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Ambient Vibration Based Model Updating of A Historical Masonry Church

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Keywords

Historical masonry structures,
FE model updating procedure,
Ambient vibration test,
Dynamic characteristics.

Abstract

This paper presents a finite element model updating procedure of historical Santa Maria Church in Trabzon, Turkey. This process involves ambient vibration method, which is non-destructive experimental measurement, and numerical evaluation using finite element method. Scope of paper, the experimental dynamic characteristics were identified of the church building and the initial finite element model was developed. To minimize the differences between numerical and experimental dynamic characteristics, the manual FE model updating procedure was used. The maximum difference of 34.81% between the numerical and experimental frequencies was reduced to 2.22% with the FE model updating procedure and structural behavior was tried to be determined as close to actual as possible.

1. Introduction

Historical masonry buildings are highly vulnerable to under external factors and experience deterioration in material characteristics and strength over time. Therefore, the finite element (FE) model updating procedure, which allows for the most accurate structural behavior predictions, is quite significant for historical masonry structures built with different construction techniques and materials.

Using the FE model updating procedure, it is possible to estimate the uncertain parameters such as material properties, geometrical characteristics, and boundary conditions in the FE model of structures and identify the structural behavior as close to actual as possible [1-2]. The FE model updating procedure can be classifying two procedures as manual or automated updating. The manual updating procedure is accomplished by trial and error. On the other hand, automated model updating procedure is performed by specialized software [3-4].

To determine the experimental dynamic characteristics, modal testing is used. The modal testing is conducted by two methods, forced vibration test (FVT) and the ambient vibration test (AVT). In AVT, which is non-destructive method to obtain the dynamic characteristics of a structure, the data are collected from the ambient vibrations of the structure and are then processed. On the other hand, modal tests are carried out with a known excitation force and structural response is measured. AVT is more appropriate method to identify the dynamic characteristics of historical structures compared to FVT because it is a totally non-destructive [5-6]. Also, there are many studies using AVT method historical structures [7-11].

In this paper, numerical and experimental dynamic characteristics of historical Santa Maria Church were investigated to show the requirement of the FE model updating procedure for a historical structure. While manual updating procedure was conducted in FE updating procedure, AVT method was employed to obtain the experimental dynamic characteristics of the church building.

2. Testing Process a Brief History of the Santa Maria Church

Santa Maria Church is a unique historical structure located in Trabzon, Turkey. The church building is one of the important historical structure of the Trabzon province, and it is still in use. It is known that it was built between 1869 and 1874 according to historical records. Fig. 1 depicts location and plan view of the church building.

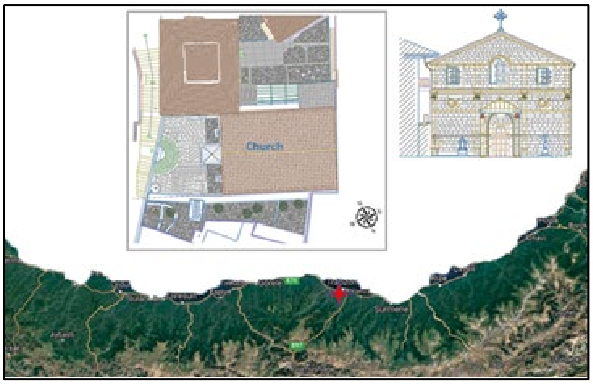


Figure 1. The location and plan view of the Santa Maria Church

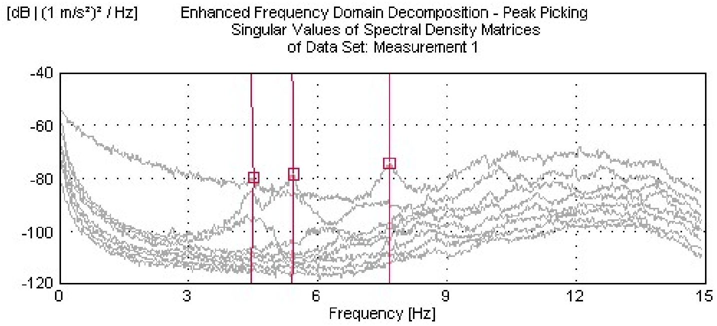
The church building was constructed of stone masonry. The structure is 14x20m in size and has a square plan. The building's height is approximately 12.4m. Vaults and arches were used to cover the roof of the church, which features a wide courtyard. Fig. 2 shows views of the church building.

