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RESEARCH ARTICLE

Investigation on Similarity between Dynamic Behavior of a Reduced-Scale One Span Historical Masonry Arch Bridge Model and Prototype Bridge

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Abstract

Experimental investigations of large and complex structural systems can be carried out by reduced-scale models in terms of convenience, time-saving and economical. This can be applied to different fields of study such as vibration, impact and explosion problems in structural engineering and allows reliable analysis to understand the static and dynamic behavior of real structures called a prototype. This study aims that a 1/3 reduced-scale model is created in the laboratory environment considering similitude requirements by selecting a single span historical masonry arch bridge as a prototype structure. For this purpose, the Operational Modal Analysis (OMA) Technique is utilized for experimental study to determine modal parameters of the prototype and model bridges. The similarity of the dynamic behavior of the reduced-scale bridge model and prototype are investigated. The analysis of the similarity in the dynamic behavior of the prototype and model bridge consists of comparing the natural frequencies and mode shapes by utilizing the modal assurance criterion (MAC) corresponding to the translational, bending and torsional modes. As a result of the study, it is concluded that the dynamic behavior of the reduced-scale bridge model is similar to the dynamic behavior of the prototype bridge.

Keywords: Reduced-Scale Model, Similitude Requirements, Operational Modal Analysis, Enhanced Frequency Domain Decomposition

1. Introduction

Engineering analysis and design often require simulations where direct experimental studies on the real system called prototype are not possible or costly. To simulate the prototype with a mathematical model, characteristic equations defining the behavior of the system must be well defined. Such operations often require more assumptions to simulate the behavior of the system. Advantage of generating mathematical modeling of a system is that it is possible to obtain complete and detailed solutions without any experimental costs. On the other hand, the need for a large number of assumptions in the formation of a mathematical model appeared as a disadvantage of the approach. In addition, in many cases, it is difficult to obtain a mathematical solution due to the complexity of the basic equations.

Alternatively, the similitude technique is based on the representation of the prototype with a simulated model. A simulated model is defined as a system that is geometrically similar, but not completely identical to the prototype. In experimental practice, such systems are called models and are generally

smaller than the prototype. One of the major advantages of the similitude technique is that it allows the investigation of very complex problems. In many cases, the assumptions used in the similitude technique are less than those used in a mathematical model for similar models. Another important advantage of the similitude technique is that it allows the experimental work to be performed on the prototype bridge to be carried out in a more cost-effective in a laboratory environment. Experimental analysis of large and complex systems can be performed by reduced-scale models in terms of convenience, time saving and economical. Many studies related to reduced-scaling are available in the literature such as

automobiles, ships, space shuttles, aircraft wing, space stations, thermal models, wind tunnels, marine structures, bridges and buildings. It is applied to different fields of work such as vibration, collision, and explosion problems in structural engineering and allows a reliable analysis of the static and dynamic behavior of the prototype.

Clough and Niwa (1982) [1] investigated the nonlinear behavior of concrete arch dams under the influence of earthquake on a 6 m shake table. The required material properties were calculated to generate a 1/150 reduced-scale dam model. As a result of the study, it is emphasized that non-linear earthquake behavior and the real destruction mechanism of concrete arch dams can be identified. In another study done by Wilby et al. (1982) [2], two identical reduced-scale six-story three-dimensional reinforced concrete structures, consisting of columns, beams, and slabs, were constructed. Each structure has a single opening in each direction and consists of reduced-scale models of approximately 1/5 of the full-scale structure. The study compared the deformations of the models under dynamic loading with the values obtained from dynamic analysis to a frame system created in the computer program and stated that the accuracy of the predicted behavior was directly dependent on the stiffness and damping values. El-Shafie (1997) [3] examined the behavior of 1/3 reduced-scale hollow reinforced concrete masonry. 9 samples of 1/3 scale hollow shear walls were tested by applying the horizontal load from the top point. The effects of the size, location, and geometry of the opening on the horizontal load capacity of the masonry wall, internal forces and the type of destruction were investigated. Also, the stiffness and damping properties of the models were calculated by analytical methods. Alves and Oshiro (2006) [4] applied axial and horizontal impact forces to two models consisting of steel and aluminum. As a result of the study, they stated that reduced-scale

