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Modal identification of a reduced-scale masonry arch bridge with experimental measurements and finite element method

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ABSTRACT

This study aims to investigate modal parameters such as mode shapes, natural frequencies and damping ratios of a reduced scale one-span historical masonry arch bridge constructed in laboratory conditions by performing numerical and experimental analysis. Sarp Dere historical masonry bridge, in Ordu, Ulubey, has 15.5 m in length and 4.75 m in width was chosen as a prototype model. The reduced-scale bridge model and structural details were carried out in the scale of 1:12.5. Operational Modal Analysis (OMA) technique was used for experimental study. The experimental modal parameters of the bridge model were figured out by using Enhanced Frequency Domain Decomposition (EFDD). ANSYS software was used to create 3D finite element (FE) model and to expose the analytical modal parameters of the reduced-scaled bridge model. Moreover, FE model of the reduced-scale bridge model was calibrated based on the experimental results by using the Response Surface based FE model calibration technique to obtain more accurate results. The analysis results of experimental, initial and calibrated FE model were compared. It is noted that there are significant differences between the modal parameters obtained from experimental and initial FE model. Model calibration techniques are beneficial to get a more reasonable FE model.

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1. Introduction

Historical masonry structures have significant valuable for countries due to reflecting their heritage and culture. One the most important masonry structures are masonry arch bridges generally used as a primitive railway infrastructure. Masonry arch bridges can have various styles, sizes and spans. These structures have social, economic and strategic importance; therefore, masonry arch bridge must be repaired, strengthened and protected. Historical masonry arch bridges are exposed to the dynamic loadings of traffic, wind and earthquakes. Therefore, it is critical to determine the modal parameters (such as natural frequencies, mode shapes and damping ratios) of these kinds of structures.

Due to importance of masonry structures for historical point of view, many researches have focused on methods including both experimental and analytical investigations to understand dynamic behavior of these types of structures. AVT Ambient Vibration Test (AVT) or Operational Modal Analysis (OMA) method is one of the most suitable and efficiency method to experimentally determine the modal parameters of these kinds of structures because it is a non-destructive method. Furthermore, these kinds of structures have complicated geometry and uncertain material properties and boundary conditions; therefore, it is difficult to obtain finite element (FE) model of these kinds of structures that truly reflects modal parameters. Thus, FE model generally needs calibration techniques. The procedure includes that modifies or updates the uncertainty parameters in the initial finite element model according to experimental test results to achieve more accurate structural numerical model according to the study done by Friswell MI and Mottershead JE (1995).

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Bayraktar et al. (2009) investigated the dynamic characteristics of the Hagia Sophia bell-tower located in Trabzon, Turkey by using ambient vibration test and operational modal analysis. The modal parameters of the structure were obtained and compared the finite element analysis results. While there are some differences between natural frequencies, a good agreement is achieved between mode shapes. Foti et al. (2012) performed an experimental test on a bell tower to investigate the dynamic structural behaviour of slender masonry structure. Operational modal analysis was performed for experimental works. The main frequencies and damping ratios were obtained from measurements at some relevant locations. Finite element model of the structure was developed and the analysis results compared the experimental results. The initial mechanical values of the structure were calibrated following an iterative approach until a good harmony between numerical and experimental frequencies were achieved. Gentile et al. (2015) investigated the modal parameters of the historic bell tower of the church and got the ambient response of the structure. For operational modal analysis, the study used stochastic subspace identification method. The finite element model of the structure was updated according to the experimental results and calibration procedure consisted of systematic manual tuning, sensitivity analysis, and simple system identification algorithm. After the calibration procedure, the differences between modal parameters of the experimental and finite element analysis results did not exceed %1.20 and enough correlation in terms of mode shapes was acquired.