Figure 2. Views of the church building

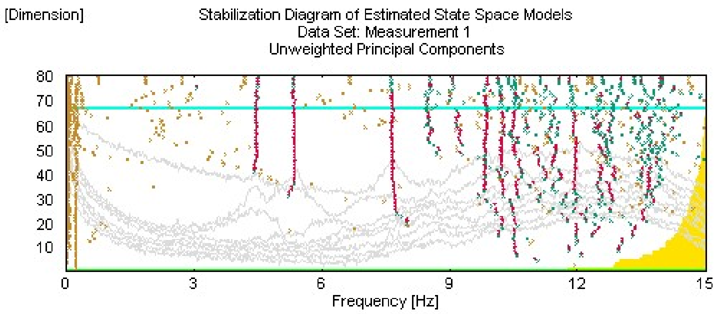
3. Experimental Dynamic Characteristics of the Santa Maria Church

The AVT method was used to determine experimental dynamic properties such as natural frequencies, mode shapes, and damping ratios. AVTs measurement lasted 30 minutes and vibration signals were recorded using data from eight accelerometers situated on the top of the church building.

To process the data, several methods are used, including the Enhanced Frequency Domain Decomposition (EFDD) method in the frequency domain and the Stochastic Subspace Identification (SSI) method in the time domain. The modes in the EFDD method, which is an improved version of the FDD method based on the Fast Fourier Transform (FFT) analysis, are easily identified by picking the peaks in singular value decomposition plots produced from the spectral density spectra of the responses. The SSI method, on the other hand, is a general stochastic state space model. This method is suitable for defining a linear vibratory structure by experimental measurement [12, 13]. The EFDD and SSI methods were employed in this paper to determine dynamic characteristics. Fig. 3 shows the singular values of spectral density matrices (SVSDM) of the data set resulted in by the EFDD method and the stabilization diagram obtained by the SSI method. As can be observed Fig. 3, three natural frequencies were acquired between 0 and 15Hz. In addition, Fig. 4 shows the first three mode shapes for the church building. The first one is transverse mode, the second is longitudinal mode, and the third is torsional mode.

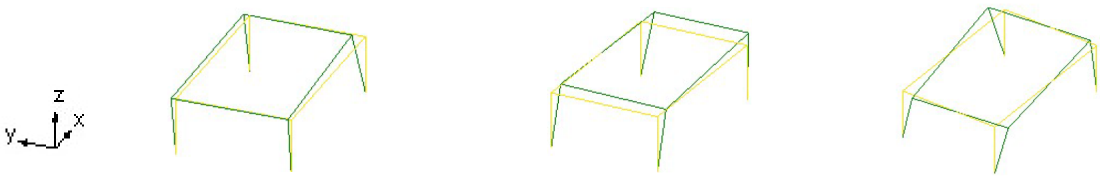


(a)



(b)

Figure 3. (a) SVSDM and (b) stabilization diagram



1st Mode (Transverse) | 2nd Mode (Longitudinal) | 3rd Mode (Torsional)

Figure 4. The first three experimental modes shapes

The experimental natural frequencies and damping ratios of the church building obtained from the EFDD and SSI methods are presented in Table 1. The natural frequencies were calculated within 4.46Hz-7.68Hz and the damping ratios were obtained between 1.36-3.17%. It can be seen that there is good agreement between the natural frequencies.

Table 1. Experimental natural frequencies and damping ratios obtained from EFDD and SSI method

Mode	Frequency (Hz)			Damping Ratios (%)	
	EFDD	Diff. (%)	SSI	EFDD	SSI
1	4.46	0.22	4.47	1.43	2.01
2	5.41	0.93	5.36	1.36	3.17
3	7.67	0.13	7.68	1.97	1.94

4. Initial FE Model and Numerical Dynamic Characteristics of the Santa Maria Church

The FE model of the church was developed using Abaqus software [14]. In the FE models, the masonry elements were represented by a linear tetrahedron C3D4 finite element with four nodes. Meshing size selected was 50cm. The base/support was assumed fixed as a boundary condition. Some views of the FE model are shown in Fig. 5. The major structural elements of the church are stone masonry walls, brick masonry walls, pillars, timber elements, RC elements, and vaults. Table 2 shows the elastic parameters considered in the initial FE model for these structural elements. These values were taken from the relevant literature for the masonry structures [15-18].

