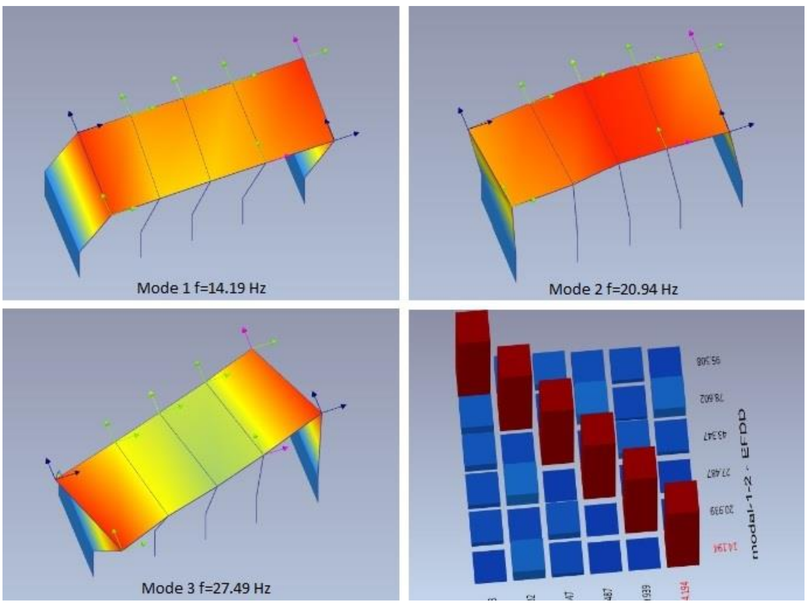

Figure 4. The first three effective modes and MAC Table of EFDD.

In the ARTeMIS Modal Pro software, column elements were defined as frame elements and surface elements such as walls and vaults were defined as surface elements. Accelerometers whose positions and directions were determined in the experiment were introduced to the program and placed in their required positions. After the acceleration recordings were entered into the program, natural frequency values (Table 2) and mode shapes (Figure 4) of the structure were obtained according to different solution methods. Mode 1 became the long direction (x-axis), Mode 2 the short direction (y-axis), and Mode 3 became the torsion around its axis.

3.2. Incremental Cyclic Loading Test

As shown in Figure 5a, a displacement and load controlled loading system was used to push the masonry structure from the body wall. Steel profiles were used to distribute the load to be transferred from the load cell to the wall as horizontally as possible. Approximately 4 kN of force and its multiples were applied to the structure in the horizontal direction, in the form of loading and unloading. As a result of this, lateral displacement amounts due to the load were determined by the linear displacement transducer placed in different regions in the structure. Figure 5b shows the LDT layout.

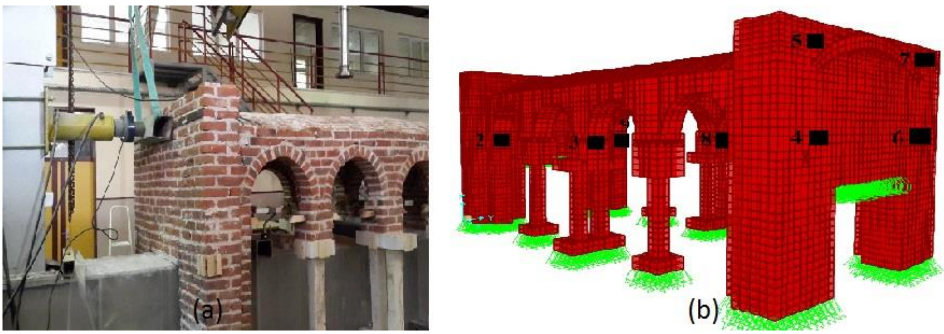

Figure 5. a) Application of the Incremental Cyclic Loading Test b) LDT layout.

Figure 6 shows the lateral load-displacement curves of the structure resulting from lateral loading. LDT which are symmetrical with respect to the long direction (x-axis) are given on the same graph.