The study done by Çalık et al. (2014) related to investigation of the dynamic characteristics of the masonry vault of Küçük Fatih Mosque by using Ambient Vibration Test. The natural frequencies, mode shapes and the modal damping ratios of the damaged and restored structure were identified by measuring the vibrational responses of the vault under environmental effects. It is concluded that the first five natural frequencies of the damaged and restored vault increased and damping ratios varied irregularly. Sevim et al. (2011) examined importance of model calibration effects on the earthquake response of masonry arch bridges by using OMA. Modal analysis results of finite element models of Osmanlı and Senyuva historical arch bridges were calibrated according to the in situ modal test results. Earthquake excitation recorded during the Erzincan Earthquake in 1992 was applied to initial and adjusted finite element model of two historical arch bridges and demonstrated the importance of model calibration and ambient vibration testing. Brencich and Sabia (2008) examined Tanaro Bridge constructed in 1866. Dynamic test was performed and natural frequencies, damping ratios and mode shapes of the historical bridge were obtained. The study performed by Bayraktar et al. (2010) is about analytical modelling, modal testing, and finite element model updating for a two-span masonry arch bridge. The results demonstrated that maximum differences in the natural frequencies are decreased on average from 18 to 7% and a good agreement is achieved between analytical and experimental dynamic characteristics after finite element model updating. Nohutcu et al. (2015) investigated the numerical and experimental modal parameters of a historical mosque called Hafsa Sultan in Manisa, Turkey by using FE method and OMA, respectively. Because there were some differences between natural frequencies between FE model and OMA, the finite element model of the structure was calibrated based on the results obtained from ambient vibration test by changing material parameters. More realistic numerical model of the mosque was obtained after calibration process.

A few studies have focused on the response surface method for the structural finite element model calibration in the civil engineering field such as Xin et al. (2015), Marcin et al. (2014), and Zhouhong et al. (2015). Ren and Chen (2010) presented the procedure by a simulated simply supported beam and a full-size precast continuous box girder bridge tested under operational vibration conditions. The results compared with those determined from the traditional sensitivity-based FE model calibration method. It is presented that the model calibration process becomes efficient and converges fast compared with the traditional sensitivity-based model calibration method. The study concluded that the response surface-based FE model calibration procedure is easy and fast to be implemented in practice. Deng and Cai (2010) studied model updating procedure by using response surface method. They used simply supported beam as a numerical example. Also, they applied this method to the model updating of an existing bridge. The study concluded that response surface method works well and obtain reasonable physical explanations for the updated parameters.

This study deals with investigating effectivity of response surface-based finite element model calibration method for historical masonry arch bridges. For this purpose, a reduced-scale model of Sarp Dere historical masonry bridge was built in laboratory conditions and its modal parameters were investigated. Finite element model of the scaled bridges was developed in ANSYS and experimental results were compared with the initial finite element model of the bridge. Calibration of the finite element model was utilized depending on the Operational Modal Analysis results of the reduced-scale model of the bridge by using the response surface-based finite element model calibration method. Correlation studies were conducted between the experimental and analytical modal parameters results of the reduced-scaled historical masonry arch bridge to minimize the uncertain finite element modeling parameters such as material properties and boundary conditions. For future study, the effects of damaged and repaired reduced-scale bridge model on the modal parameters can be investigated by using response surface-based model calibration technique according to the results obtained in this study.

2. Formulation

In general, Enhanced frequency domain decomposition (EFDD) technique is used for Operational Modal Analysis in the civil engineering industries. In the EFDD technique, the spectral density matrix is approximately separated into a set of single degree of freedom (SDOF) systems utilizing the Singular Value Decomposition. It is possible to get exact results in the case where loading is white noise, the structure is lightly damped, and if the mode shapes of close modes are geometrically orthogonal. Even if these assumptions are not satisfied, the results are significantly reasonable according to Brincker et al. (2000) The relationship between unknown input $x(t)$ and the measured responses $y(t)$ is expressed based on Ewins (1984) and Bendat and Piersol (2004) as;

$$\left[G_{yy}(jw)\right] = [H(jw)]^{*}[G_{xx}(jw)][H(jw)]^{T} , \qquad (1)$$

where $G_{xx}(jw)$ is the power spectral density (PSD) matrix of the input, $G_{yy}(jw)$ is the PSD matrix of the responses, $H(jw)$ is the frequency response function (FRF) matrix, and * and superscript T donate complex conjugates and transpositions, respectively.

