Research Article

Model updating of a reduced-scaled masonry bridge by using response surface method

Emre Alpaslan [a,*], Zeki Karaca [a]

[a] *Department of Civil Engineering, Ondokuz Mayıs University, 55139 Samsun, Turkey*

ABSTRACT

Historical structures reflect the historical and cultural properties of countries and also contributes to the economy in terms of cultural tourism. Therefore, it is important to understand the structural behavior of these kinds of structures under dynamics loads such as earthquakes, etc. to protect and transfer them safely to future generations. For this reason, this study aims to investigate the dynamic behavior of a reduced-scale one-span masonry arch bridge constructed in laboratory conditions by performing experimental and numerical analysis. Operational Modal Analysis (OMA) Technique was performed under ambient vibrations for experimental study to determine modal parameters of the reduced-scaled bridge model. Sensitive three-axial accelerometers were located on critical points on the bridge span and signals originated by accelerometers were collected to quantify the vibratory response of the scale bridge model. The experimental natural frequencies, mode shapes and damping ratios resulting from these measurements were figured out by using Enhanced Frequency Domain Decomposition (EFDD) technique. ANSYS software was utilized to carry out 3D finite element (FE) modeling of the reduced-scale masonry bridge and determine the natural frequencies and mode shapes of the bridge numerically. Experimental results were compared with FE analysis results of the bridge. Significant differences appeared when comparing the results of the experimental and numerical with the initial conditions. Therefore, the finite element model is calibrated by using the response surface (RS) method according to the experimental results to minimize the uncertain finite element modeling parameters of the reduced-scale bridge model such as material properties.

ARTICLE INFO

Article history:
Received 11 December 2019
Revised 13 January 2020
Accepted 22 February 2020

Keywords:
Response surface method
Modal calibration
Finite element model
Operational modal analysis
Reduced-scale model

1. Introduction

Historical masonry structures have significant value for countries due to reflecting their heritage and culture. These kinds of structures also contribute to the countries economically in terms of cultural tourism. Historical structures have been damaged or failed partially or completely since they have exposed to loads such as earthquakes, wind and explosion effects for many years. Also, deterioration of the building materials, time-dependent deformations, excessive and irregular loading caused by misuse, ground settlements, flood disasters, fires, etc. are other factors that play a role to cause serious damages to the structures. To protect the historical structures, the structural behaviors of these structures should be investigated.

Nomenclature

$G_{xx}(jw)$	power spectral density (PSD) matrix of the input signal
$G_{yy}(j\omega)$	PSD matrix of the output signal
$H(j\omega)$	frequency response function (FRF) matrix
$*$	complex conjugate
T	transpose
y_{RS}	function value of the obtained RS model
y	FE calculation results
$\bar{y}$	mean of y
N	number of confirmation sample points in design space

* *Corresponding author*. Tel.: +90-362-312-1919 ; Fax: +90-362-457-6094 ; E-mail address: emre.alpaslan@omu.edu.tr (E. Alpaslan)
ISSN: 2149-8024 / DOI: https://doi.org/10.20528/cjsmec.2020.01.005

Due to the importance of masonry structures for a historical point of view, many researchers have focused to understand the dynamic characteristics of such structures using experimental and numerical methods. Experimental modal analysis (EMA) and OMA methods are used to determine the dynamic characteristics of structures such as mode shapes, natural frequencies, and modal damping ratios. In the EMA method, the specific input force (impulse hammer, drop weight and electrodynamics shaker) is applied to the structure to obtain its modal parameters. In the OMA method, the dynamic characteristics of the structure can be obtained by using vibrations in the structure under the environmental effects (wind, traffic, etc.) without applying any external force to the structure. The use of this method is more appropriate and common, especially in historical buildings since it is both fast and practical and does not have any risk of damaging the structure. In the literature, historical structures such as historical bridges, historical minarets, and historical towers are studied by using the OMA method (Brencich and Sabia, 2008; Gentile and Gallio, 2008; Diaferio et al., 2011; Foti et al., 2012; Oliveira et al., 2012; Gentile et al., 2015).

In civil engineering, FE models are one of the most common methods used to obtain the responses of structures under dynamic loads such as earthquakes, wind, traffic, and explosion. While creating a numerical model of any structure, assumptions about many unknown and uncertain system parameters such as geometrical and material properties, loading and boundary conditions must be made. For these reasons, the accuracy and validity of the established numerical models should be investigated. Model update techniques have been developed and named as a model calibration or, more clearly, parameter estimation or determination. In general terms, the model calibration technique aims to update or reevaluate the unknown structural system properties used as a parameter in numerical modeling. The data (acceleration-time values, frequency response functions, natural frequencies, and natural mode shapes, modal stresses, and curvature grades, modal elasticity) obtained from the vibration experiments give detailed information about the general and local behaviors of the structure. Therefore, this vibration data has an important role in the FE model calibration process.

Model updating methods are divided into two groups as non-iterative and iterative methods. Non-iterative methods directly update the stiffness and mass matrices of the numerical model through a closed-form direct solution. However, such methods cause the loss of structural connectivity, and the proposed corrections are not always physically meaningful. On the other hand, iterative methods require sensitivity matrices to conduct iteration in minimizing the objective function. However, the sensitivity-based method seems not practical in case of high degrees of freedom structural system, as it results in the problem of slow convergence and a time-consuming process due to the increase in the degree of freedom. Therefore, the RS method has appeared as an alternative tool in the FE model calibration process due to simplicity and provides fast optimization because of smooth gradients, thus decreasing the convergence problem (Umar, 2018). RS methodology is a combination of statistical and mathematical techniques to represent the relationship between the inputs and outputs of a physical system by explicit functions. This methodology has been widely employed in many applications such as design optimization, response prediction, and model validation and damage detection.