Using the graphical results shown in Figure 5 in FE analysis, the partial strength losses due to the amount of damage caused by the lateral force were examined within the scope of the change in slope of lateral load-horizontal displacement graph. Firstly, the displacement values of the structure against the lateral force were determined using lateral load-horizontal displacement graph. Then, the displacement values were determined by applying a loading in the FE model, similar to that in the experiment. By comparing the two results, the elastic modulus in FE model was updated until the difference was minimized. When the best results were obtained, the elastic modulus of the structure was determined. Thus, the elastic modulus change graph resulting from the damages caused by the loads applied to the structure was obtained (Figure 7).

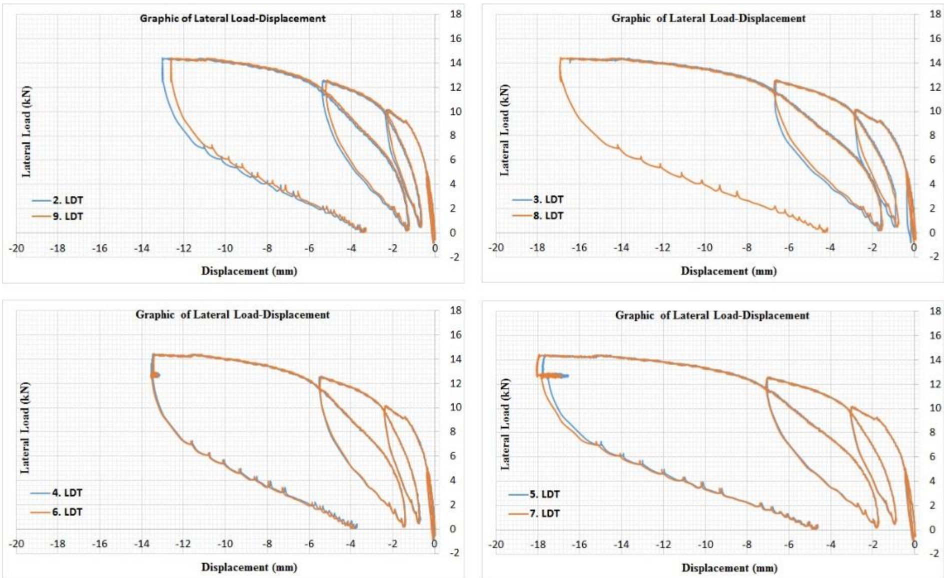

Figure 6. Lateral Load-Displacement graphs of the structure.

4. FINITE ELEMENT MODEL

The masonry structure model was modeled by the Finite Element Method using SAP2000 [18] program. Mortar and brick materials were homogenized and defined as a single element. The structure was created using a total of 24138, 6 and 8-point prismatic elements (Figure 7a). Convergence analysis was performed to determine whether the appropriate number of mesh was reached. Although similar results were obtained in lower numbers of elements, it was studied with as small element sizes as possible in order to use as many dimensional elements as possible in modeling and to apply laboratory conditions better.

For FE model, the mechanical properties of the masonry were determined using the experiments on the material, literature data, and lateral load-displacement curves (Table 1) [16]. The variation of elastic modulus due to lateral load is presented in Figure 8.

Furthermore, Figure 7 shows the first three mode types obtained as a result of the modal analysis of FE model. Active mode shapes that are similar to AVT are as follows; Mode 1: the long direction (x-axis), Mode 2: the short direction (y-axis), and Mode 3: the torsion around its axis.

Table 1. Material properties for FE model (SW: Specific Weight, E: Elastic Modulus).

Material	SW (g/cm^3)	E (MPa)	Poisson's Ratio
Brick - Mortar	1.83	147	0.3
Marble	2.46	30000	0.3