3. Application

In this study, Sarp Dere historical masonry arch bridge has 15.5m in length and 4.75m in width was considered as a prototype model. The historical bridge is one-span masonry bridge which carries Ottoman architectural features. The main line of the arch consists of 47 stones and the side walls of the bridge have 50 cm width. Restoration of the bridge was completed in 2012 under the supervision of the 7th Regional Directorate of Highways. Figs. 1(a-d) present the masonry bridge and its geometrical properties. A reduced-scaled model of the one-span historical bridge was constructed in laboratory conditions to estimate the dynamic characteristics of the prototype bridge model, which are natural frequencies, mode shapes and damping ratios. The model and structural details including masonry bricks, mortar joints and filling material were implemented in the scale 1:12.5. The scaled bridge model has 159 cm in length and 36 cm in width. The bridge model was consisted of arch, side walls, filling material and parapets. Gas concrete also known as autoclaved aerated concrete was used as a construction material of the arch, side walls and parapets. According to Turkish Standards (TSE 453), autoclaved aerated concrete is a porous lightweight concrete produced by the mixture of fine grain siliceous aggregate and an inorganic binder (lime and/or cement). In the production procedure, its unit weight is decreased by adding a pore-forming agent and it is exposed steam curing to provide its mechanical strength. The reason of the material choice is to be comforted with geometrical scale proportion of the model bridge elements due to its ability of workability. Modulus of elasticity of autoclaved aerated concrete has been given as a function of the density and compressive strength of the material. The modulus of elasticity for a autoclaved aerated concrete having a density range of 500 to 700 kg/m^3 was reported to be 1.4 to 2.8 103 MPa according to MacElroy and Kimpflen (1990). Each gas concrete elements were immersed in mortar mixture to be able to obtain appropriate mechanical properties comply with the prototype bridge elements. The filling material is natural soil with %10 chaffy. The mechanical properties of the construction material are shown in Table 1. The arch of the historical bridge model is formed as various curvatures, four different radius and central angle and includes total 47 stone. The side walls have 4 cm in width on both downstream and upstream sides. Horosan mortar consisting of brick-dust and lime paste was used as a fastener material of the construction elements. The scaled bridge model was supported by two separate abutment composed of the mixture of the cement paste and gas concrete. Fig. 1(e) demonstrates the reduced scale bridge model.

3.1. Modal test and experimental modal parameters

Operational modal analysis was carried out to determine dynamic characteristics of reduced scale bridge model. One-axial accelerometers and data acquisition system were used to get signals obtained from small artificial vibrations in order to vibrate the reduced-scaled bridge model for the experimental measurements. 12 accelerometers were utilized in total and were put into six different locations on both Y and Z direction on the span of the bridge model. Fig. 2 represents the test setup of experimental study of the reduced-scaled bridge model. Moreover, one reference accelerometer was disposed on the middle point of the span in order to combine the six measurement data taken in each axis. The signals gathering from accelerometers were obtained by using data acquisition network access software Testlab_V2. Measurement duration was chosen as 15 minutes and the frequency range was taken as 0-50 Hz. The data collected from the accelerometers corresponding to specified points are illustrated in Fig. 3. ARTeMIS 1.5 software (2013) was performed to obtain the experimental modal parameters of the reduced-scale historical masonry bridge model. The natural frequencies, modal damping ratios and mode shapes of the scaled bridge model were procured by performing EFDD technique. The signal time series for all channels and the singular values of spectral density matrices of data set obtained from the EFDD technique are demonstrated in Figs. 4 and 5, respectively. Furthermore, experimentally obtained natural frequencies and mode shapes of first three modes of the scaled bridge model are shown in Fig. 6. The first three mode shapes of the reduced-scale bridge model can be expressed as lateral mode in y-direction for the first mode and transverse modes for second and third modes.

Table 1. Mechanical properties of construction materials.

	Unit Weight (g/cm^3)	Modulus of Elasticity (N/mm^2)	Poisson's Ratio
Gas concrete	0.800	1600	0.20
Chaffy soil	1.365	1500	0.05