Ren and Chen (2010) presented the RS-based FE model updating procedure for civil engineering structures in structural dynamics. Residuals between analytical and measured natural frequencies were chosen as the objective function. The proposed procedure was demonstrated by a simulated simply supported beam and a full-size precast continuous box girder bridge tested under operational vibration conditions. The results were compared with those obtained from the traditional sensitivity-based FE model updating method. The real application to a full-size bridge appeared that the FE model updating process was efficient and converges fast with the RS to replace the original FE model. Casciati (2010) used RS method based on detecting a change in the statistical distribution of the error associated to the function that approximates the relationship among measurements obtained on different sensors locations across the structure. The results from ambient vibration tests demonstrated that the correct damage scenarios can be achieved by using the method. Deng and Cai (2010) applied the RS method in a simply supported beam and model updating of an existing bridge. The structural parameters were updated using the genetic algorithm by minimizing an objective function. The results of the study demonstrated that this method works well and achieves reasonable physical explanations for the updated parameters. The D-optimal design was performed to generate RS models by updating uncertain parameters by Fang and Perera (2011). The accuracy of the proposed method was demonstrated experimentally by testing on a reinforced concrete frame and a full-scale bridge and numerically on a beam model. The modulus of elasticity and the moment of inertia as input parameters and modal frequencies as output parameters were chosen. In addition to the numerical study, the method provides sufficient accuracy for damage estimation in real structures with single and multiple damage scenarios.

Deshan et al. (2015) proposed a new FE model updating method of bridge structure by combining the substructure FE model updating method with the response surface model updating method for updating the FE model of a certain combined cable-stayed suspension model bridge. Samples of updating parameters were obtained by the homogeneous design method. The experimental results illustrate that the updated parameters obtained from the proposed method has a reasonable physical meaning, and the proposed finite element model updating method can be effectively used for the finite element model of the bridge structure. Zong et al. (2015) presented an application of the RS method for the FE model updating of bridge structures. A third-order polynomial response surface was created and then utilized to improve the computation efficiency in the model updating. The proposed procedure is demonstrated on a full-size long-span prestressed continuous rigid-frame bridge. The real application to a full-size bridge has illustrated that the FE model updating process is efficient and converges fast compared to the traditional sensitivity-based model updating method. The updated FE model can relatively reflect the actual condition of the bridge in the design space of parameters and can be further applied to FE model validation and damage identification. The study has also emphasized that a high-order RS function would be necessary to consider more input parameters in the case of more complex civil engineering structures. Hacıefendioğlu et al. (2017) investigated the influences of uncertainty in material parameters on the stochastic response of a historic masonry bridge subjected to random ground motion. For this purpose, probabilistic analysis of the bridge was carried out with Monte Carlo simulation obtained through the RS method. The probabilistic responses of the bridge at specific node points were compared with the same response obtained by using deterministic material properties. The study concluded that increasing the coefficient of variation values of material parameters, elastic modulus, Poisson's ratio, and mass density, produced a greater effect on the stochastic response of the bridge.

Worden and Cross (2018) have investigated the changes in environmental conditions on the civil infrastructures which are usually openly exposed to the weather and may be subject to strongly varying operational conditions. The approach is based on constructing a data-based RS model that can represent measurement variations as a function of environmental and operational variables. The models can then be used to take out environmental and operational variations so that change detection algorithms signal the event of damage alone. The study has proposed a Treed Gaussian Process model as developing RS on the Z24 Bridge in Switzerland and Tamar Bridge in the US. The proposed model has provided an effective approach to RS modeling and that in the Tamar case, a linear model is, in fact, sufficient to solve the problem. Fang (2020) has proposed a new method based on the fourth-order polynomial RS model in order to solve the problem of high risk and low precision of existing damage detection methods for long-span Bridges. The parameters of the FE model of the bridge were modified according to the RS model. Based on the FE model, the modal strain energy before and after the damage of the element was calculated, and the damage index of the element was calculated, so as to understand the damage detection of the long-span bridge structure. Experimental results have demonstrated that the proposed method can accurately detect the damage location of long-span Bridges under different damage conditions.

Most previous studies investigated the RS method updating approach of different civil engineering structures. Moreover, there is a limited number of studies relating to FE model updating of historic masonry structures by using the RS method, especially masonry bridge-type structures. Therefore, this paper aims to reveal that the RS method is a suitable and accurate method for model updating in masonry bridge structures. For this purpose, a reduced-scale masonry bridge model constructed in the laboratory environment by considering the similarity requirements of the single-span Historic Sarpdere Bridge based on a part of the doctoral dissertation by Alpaslan (2019) was used for both experimental and numerical study to obtain a more realistic FE model that can reflect the modal behavior of the masonry bridge structure by using RS based FE model updating approach. OMA method was performed to identify the dynamic behavior of the reduced-scale bridge under environmental vibrations. FE model of the reduced scale bridge was developed in ANSYS (2013) software program and natural frequencies and mode shapes of the bridge obtained numerically. The results of the modal parameters obtained from the field measurements are compared with those identified by the FE model. Significant differences were observed in natural frequency values between experimental and numerical analysis. Therefore, calibration of the FE model was performed based on the experimental results of the reduced-scale bridge by using the RS method. Correlation studies were conducted between the experimental and numerical natural frequencies of the reduced scale bridge to minimize the uncertain finite element modeling parameters.