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models with different materials under the effects of impact load can exhibit the behavior of the prototype. Petry and Beyer (2012) [5] studied the relationship of different structural elements on a 1:2 scale of a 4-story structure consisting of reinforced concrete and non-reinforced masonry systems using a shake table. They stated that the models made of reinforced concrete generally show a close relationship for the static and dynamic behavior of the prototype structure as opposed to the models created from masonry structures. Chegini and Palermo (2014) [6] created two reduced-scale bridge models that represent a two-bay short-span concrete bridge, one is non-skew and the other is skew with a slope of 35°, in the laboratory. They examined the dynamic behavior of the models by giving a sine wave through the shaking table. As a result of the study, it was observed that the effect of skew resulted in an unsymmetrical rotation in the slab. Çaktı et al. (2016) [7] modeled the 1:10 scale model of the 15th century Mustafa Paşa Mosque in Skopje with a discrete element approach. They examined the dynamic behavior of the reduced-scale model using the shaking table. As a result, they emphasized that the discrete element approach is a suitable technique for dynamic nonlinear modeling of complex masonry structures.

As can be seen from the mentioned studies, reduced-scale models have been constructed and static and dynamic analyses have been carried out in the laboratory environment to examine the dynamic behaviors of real structures and. However, there are few studies about the reduced-scale modeling of historical structures. Therefore, This study is based on a part of the doctoral dissertation [8] and focused on that a 1/3 reduced-scale model was created in the laboratory environment considering similitude requirements by selecting a single span historical masonry arch bridge as a prototype structure. OMA technique is performed for experimental study to determine modal parameters of the prototype and model bridges. The similarity of the dynamic behavior of the reduced-scale bridge model and prototype was investigated. The study is expected to contribute to the investigation of the dynamic behavior of historic bridges by using reduced-scale models constructed in the laboratory and analyzing the similarities between the dynamic behavior of these models and prototype.

2. Materials and Methods

2.1. Enhanced Frequency Domain Decomposition

In general, EFDD technique is used for OMA 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. The relationship between unknown input $x(t)$ and the measured responses $y(t)$ is expressed as [9, 10];

$$G_{yy}(j\omega) = H(j\omega) * G_{xx}(j\omega)H(j\omega)^T \quad (1)$$

2.2. Modal Assurance Criterion

The Modal Assurance Criterion (MAC) can be used in the application of modal analysis due to its capability to compare different mode shapes in one number. The MAC values are between 0 and 1. If there is enough agreement between mode shapes, the MAC value is around 1. For two different mode shapes $\{\varphi_x\}$ and $\{\varphi_y\}$, the MAC value can be calculated as follow [11];

$$MAC(r, s) = \frac{|\{\varphi_x\}_r^T \{\varphi_y\}_s|^2}{(\{\varphi_x\}_r^T \{\varphi_x\}_r \{\varphi_y\}_s^T \{\varphi_y\}_s)} \quad (2)$$

2.3. Reduced-Scale Modeling

The technique that describes the relationship between model and prototype is called modeling. Modeling is an experimental method and its application is based on dimensional evaluations. This method uses certain dimensional properties of the variables that arise in the non-dimensional problem. The effectiveness of the method can be improved by using the necessary information about the systems to be examined analytically or experimentally. When this information is

obtained about the system, both model design and experimental work can be simplified to a certain extent depending on the importance and amount of available information [12]. In this study, the similarity between the prototype and the model bridge is examined as a comparison of the identified frequency values, therefore, only the frequency scale factor is mentioned herein. Comprehensive explanations can be found from the study done by Jha et al. (2005) [13]. In the case of similarity, the linear relationship for relevant variables between prototype and model is expressed as a constant ratio called scale factor, λ . This ratio is expressed as;

$$\lambda_i = \frac{\text{Magnitude of } i^{\text{th}} \text{ variable in prototype}}{\text{Magnitude of } i^{\text{th}} \text{ variable in model}} \quad (3)$$

Especially when vibrations of the structures are examined, it is logical to neglect the law of gravitational due to the negative effects of gravity on natural frequency. In cases where gravity is neglected, the scaling problem in dynamic analysis can be easily resolved and the frequency scale factor, λ_ω can be obtained as follows [13];

$$\lambda_\omega = \frac{1}{\lambda_t} \sqrt{\frac{\lambda_E}{\lambda_\rho}} \quad (4)$$

2.4. Historical Sarpdere Masonry Bridge

The Historical Sarpdere Bridge located on the Ordu-Ulubey road, 33 km from Ordu and 9 km from Ulubey, in the Şihlar village was chosen as a prototype. The bridge was built as a single-span bridge in the 1870s during the Ottoman Empire and became one of the most important bridges between Ordu and Sivas. In time, it was aimed to preserve this historical culture due to the deterioration of the material properties and boundary conditions of the historical arch bridge. In 2012, the restoration work was completed by the 7th Regional Directorate of Samsun Highways (Fig. 1). The historic Sarpdere Bridge is an arch bridge built of natural stone. The bridge is 15.50 m long and 4.75 m wide. The bridge is composed of the arch part which has four different radii, sidewalls, filling material, walkway, and railing. The geometric features of the historical bridge are shown in Fig. 2. Horasan mortar is used as the binding material. Limestone was used in bridge construction. The mechanical properties of the materials shown in Table 1 were used by taking advantage of a study on the same bridge done by Aydın and Özkaya (2018) [14].