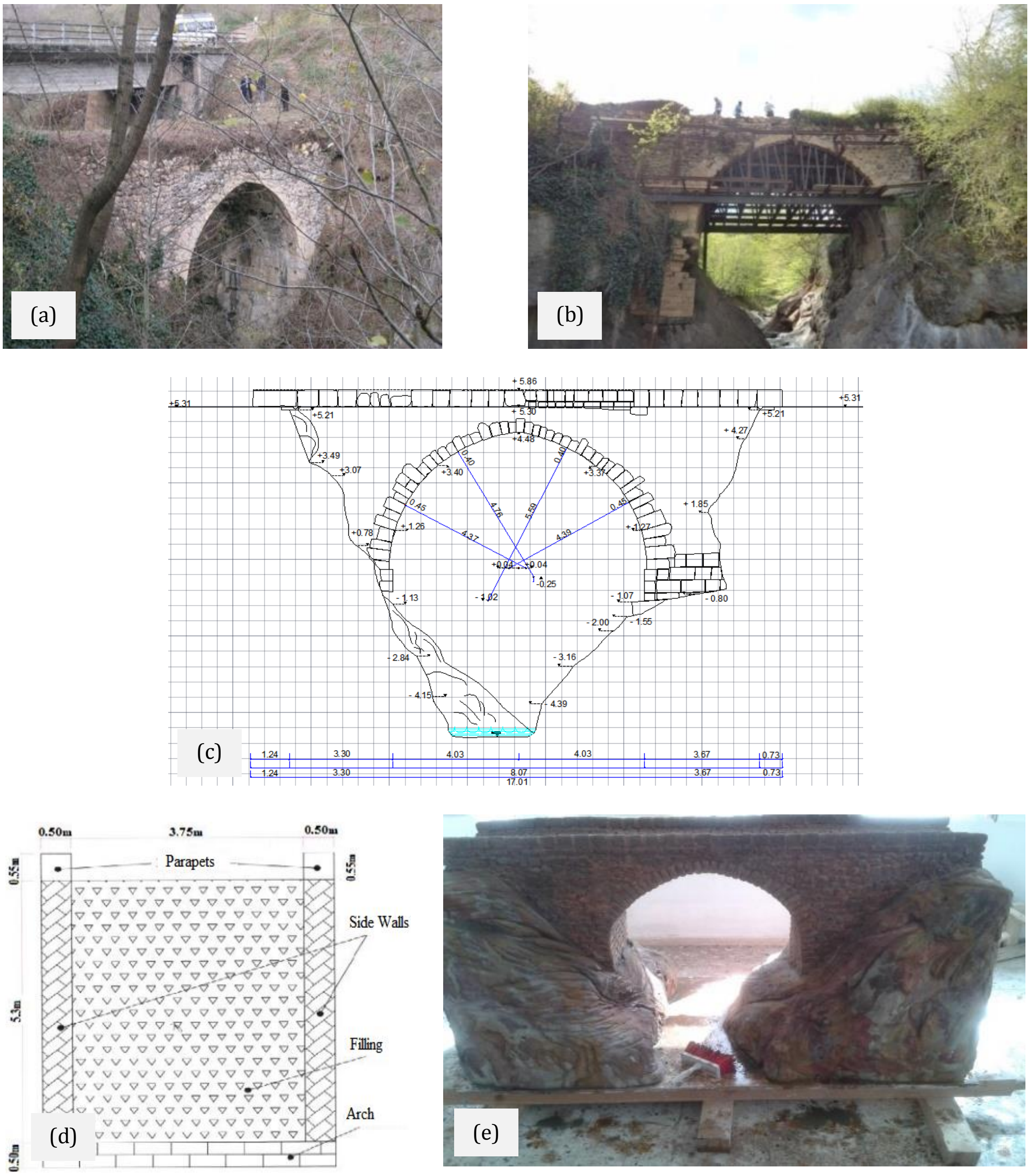


Fig. 1. (a) Sarp Dere Bridge; (b) Restoration of the Bridge; (c) Longitudinal cross-section of prototype bridge (the unities are in m); (d) Transverse cross section of prototype bridge; (e) Reduced scale bridge model.

Fig. 2. Test setup of reduced-scaled bridge model.