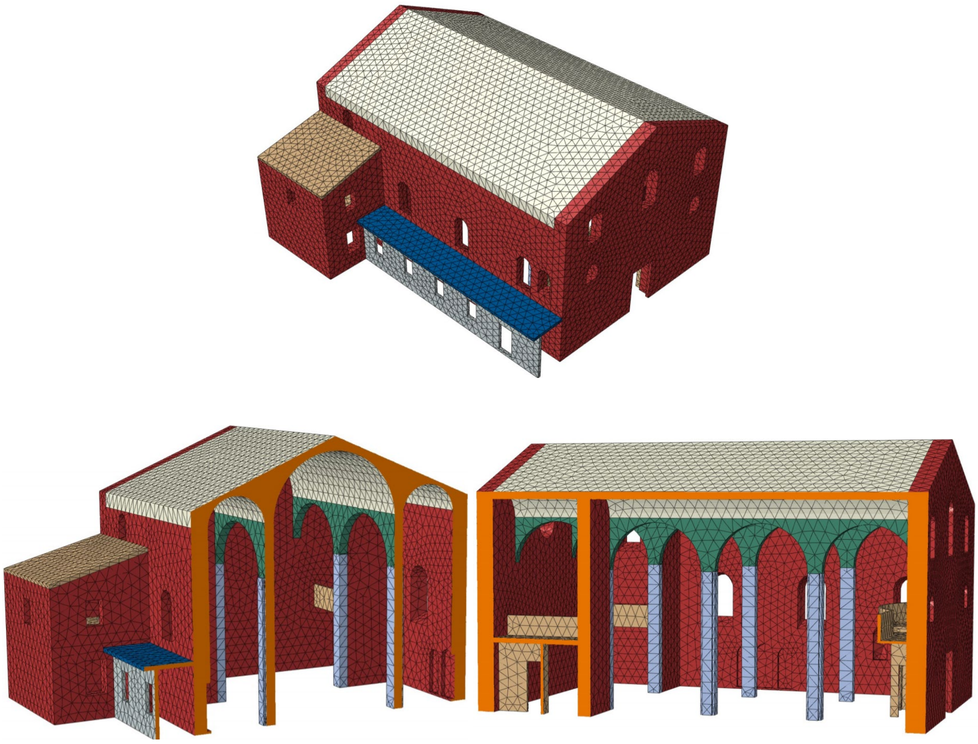


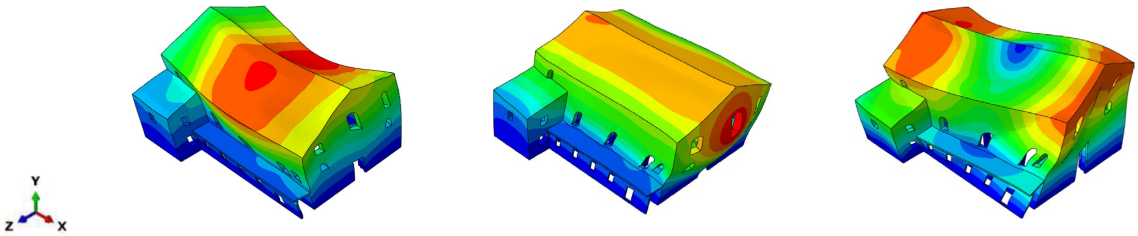
Figure 5. FE model of the Santa Maria Church

Table 2. Material properties included in the initial FE model

Elements	Young's modulus (N/m^2)	Poisson Ratio (-)	Material density (kg/m^3)
Stone Masonry Wall	2.0E9	0.2	2000
Brick Wall	2.0E9	0.2	1750
Timber Elements	1.0E9	0.2	500
Pillar	2.0E10	0.2	2400
RC Elements	2.0E10	0.2	2400

Modal analyses were carried out and the numerical dynamic characteristics were identified. Fig. 6 shows the first three mode shapes and corresponding natural frequencies for the church building. As can be seen, the mode shapes were obtained as transverse, longitudinal and torsional modes.