2. Materials and Method

2.1. Reduced scale masonry bridge model

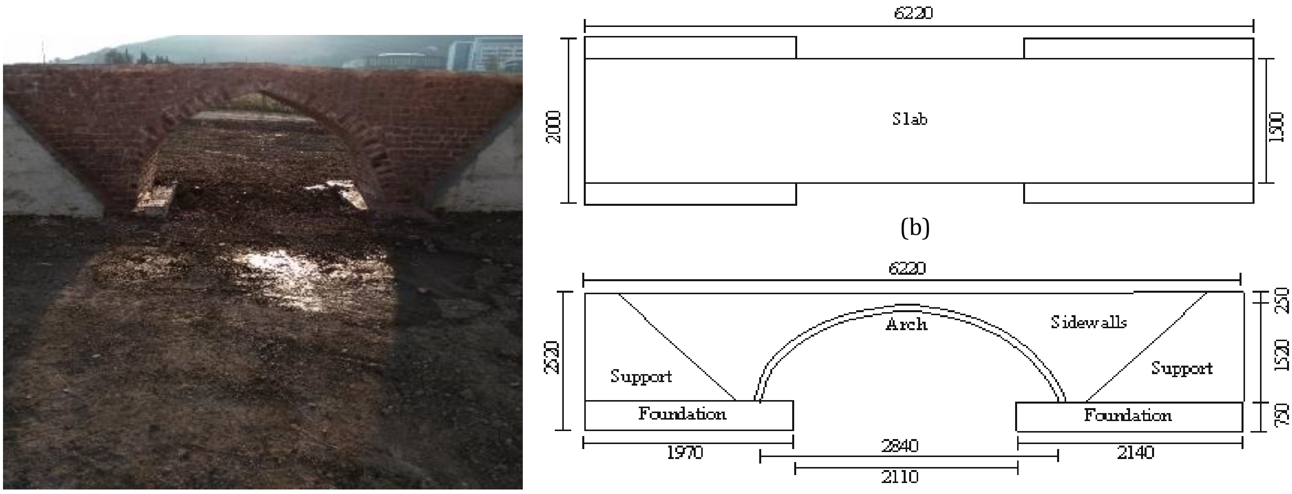
In the construction of the bridge model, andesite stones were used for the arches, sidewalls, and slab elements. Arch stones were cut to be 5x10 cm, 10x10 cm, 15x10 m and 20x10 cm. Crushed andesite stones were used for the side walls. The slab stones were supplied as 30x80x4 cm and 30x100x4 cm plates. Straw soil was used as filling material. The right and left abutment of the masonry bridge model was designed as concrete. Khorasan mortar was used as the binding material for the arch, sidewall and slab elements on the bridge model. Khorasan mortar consisted of 40% building tile powder, 40% stone powder and 20% hydrated lime powder. The workability of the mixture was obtained by adding water.

The construction steps of the masonry bridge model are represented in Fig. 1. Abutments were completed, the necessary framework process was performed and the arrangement of arch stones was started from both sides simultaneously. Some of the arch stones were placed perpendicularly in order to strengthen the joints between arch and the sidewalls filling material. The side walls are then arranged on both sides. After the filling process, the slabs were placed and the masonry bridge model was completed. The arches, sidewalls, and slab stones are arranged in a staggered manner. The side walls consisted of two rows of crushed stones with a total thickness of 15 cm. The reduced-scale masonry bridge model bridge and its geometry are represented in Fig. 2. The mechanical properties of materials used in the construction of the reduced-scale bridge model were investigated experimentally. Unit weight and compressive strength of assemblages were determined within the scope of experimental study. The assemblages with Khorasan mortar were prepared in two different ways as single and staggered form as demonstrated in Fig. 3. The experimental results are presented in Table 1. The modulus of elasticity of the samples was calculated by using the empirical equation, Eq. (1), obtained from a study in the literature by Ocak (2009) which is based on calculating the modulus of elasticity by iteration method. The UCS values in the equation show the average compressive strength of the test specimens.

$$E = 6.195 \cdot e^{0.0074UCS} \text{ (GPa)} \tag{1}$$

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

Fig. 1. Construction steps of masonry bridge model: (a) Arch; (b) Side walls; (c) Filling; (d) Slab.



(a) (c)

Fig. 2. (a) Reduced-scale masonry bridge model; (b) Top view; (c) Front view (mm).

Fig. 3. Experimental assemblage samples with Khorasan mortar.

Table 1. Physical and mechanical properties of the assemblages.

Width x Length x Height (cm x cm x cm)	Unit Weight (gr/cm^3)	Axial Compression P_{max} (kN)	Compressive Strength (MPa)	Mean (MPa)	Modulus of Elasticity (MPa)
9.9x19.5x32	2.25	432	22.4		
10.0x14.8x30.8	2.22	349	23.6		
10.0x19.9x32.3	2.15	594	30.0	24.7	7438
10.0x20x32.1	2.16	559	28.0		
10.0x14.7x31.5	2.13	341	23.2		
10.0x19.7x31.9	2.20	420	21.3		

The flowchart of the study is summarized in Fig. 4. The first step is that the initial finite element model of the bridge model is generated by using the material and geometrical properties and modal analysis are performed to investigate the dynamic behavior of the bridge model. Then, experimental studies are conducted on the bridge model considering the natural frequency values obtained from the numerical analysis. Natural frequencies, mode shapes and damping ratios of the bridge are identified by using the vibration records. Finally, the initial FE model was calibrated according to the obtained natural frequency values experimentally. In this process, it was tried to represent the dynamic behavior of the bridge model more accurately.