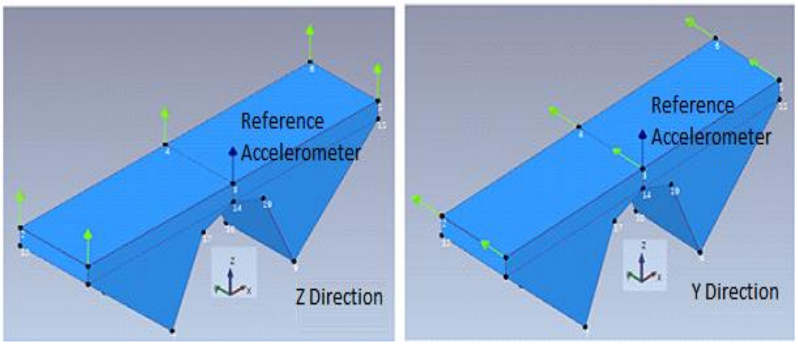


Fig. 3. Configuration of the accelerometers.

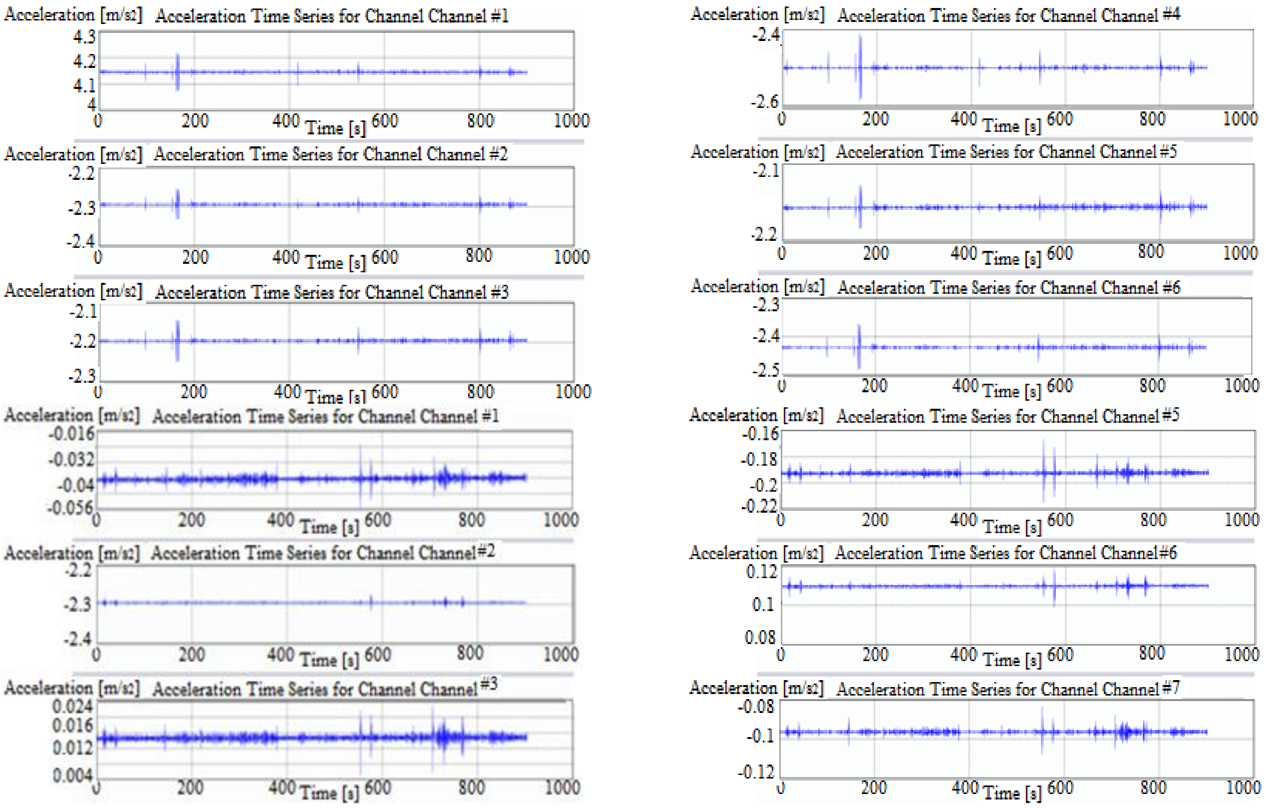


Fig. 4. Signal time series for channels.