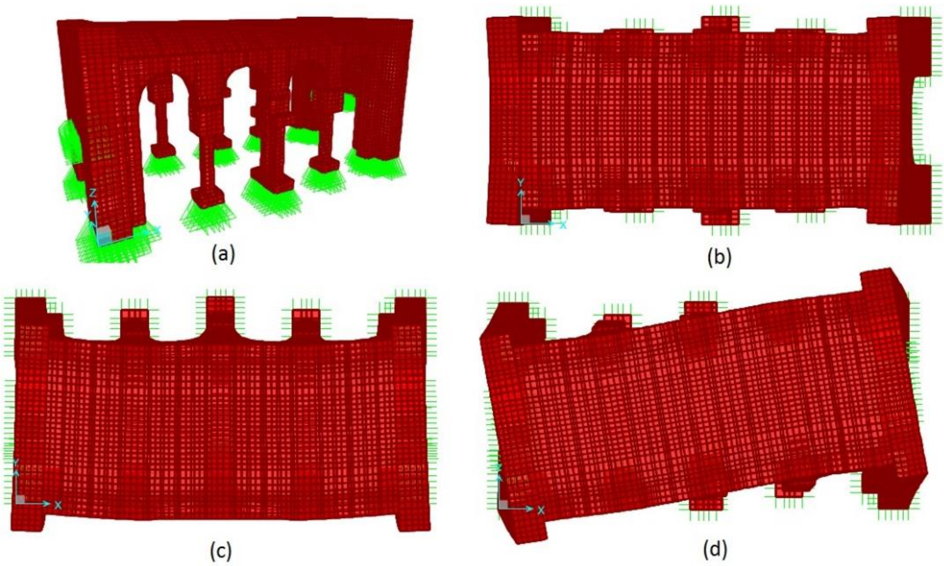

Figure 7. Finite Element Model a) Overview, b) Mode 1, c) Mode 2, d) Mode 3.

5. ANALYSIS RESULTS

The results obtained from experimental and numerical analyses were examined comparatively. Ambient Vibration Test results were analyzed with three different methods in the ARTeMIS Modal Pro software. Natural frequency values obtained from three different methods showed very close results (FDD: Frequency Domain Decomposition; EFDD: Enhanced Frequency Domain Decomposition; CFDD: Curve-fit Frequency Domain Decomposition). Elastic modulus of FE model was calibrated to AVT results and starting values of elastic modulus was determined. Table 2 shows the natural frequency values obtained by the FE model and AVT.

Table 2. Natural frequency values.

	Natural Frequency Values (Hz)				
	AVT			FE model	
Analysis Type	FDD	EFDD	CFDD	E=800	E=147
Mode 1	14.26	14.19	14.21	14.13	07.61
Mode 2	20.61	20.94	20.92	20.40	10.01
Mode 3	27.15	27.49	27.42	24.08	10.85

Figure 8 shows the changes in the elastic modulus due to damages caused by the Incremental Cyclic Loading Test. It is seen that the initial elastic modulus decreases rapidly when small displacement values due to lateral load start to occur in the structure. In the regions where the structure is completely nonlinear, the elastic modulus approaches zero and it is not possible to use this method. In the structure, the effects of the nonlinear behavior on the structure could be better seen after the 6 kN value was exceeded during the Incremental Cyclic Loading Test (Figure 6). Furthermore, it can be seen from the first three active mode values in the graphs shown in Figure 9 that, the variable elastic modulus values affect the natural frequency values to a great extent.

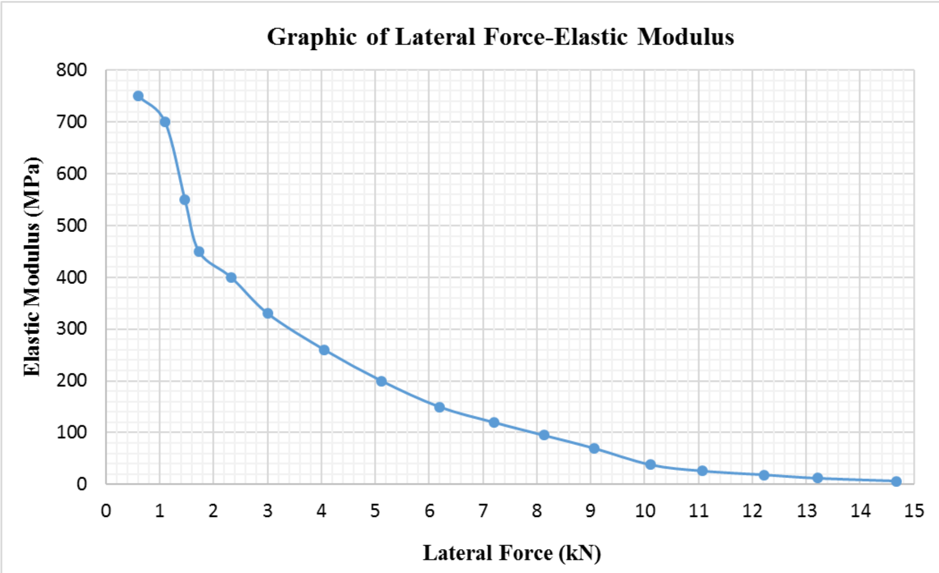

Figure 8. Graphic of Lateral Force-Elastic Modulus.