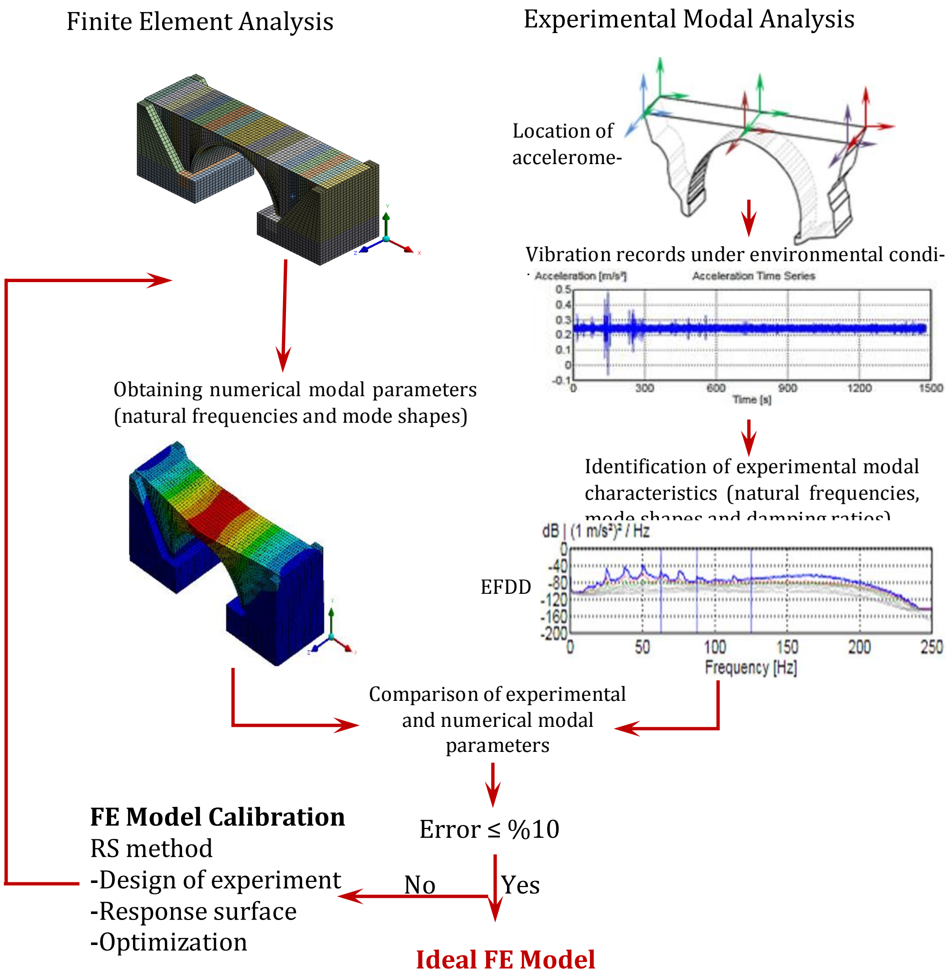


Fig. 4. Flowchart of the study.

2.2. Enhanced frequency domain decomposition

In general, the EFDD technique is used for OMA in the civil engineering industries. In the EFFD 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. The relationship between unknown input x(t) and the measured responses y(t) is expressed as (Brincker and Zhang, 2009; Bendat and Piersol, 2010);

$$G_{yy}(j\omega)=H(j\omega)^{*}G_{xx}(jw)H(jw)^{T} \quad (2)$$

2.3. Response surface method

RS method is an approximate optimization method that looks at various design variables and their responses, which seeks the best experimental design using the minimum number of design samples, to determine the combination of design variables. RSM can achieve a satisfactory accuracy between the measured data and the FE model-generated data (Cheng et al., 2007; Landman et al., 2007). The ANSYS DesignXplorer (2013) used in this study employs the approximation method in RS creation. RS method used in the calibration process of the numerical model consists of the three steps as the design of experiments, response surface and optimization. The accuracy of using RS method are depended on the number of variable input parameters. The method is not effective considering large number of input parameters. Therefore, there is a limitation of input parameters (fewer than 20 is ideal) for RS method in ANSYS DesignXplorer (2013) to be able to generate an appropriate and accurate DoE and RS.

2.3.1. Design of experiments

Design of experiments is a technique used to scientifically determine the location of sampling points. There are a variety of design of experiments algorithms or methods in engineering studies namely star, full factorial, central composite, and Box-Behnken designs. A common feature of all the techniques used is to locate sampling points in the space of random input parameters in the most efficient way or to try to position them with the least sampling point to obtain the necessary information. Sample points in effective locations not only reduce the required number of sampling points but also increase the accuracy of the response surface obtained from the results of the sampling points. In this study, the central composite design for three variables is selected as a sampling method.

2.3.2. Generation of RS model

In this study, genetic aggregation technique was used to generate RS models. The technique automates the selection, configuration, and creation of the RS. It automatically generates the most suitable approach for each output and provides more reliable results than other RS models due to multiple solutions of RS and cross-validation processes. The fitted RS models should be used to conduct the FE model updating after validated through their fitness. R^2 criterion and root mean squared error (RMSE) criterion are usually utilized for multi-RSM and complicated models (Box and Draper, 1987; Fang and Perera, 2009). R-square Statistic and Relative Mean Square Error are presented in Eq. (3) and Eq. (4) are regarded as the criteria to check the fitness of the fitted RS models.

$$R^2 = 1 - \frac{\sum_{j=1}^{N} \left[y_{RS}(j) - y(j) \right]^2}{\sum_{j=1}^{N} \left[y(j) - \bar{y} \right]^2} \tag{3}$$

$$RMSE = \frac{1}{N * \bar{y}} \sqrt{\sum \left[y_{RS}(j) - y(j) \right]^2} \tag{4}$$

The larger the value of R-square is, the more accurate the RS model. The smaller the value of RSME is, the more accurate the RS model.