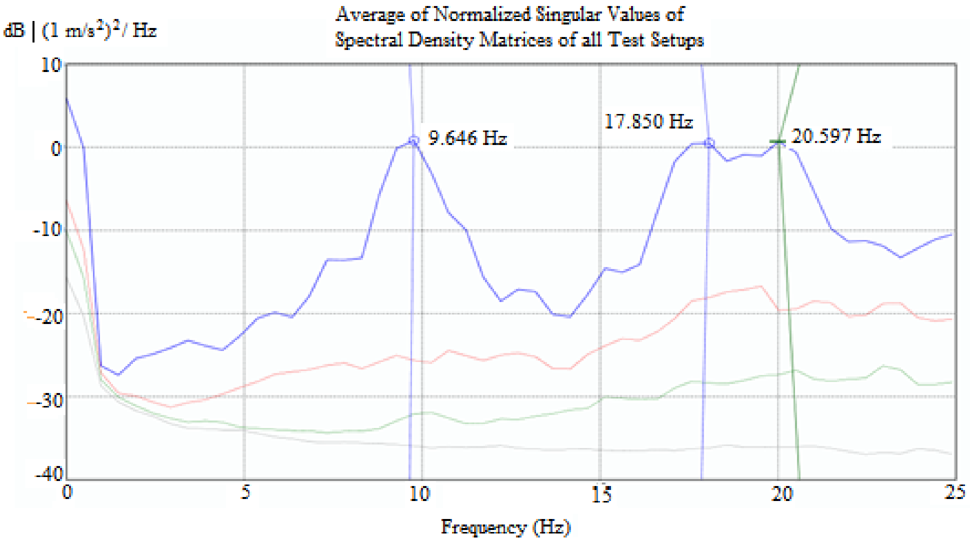
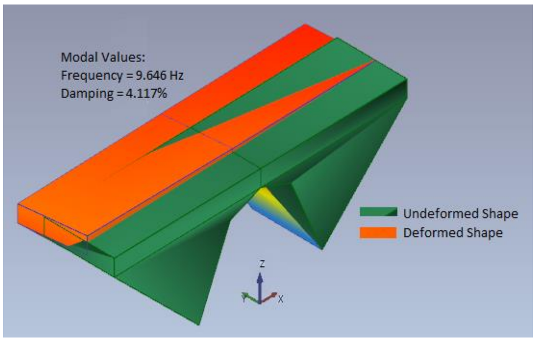
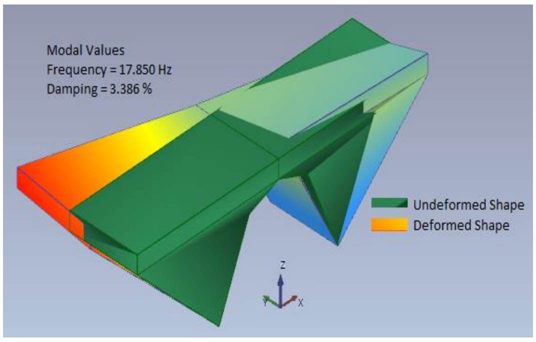


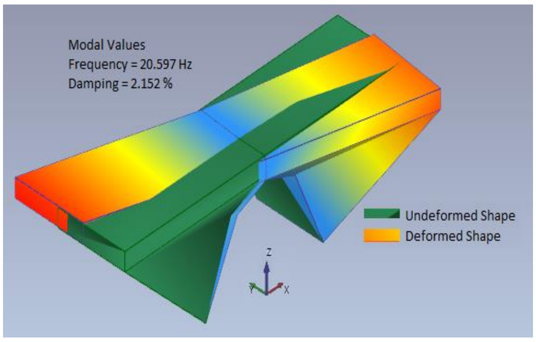
Fig. 5. Average of normalized singular values of spectral density matrices of all test setups.



(a) Mode 1 (lateral mode)



(b) Mode 2 (1st transverse mode)



(c) Mode 3 (2nd transverse mode)

Fig. 6. Experimentally identified first three mode shapes of the scaled bridge model.