Table 3 includes differences of the numerical and experimental natural frequencies, and these differences indicates that there is not enough correlation between the numerical and experimental natural frequencies. The differences are more than the literature-recommended limit of 5% [3]. It should be noted that it is essential that the initial FE model should be updated to minimize the differences.



First Mode	Second Mode	Third Mode
(Transverse)	(Longitudinal)	(Torsional)
f1=5.90Hz	f2=7.04Hz	f3=10.34Hz

Figure 6. First three numerical mode shapes and natural frequencies for the initial FE model

Table 3. Comparison of experimental and initial FE model natural frequencies

Mode	Frequency (Hz)			
	EFDD	SSI	Initial Model	Max. Diff. (%)
1	4.46	4.47	5.90	32.28
2	5.41	5.36	7.04	30.13
3	7.67	7.68	10.34	34.81

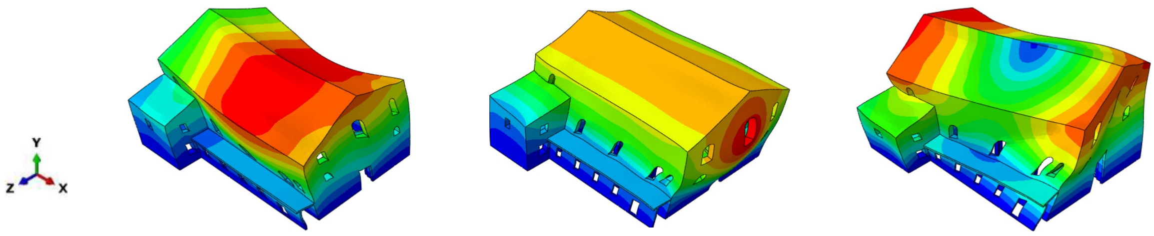
5. FE Model Updating Procedure

To minimize the differences between numerical and experimental dynamic characteristics, the FE model updating procedure is used. As previously stated, the FE model updating procedure can be characterized as manual or automated. The manual model updating procedure was used in this paper to minimize the differences between numerical and experimental dynamic characteristics. Table 4 shows the final material properties of church building.

Table 4. The final material properties

Elements	Young's modulus (N/m2)	Poisson Ratio (-)	Material density (kg/m3)
Stone Masonry Wall	1.20E9	0.2	2300
Brick Wall	1.25E9	0.2	1750
Timber Elements	5.00E8	0.2	500
Pillar	2.0E10	0.2	2300
RC Elements	2.0E10	0.2	2400

Figure 7 depicts the first three mode shapes and corresponding natural frequencies for the church building. Also, Table 5 compares the experimental and updated natural frequencies. The greatest difference was calculated as 2.22%. The method used minimized the maximum difference from 34.81% to 2.22%. The authors thought that the updated FE model of the church building is more representative of the current behavior.



First Mode	Second Mode	Third Mode
(Transverse)	(Longitudinal)	(Torsional)
f1=4.54Hz	f2=5.29Hz	f3=7.73Hz

Figure 7. Final mode shapes and corresponding natural frequencies

Table 5. Comparison of experimental and updated natural frequencies

Mode	Frequency (Hz)			
	EFDD	SSI	Updated Model	Max. Diff. (%)
1	4.46	4.47	4.54	1.79
2	5.41	5.36	5.29	2.22
3	7.67	7.68	7.73	0.78

*The comparison was calculated in accordance with EFDD results

6. Conclusion

FE model updating procedure, which enable to make real structural behavior predictions as credible as possible, is especially important for historical structures which are a significant part of cultural heritage. The purpose of this paper is to show the necessity of the FE model updating procedure for a historical building. In accordance with this purpose, experimental and numerical dynamic characteristics of the historical Santa Maria Church in Trabzon, Turkey was evaluated and FE model updating procedure was carried out. The following conclusions are drawn from the study:

- The first three experimental and initial numerical frequencies were obtained between 4.46-7.68Hz and 5.90-10.34Hz for the church building, respectively. Also, experimental damping ratios were obtained between 1.36-3.17%.
- Experimental and numerical mode shapes of the church building were obtained as transverse, longitudinal and torsional modes.

The maximum difference between the experimental and initial numerical frequencies was 34.81%. To reduce the differences between the numerical and experimental frequencies, the model updating procedure was employed. With the model updating procedure, the maximum difference was minimized from 34.81% to 2.22%.

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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