2.3.3. Optimization

In the structural dynamic, the natural frequencies and modal shapes are crucial parameters for the structural response features. In this study, the natural frequency was taken as a response feature. The primary model previously obtained is updated herein to seek the reference values of input parameters by minimizing the response discrepancies between the primary RS model and the experimental model. The measured frequencies from the minaret employing OMA are used as the objective responses. Optimization computation in this study is carried out with the screening approach. This approach is a non-iterative direct sampling method by a quasi-random number generator based on the Hammersley algorithm. In general, the screening method is the most convenient way to carry out a preliminary design study, since it is a low-resolution, fast and detailed study that can be useful to quickly find approximate solutions (ANSYS, 2013).

3. Results

3.1. Initial finite element model of reduced-scale bridge model

3D dimensional FE model has been created by using ANSYS Workbench (2013) software program to obtain the natural frequency and mode shapes of the reduced-scale bridge model numerically. The FE model of the reduced-scale bridge is composed of one arch, filling and slap, and two sidewall parts. In addition, concrete abutments were placed on the right and left sides of the FE model. In the initial FE model, the contact type between the infill and the all other parts was chosen as frictional contact and friction coefficient was selected as 0.01. Body contact element was used for connection of all other parts and the SOLİD186 three-dimensional solid element model having 20 joints with the degree of freedom in each x, y and z-direction were chosen as an element type. The material properties represented in Table 2 were used in the initial FE. At the support points where the reduced-scale bridge model contacts to the ground, the bottom parts of the concrete abutments were assumed as fix support. Therefore, all the DOFs at these support points were restrained. It was assumed that the material would have elastic behavior and analyzes were performed by neglecting the decrease in stiffness. The FE model consists of 24772 elements and 135159 nodes. The FE model of the reduced-scale bridge is demonstrated in Fig. 5. The transverse, bending and torsional mode shapes obtained from the numerical analysis of reduced-scale bridge model are illustrated in Fig. 6 and also their corresponding natural frequency values are presented in Table 3.

Table 2. Material properties used in the FE model.

	Modulus of elasticity (MPa)	Unit weight (kg/m³)	Poisson's ratio
Arch	7400	2200	0.2
Side walls	7400	2200	0.2
Slab	7400	2200	0.2
Infill	1500	1500	0.05
Concrete	28000	2400	0.2

Table 3. Initial FE model natural frequencies.

Mode	Initial FE model
	Natural frequencies (Hz)
1	71.37
2	114.35
3	146.56

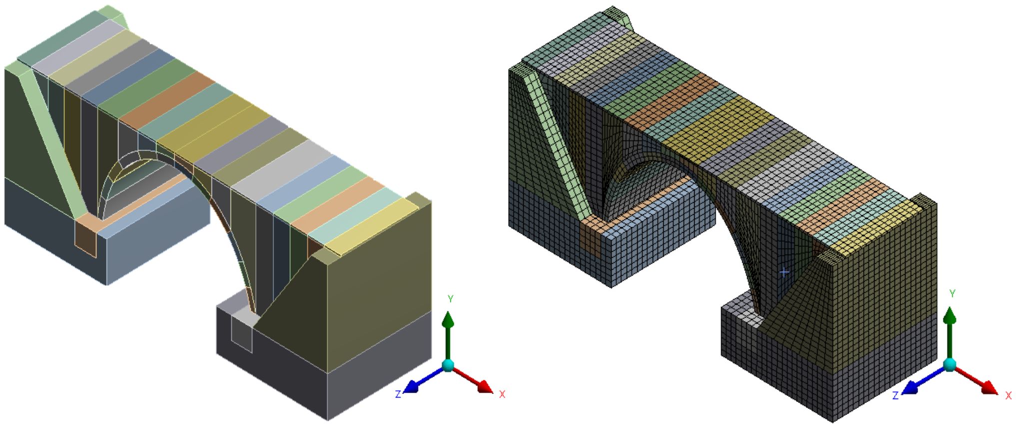
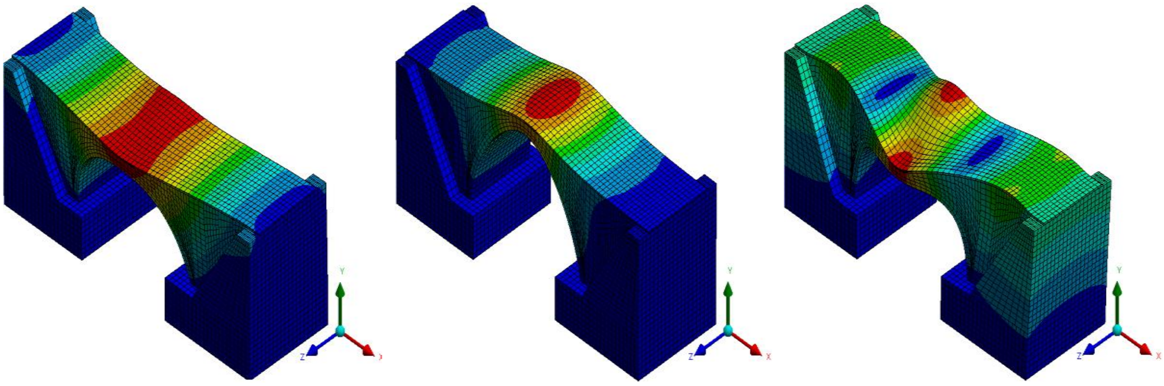


Fig. 5. FE model of the reduced-scale bridge.