3.2. Finite element modelling

Three dimensional finite element model of scaled bridge model was created in ANSYS (2013) software to evaluate the dynamic characteristics of the bridge which are natural frequencies and natural mode shapes. SOLID186 elements for the three-dimensional modelling of solid structures were used to model the bridge model. This element is defined by 20 nodes; each node has 3 translational degrees of freedom, namely, u_x, u_y and u_z. It supports plasticity, hyperelasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities (ANSYS 2013). The mechanical properties of the scaled bridge model, the modulus of elasticity, Poisson's ratio and mass density, were used as shown in Table 1. In the model, linear elastic material behaviour is assumed and the stiffness degradation is neglected. The finite element model of the scaled bridge includes 21854 solid elements and 113250 nodes in total. The three dimensional FE model of the scaled bridge created using section properties of the prototype bridge. The boundary conditions of the FE model of the bridge were created as reduced-scale bridge model. In the FE model, the bridge supported on two abutments on two sides and the model was sit on a platform as illustrated in Fig. 7. For initial FE model, it was assumed that boundary condition of the bridge's foundation was assumed to be rigid; therefore, all of the degrees of freedoms under the platform of the bridge model were accepted as fix support.

3.3. Finite element model calibration

The natural frequencies and modal shapes of the reduced-scaled bridge model were computed from the finite element analysis according to the initial mechanical parameters and boundary conditions as indicated in Section 3.2. The natural frequencies obtained from the initial conditions are shown in Table 2. It can be realized that there are significant differences between the frequencies obtained from analytical and experimental analyses according to the initial conditions.

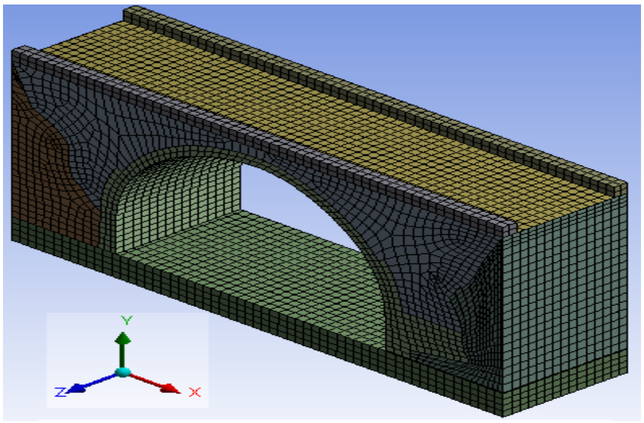


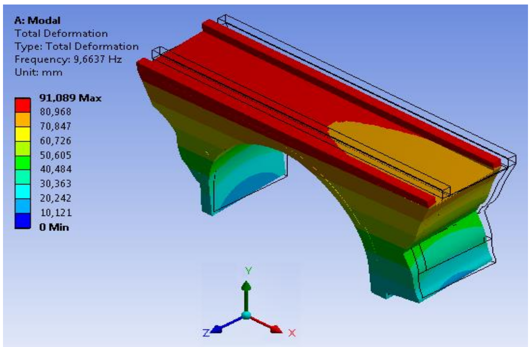
Fig. 7. Finite element model of the scaled bridge model.

These differences may due to uncertainties elastic mechanical properties of materials, inaccurate boundary conditions and assumptions of structural geometry. Therefore, the FE model calibration should be performed to achieve more accurate results. The material properties and boundary conditions of finite element model can be changed in order to calibrate the modal parameters of finite element model and get more accurate results reflected the dynamic behaviour of reduced-scaled bridge model. In this study, the elastic mechanical properties of boundary conditions (abutments) of finite element model were changed. Moreover, the platform under the bridge was modelled by a flexible boundary, which permits a more flexible dynamic behaviour of the structure. During the calibration process, the material properties of reduced-scale bridge model (the elastic modulus, unit weight and Poisson's ratio) were not changed.