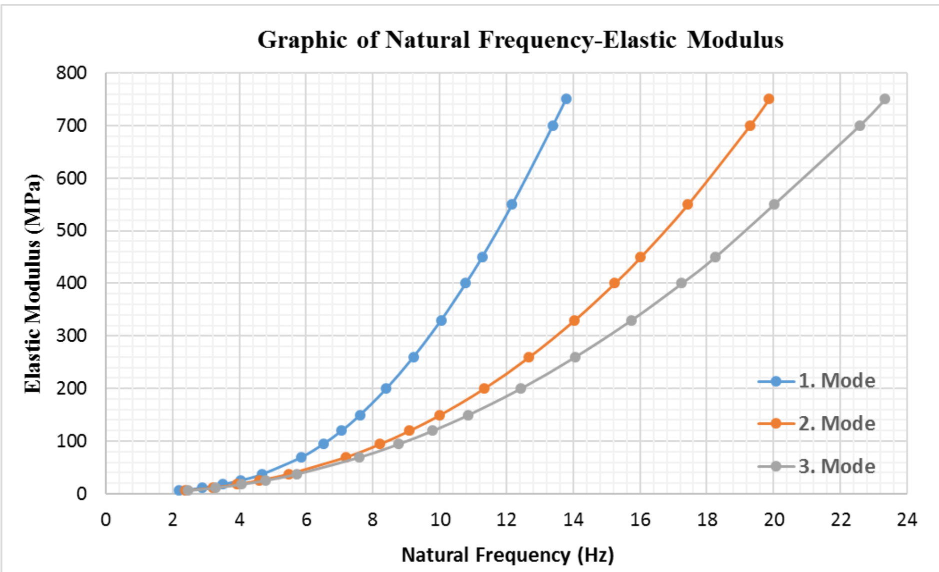

Figure 9. Graphic of Natural Frequency-Elastic Modulus.

6. CONCLUSION

Two different experiments, Ambient Vibration Test (AVT) and Incremental Cyclic Loading Test, were conducted on the masonry structure model which was constructed using brick and mortar materials. The initial natural frequency values of the structure were determined by AVT.

Horizontal displacement corresponding to the applied lateral load were determined by the Incremental Cyclic Loading Test. Using the Incremental Cyclic Loading Test results in the FE model generated in the computer program, the strength losses occurring in the structure with different damage amounts were examined through the elastic modulus.

Considering that it is very difficult to determine the material parameters in masonry structures, it is not easy to ensure getting realistic results from the Finite Element Model. Therefore, the mechanical parameter values to be used must be carefully selected. This is because the behavior of the structure under earthquake or other environmental influences is directly affected by the selected parameter data. According to Ambient Vibration Test, it is seen that the initial elastic modulus to be used in the Finite Element Model should be around 800 MPa. Similarly, according to the data obtained from the Incremental Cyclic Loading Test, it is seen that the initial elastic modulus of the structure should have similar values. However, the masonry structures that is scale model exhibit more rigid behavior under small displacements and ambient effects than they actually are. As a result of this situation is obtained bigger elastic modulus value than is required. As a result of within the scope of the previous study, it was determined that the final elastic modulus of the structure should be around 147 MPa. If the structure were closer to the real dimensions, it would exhibit a more slender behavior and the two values would converge. Therefore, when determining the final elastic modulus value, the special conditions of the structure, such as displacement capacity, dimensions, etc., must be considered. In addition to these, it is seen that the most accurate values can be obtained by using the types of analysis in which non-linear behavior is also taken into consideration.

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