Transverse mode Bending mode Torsional mode

Fig. 6. Mode shapes of the reduced-scale bridge FE model.

3.2. Experimental study

The vibrational response of the reduced-scale masonry bridge model was taken under the environmental effects by using the OMA method. A total of six single-axis accelerators with a range of 0-400 Hz was used in the experimental study. The measurement time and frequency range were selected as 30 min and 0-500 Hz, respectively. Fig. 7 represents the experimental study applied for the reduced-scale masonry bridge model. Vibration recordings were taken as two measurements using reference accelerometers. The accelerometers were located to the projection of the center of the bridge and the arch span. The configuration of the accelerometers is shown in Fig. 8. Arrows in blue color represent reference accelerometers. Vibration signals from accelerometers are recorded using Testlab_V2 software via the data acquisition system. The experimental modal parameters of the masonry bridge were analyzed using ARTeMIS Modal 1.5 (2012) software program.

Fig. 7. Experimental application of reduced-scale masonry bridge.

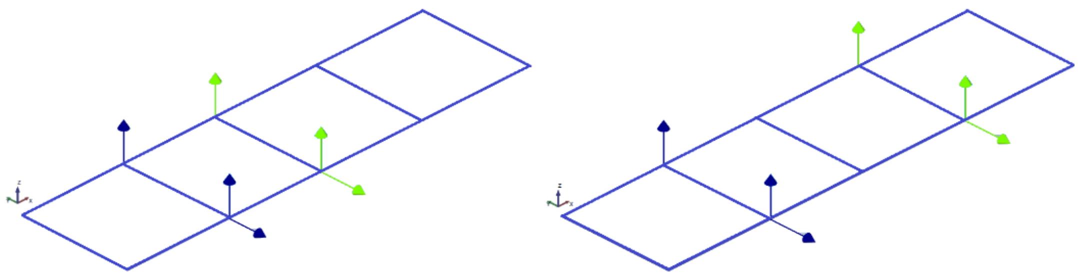


Fig. 8. Configuration of accelerations.

Natural frequencies, mode shapes and damping ratios of reduced-scale bridge model were obtained by using the EFDD method. The singular values identified by the EFDD method are represented in Fig. 9. Mode shapes were identified as the transverse, bending and torsional mode. The natural frequency and damping ratio values corresponding to these three modes of the structure are demonstrated in Table 4. In addition, the mode shapes of the experimentally obtained reduced scale bridge are shown in Fig. 10.

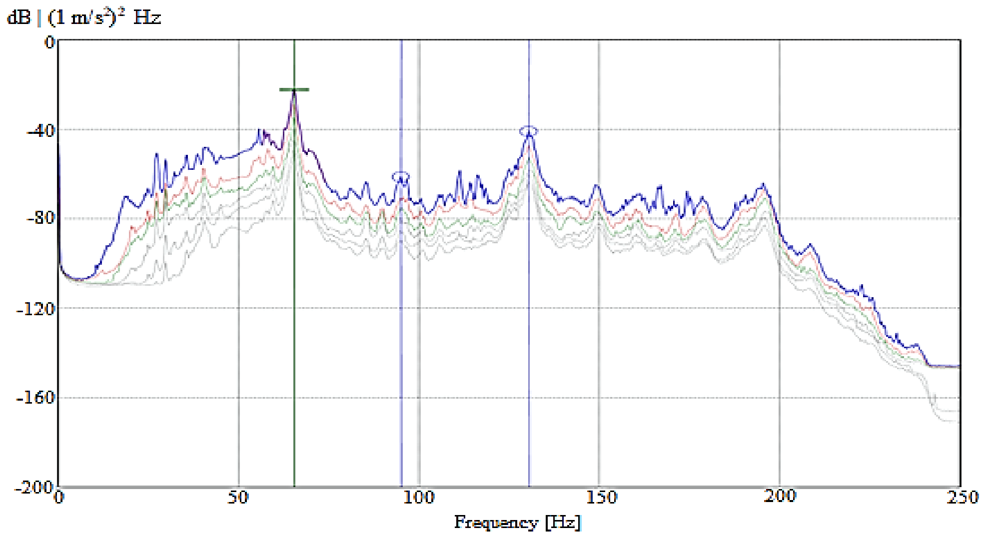
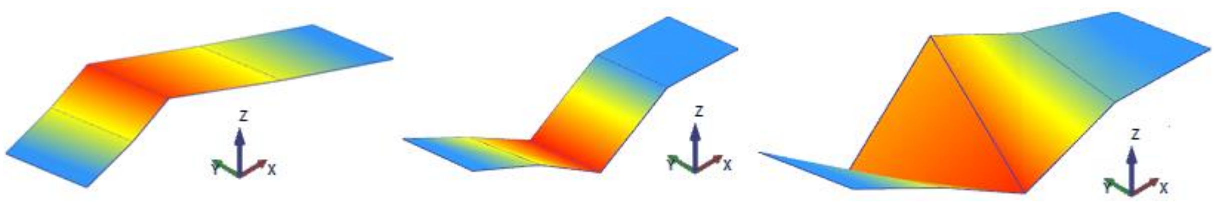


Fig. 9. Average of normalized singular values of spectral density matrices of all test setups.

Table 4. Experimentally identified natural frequencies and damping ratios.

Modes	Natural frequencies, f (Hz)	Damping ratios, ξ (%)
Transverse	65.46	0.526
Bending	95.09	0.561
Torsional	130.55	0.368



(a) (b) (c)

Fig. 10. Experimentally identified mode shapes of the masonry bridge model; (a) Transverse mode; (b) Bending mode; (c) Torsional mode.