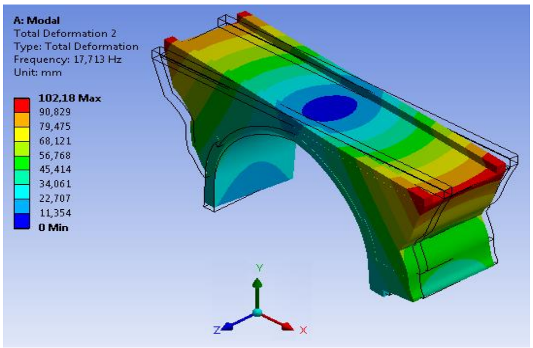
The manual or automatic model calibration methods are benefited in many studies. In this study, the response surface-based FE model calibration for OMA was applied to the reduced-scaled historical masonry bridge. Natural frequencies evaluated from Eigen analysis of the FE model were compared to the experimental analysis; the optimal results were found using the optimizations method based on Casciati (2010). The aim of this method is to close the gap between the numerical results and the experimental ones. The frequencies obtained from the analytical analyses which are for before and after calibration and experimental modal parameters are shown in Table 2. The differences of the first three modal frequencies for experimental and initial FE model varied between 0.3 - 5.8%. After model calibration, the differences of modal frequencies for experimental and calibrated FE model decreased to 0.2 – 0.8%. Model calibration technique demonstrated that the natural frequencies computed from the FE method show a good compatibility with those found from EFDD technique. The analytically defined first three mode shapes of the bridge are demonstrated in Fig. 8. It can be seen that there is enough agreement between mode shapes when the analytical and experimental results are compared with each other. Furthermore, the first three damping ratios of the reduced scale historical masonry bridge model identified as 2.15 – 4.12% using ARTeMIS Modal Pro 1.5.

Table 2. Analytical and experimental modal parameters.

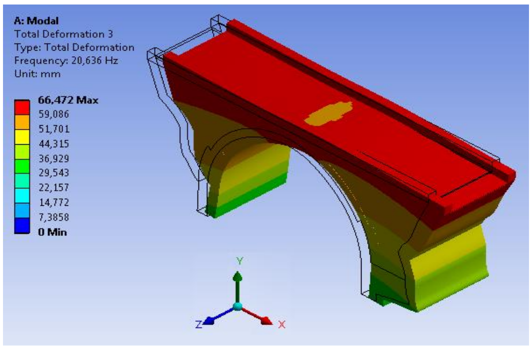
					Differences	
	Initial finite element model	Calibrated finite element model	Experimental modal analysis		Initial finite element model	Calibrated finite element model
Modes	Frequency (Hz)	Frequency (Hz)	Frequency (Hz)	Damping ratio (%)	(%)	(%)
1	10.21	9.67	9.65	4.12	5.8	0.2
2	16.64	17.71	17.85	3.39	6.8	0.8
3	20.53	20.64	20.60	2.15	0.3	0.2



(a) Mode 1 (9.67 Hz)



(b) Mode 2 (17.71 Hz)



(c) Mode 3 (20.64 Hz)

Fig. 8. Analytically identified first three mode shapes of the scaled bridge model.

4. Conclusions

In this study, modal parameters of a reduced-scale historical masonry bridge were investigated by using the Operational modal analysis. In accordance with this purpose, Sarp Dere historical masonry arch bridge located in Ordu was selected as a prototype model. The Operational Modal Analysis test is realized under environmental vibration. The Enhance Frequency Domain Decomposition (EFDD) method is used to define the natural frequencies, mode shapes and damping ratios experimentally. 3D finite element model of historical masonry bridge is modelled ANSYS software and detected the natural frequencies and mode shapes analytically.

Experimental and analytical results with the initial conditions were compared and significant differences were observed. For this reason, response surface-based FE model calibration technique was utilized to close the frequencies obtained from the analytical analysis to those of experimental analysis. Following are conclusions from this study:

- It was seen from the analytical results that the first three natural frequencies are in the range between 10 Hz and 20 Hz.
- The experimentally determined first three damping ratios of the reduced-scale historical masonry bridge model was range of 2.15% to 4.12%.
- The first three mode shapes of the reduced-scale bridge model can be classified as lateral mode and transverse modes. Similar mode shapes were obtained from the numerical analysis.
- The first and second analytical frequencies according to the initial conditions demonstrated significant differences compared to the experimental frequencies.
- Response surface-base FE calibration was performed to close the differences between natural frequencies obtained from experimental and numerical analysis.
- Calibration of the finite element model by using response surface method is seen as a good approach to

- Response surface-base FE calibration was performed to close the differences between natural frequencies obtained from experimental and numerical analysis.
- Calibration of the finite element model by using response surface method is seen as a good approach to determine to modal parameters of reduced-scale historical masonry bridges. After the finite element model calibration, the differences between experimental and analytical natural frequencies declined considerably.

According to the results obtained in this study, it is aimed to investigate the functionality of response surface-based FE model calibration technique to obtain modal parameters of damaged and repaired reduced-scale historical masonry bridge model for future study.

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