The comparison between natural frequency values obtained by experimental and numerical analysis are demonstrated in Table 5. It can be seen that the differences between natural frequency values are not satisfied, therefore, the initial FE model needs to be calibrated to obtain a more realistic FE model that represents the dynamic behavior of the reduced-scale bridge.

Table 5. Comparison of natural frequency values.

Mode	Experimental analysis	Numerical analysis with initial conditions	Error (%)
	Natural frequencies, f (Hz)		
Transverse	65.46	71.37	9.03
Bending	95.09	114.35	20.25
Torsional	130.55	146.56	12.26

3.3. Finite element model calibration of the reduced-scaled masonry bridge

There are significant differences between natural frequency values in the numerical and experimental analysis of the reduced-scale bridge. It is thought that the reason for these differences may be due to the modulus of elasticity of Khorasan mortar that may cause labor during construction. Another reason may be due to the lack of continuity of the Khorasan mortar used in the connection of stones during construction. Also, the filling material is compacted and placed during construction and this might result in important changes for material properties of the filling material. These applications can lead to a difference in the material properties used in the initial FE model of the structural components. Therefore, in order to minimize these residuals and obtain a more reliable FE model, the modulus of elasticity and unit weight of the arch, sidewalls, slap and filling material was chosen as updated parameters in the FE calibration process by using RS method. The lower and upper limits of the updated modulus of elasticity and unit weight of the structural components for experimental design are shown in Table 6. In the experimental design, a total of 81 analyzes were performed using the face-centered central composite design approach at these upper and lower limits of the updated parameters. A genetic aggregation approach is performed to generate the RS models. The validity of the RS models is checked by using R^2 and root mean squared error (RMSE) criteria. R^2 and RMSE values obtained for each corresponding mode are illustrated in Table 7. It is demonstrated that all R^2 and RMSE values are close to 1 and 0, respectively, which represents that the obtained RS models have a high regression accuracy.

After the RS models are obtained, the natural frequency values corresponding to the third mode shapes is tried to be converged with the frequency values identified by the experimental analysis. For this purpose, experimentally obtained natural frequencies are used as objective values as demonstrated in Fig. 11.

Table 6. Lower and upper limits of updated parameters.

	Limits	Modulus of elasticity (MPa)	Unit weight (kg/m^3)
Filling material	Lower	1300	1500
	Upper	1700	1900
Slab	Lower	4000	1800
	Upper	7400	2200
Arch	Lower	6000	1900
	Upper	7400	2200
Sidewalls	Lower	4000	1500
	Upper	7500	2200

Table 7. Accuracy check for response surfaces.

	Transverse Mode	Bending Mode	Torsional Mode
R^2	0.999	0.999	0.999
RMSE	0.0234	0.0633	0.0803

Name	Parameter	Objective		Constraint		
		Type	Target	Type	Lower Bound	Upper Bound
Seek P5 = 65,463 Hz; 65 Hz <= P5 <= 70 Hz	P5 - Transverse Mode	Seek Target	65,463	Lower Bound <= Values <= Upper Bound	65	70
Seek P6 = 95,092 Hz; 87 Hz <= P6 <= 1005 Hz	P6 - Bending Mode	Seek Target	95,092	Lower Bound <= Values <= Upper Bound	87	1005
Seek P7 = 130,55 Hz; 127 Hz <= P7 <= 143 Hz	P7 - Torsional Mode	Seek Target	130,55	Lower Bound <= Values <= Upper Bound	127	143

Fig. 11. Optimization objective values.

As a result of the optimization process, the updated modulus of elasticity and unit weight of the structural components are represented in Table 8 and Table 9, respectively. As can be seen, significant differences occurred in the updated material properties in the calibrated FE model. The modulus of elastic values of the components decreased by about 4%-45%. Moreover, the unit weight of the arch, sidewalls, and slab components reduced between 3%-17%. On the other hand, the unit weight of the filling material increased by approximately 7%.

The comparison between the natural frequency values identified by experimentally and numerically is indicated in Table 10. Residuals between the natural frequency values obtained from the initial FE model and experimentally obtained natural frequency values were significantly reduced. Differences between numerical and experimental natural frequencies corresponding to the transverse, bending and torsional modes vary between 0.31% and 9.08%. Therefore, it is seen that the FE model obtained as a result of the calibration process reflects the dynamic behavior of the reduced-scale masonry bridge in a more realistic way.

Table 8. The updated modulus of elasticity of reduced-scale masonry bridge components.

	Initial FE model	Calibrated FE model	Differences (%)
	Modulus of elasticity (MPa)		
Ach	7400	6355	-14.12
Side walls	7400	4569	-38.25
Slab	7400	4129	-44.20
Infill	1500	1433	-4.47

Table 9. The updated unit weight of reduced-scale masonry bridge components.

	Initial FE model	Calibrated FE model	Differences (%)
	Unit weight (kg/m^3)		
Ach	2200	2131	-3.14
Side walls	2200	2080	-5.45
Slab	2200	1843	-16.23
Infill	1500	1610	7.33

Table 10. Differences in natural frequencies between before and after calibration.

Mode	Experimental	Initial FE model	Calibrated FE model	Initial FE model	Calibrated FE model
	Natural frequencies, f (Hz)			Error (%)	
Transverse	65.46	71.37	65.25	9.03	0.31
Bending	95.09	114.35	103.73	20.25	9.08
Torsional	130.55	146.56	135.30	12.26	3.63

4. Conclusions

In this study, modal parameters of a reduced-scale masonry bridge were investigated by using the OMA method performed under ambient vibrations. The EFDD method is implemented to identify the natural frequencies, mode shapes, and damping ratios experimentally. 3D finite element model of the reduced-scale Masonry Bridge is constructed and detected the natural frequencies and mode shapes analytically by using ANSYS software. Experimental and analytical results with the initial conditions were compared to each other and significant differences were identified. For this reason, the response surface-based FE model calibration technique was utilized to close the residuals between frequencies obtained from the analytical and experimental analysis. After the finite element model calibration, the differences between experimental and analytical natural frequencies reduced considerably.

According to the results obtained in this study, the initial FE model of the structures is not sufficient to represent their dynamic behavior. Therefore, the initial FE model should be updated by considering the changes in parameters such as material properties and boundary conditions. Thus, a more realistic FE model can be created which can exhibit the dynamic behavior of engineering structures. Furthermore, it can be seen that the RS method allows to further improve the correlation between experimental and analytical modal parameters, therefore, it is an effective approach in the FE model updating process.

Acknowledgements

This study is based on the part of the doctoral dissertation done by Emre Alpaslan under the supervision of Prof. Dr. Zeki Karaca and is supported by Ondokuz Mayıs University as PYO.MUH.1904.17.009 Scientific Research Project.

References

Alpaslan E (2019). Damage Detection of Historical Masonry Bridges with Analytical Model and Experimental Techniques. *Ph.D thesis*, Ondokuz Mayıs University, Samsun, Turkey.

ANSYS Workbench (2013). Version 15. Ansys Incorporation, Pennsylvania, USA.

ARTeMIS Modal 1.5. (2012). Structural Vibration Solution, Denmark.

Bendat JS, Piersol AG (2010). Random Data : Analysis and Measurement Procedures. John Wiley and Sonsi Inc., New York.

Box GEP, Draper NR (1987). Empirical Model-Building and Response Surfaces. John Wiley and Sons, Inc., New York.

Brencic A, Sabia D (2008). Experimental identification of a multi-span masonry bridge: The Tanaro Bridge. *Construction and Building Materials*, 22(10), 2087-2099.

Brincker R, Zhang L (2009). Frequency domain decomposition revisited. *Proceedings of the 3rd International Operational Modal Analysis Conference*, Portonovo, Italy, 615-626.

Casciati S (2010). Response surface models to detect and localize distributed cracks in a complex continuum. *Journal of Engineering Mechanics*, 136(9), 1131-1142.

Cheng J, Zhang J, Cai CS, Xiao RC (2007). A new approach for solving inverse reliability problems with implicit response functions. *Engineering Structures*, 29(1), 71-79.

Deng L, Cai CS (2010). Bridge model updating using response surface method. *Earth and Space 2010: Engineering, Science, Construction and Operations in Challenging Environments*, 2311-2320.

Deshan S, Qiao L, Inamullah K, Xiaohang Z (2015). A novel finite element model updating method based on substructure and response surface model. *Engineering Structures*, 103, 147-156.

Diaferio M, Foti D, Mongelli M, Giannoccaro NI (2011). Dynamic behavior of a historic tower in Bari. *Civil Engineering Topics*, 4, 335-342.

Fang S (2020). Damage detection of long-span bridge structures based on the response surface model. *Thermal Science*, OnLine-First, 1-9.

Fang SE, Perera R (2009). A response surface methodology based damage identification technique. *Smart Material and Structures*, 18(6), 065009.

Fang SE, Perera R (2011). Damage identification by response surface-based model updating using D-optimal design. *Mechanical Systems and Signal Processing*, 25(2), 717-733.

Foti D, Chorro SI, Sabba MF (2012). Dynamic investigation of an ancient masonry bell tower with Operational Modal Analysis - A non-destructive experimental technique to obtain the dynamic characteristics of a structure. *The Open Construction and Building Technology Journal*, 6, 384-391.

Gentile C, Gallino N (2008). Ambient vibration testing and structural evaluation of a historic suspension Footbridge. *Advances in Engineering Software*, 39(4), 356-366.

Gentile C, Saisi A, Cabboi A (2015). Structural identification of a masonry tower based on Operational Modal Analysis. *International Journal of Architectural Heritage*, 9(2), 98-110.

Hacıefendioğlu K, Başağa HB, Banerjee S (2017). Probabilistic analysis of historic masonry bridges to random ground motion by Monte Carlo simulation using response surface method. *Construction and Building Materials*, 134, 199-209.

Landman D, Simpson J, Vicroy D, Parker P (2007). Response surface methods for efficient complex aircraft configuration aerodynamic characterization. *Journal of Aircraft*, 44(4), 1189-1195.

Ocak İ (2009). Prediction of intact rock's elasticity modulus based on uniaxial compressive strength. *Istanbul Earth Science Review*, 21, 91-97.

Oliveira CS, Çaktı E, Stengel D, Brancol M (2012). Minaret behavior under earthquake loading: The case of historical Istanbul. *Earthquake Engineering and Structural Dynamics*, 41(1), 19-39.

Ren WX, Chen HB (2010). Finite element model updating in structural dynamics by using the response surface method. *Engineering structures*, 32(8), 2455-2465.

Umar SB (2015). Response Surface Methodology for Damage Detectıon Using Frequency and Mode Shapes. *M.Sc thesis*, University of Technology, Malaysia.

Worden K, Cross EJ (2018). On switching response surface models, with applications to the structural health monitoring of bridges. *Mechanical Systems and Signal Processing*, 98, 139-156.

Zong Z, Lin X, Niu J (2015). Finite element model validation of bridge based on structural health monitoring-Part I: Response surface-based finite element model updating. *Journal of Traffic and Transportation Engineering (English Edition)*, 2(4), 258-278.