2.5. Construction of Reduced-Scale Masonry Bridge

In the construction of the bridge model, andesite stones were used for the arches, sidewalls and slab elements. Arch stones were cut to be 5x10cm, 10x10cm, 15x10cm and 20x10cm. Crushed andesite stones were used for the sidewalls. The slab stones were supplied as 30x80x4 cm and 30x100x4 cm plates. Straw soil was used as a filling material (Fig. 3). The right and left abutment of the masonry bridge model was designed as concrete.

Figure 1. Historical Sarpdere Bridge
(a) Before restoration (c) After Restoration

Figure 2. Geometrical properties of Historical Sarpdere Bridge (a) Front view (b) Side view

Table 1. Material Properties of Sarpdere Bridge

	Unit Weight (kg/m ³)	Modulus of Elasticity (MPa)	Poisson Ratio
Arch	1900	3000	0.2
Sidewalls	1800	2500	0.2
Slab	1800	2500	0.2
Filling material	1365	1500	0.05

Horasan mortar was used as the binding material for the arch, sidewall and slab elements on the bridge model. Horasan 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. 4. After the bridge abutments were completed, the necessary framework process was performed and the arrangement of arch stones was started from both side simultaneously. The sidewalls 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 sidewalls 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. 5.

Figure 3. Materials used in construction
(a) Arch stones (b) Sidewall stones
(c) Slab stones (d) Straw soil

Figure 4. Construction steps of the masonry bridge model (a) Arch (b) Sidewalls (c) Filling (d) Slab

Figure 5. (a) Reduced-scale masonry bridge model (b) Top view (c) Front view (mm)

Figure 6. Experimental study (a) Test setup
(b) Accelerometer configurations

3. RESULTS

3.1. Experimental Modal Identification of Sarpdere Bridge

Modal parameters of the historical bridge (natural frequency, mode shape, and damping ratio) were identified by using OMA method. Ambient vibration signals under vehicle and wind loads were obtained by using data acquisition system and two uniaxial and five triaxial accelerometers with a range of 0.1-120 Hz placed on 6 different locations at 4m intervals on the bridge. Fig. 6 shows the experimental study. The measurement time and frequency range were selected as 30 min and 0-100 Hz. Vibration signals from accelerometers are recorded using Testlab_V2 software via the data acquisition system. The experimental modal parameters of the historical bridge were analyzed using ARTeMIS Modal 1.5 software (2012) [15].

Natural frequencies, mode shapes and damping ratios of the masonry bridge were obtained by using EFDD method as represented in Fig. 7. Mode shapes were identified as translational, bending and torsional mode. The natural frequency and damping ratio values corresponding to these three modes of the structure are demonstrated in Table 2. Experimentally obtained mode shapes of the masonry bridge are shown in Fig. 8.

Figure 7. Experimental natural frequencies

Table 2. Experimentally identified natural frequencies and damping ratios of Sarpdere Bridge

Modes	Natural frequencies f(Hz)	Damping ratios $\xi(\%)$
Translational	17.556	2.326
Bending	28.926	1.157
Torsional	41.231	0.560

Figure 8. Experimentally obtained mode shapes of Sarpdere Bridge
(a) Translational mode,
(b) Bending mode, (c) Torsional mode

3.2. Experimental Model Identification of Reduced-Scale Bridge Model

The vibrational response of reduced-scale masonry bridge model was taken under the environmental effects by using the OMA method. 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. 9 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. 10. 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 historical bridge were analyzed using ARTeMIS Modal 1.5 software (2012).

Figure 9. Experimental application of reduced-scale masonry bridge

Figure 10. 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. 11. Mode shapes were identified as the translational, bending and torsional mode. The natural frequency and damping ratio values corresponding to these three modes of the structure are demonstrated in Table 3. In addition, the mode shapes of the experimentally obtained reduced scale bridge are shown in Fig. 12.

Figure 11. Average of normalized singular values of spectral density matrices of all test setups

Table 3. Experimentally identified natural frequencies and damping ratios

Modes	Natural frequencies f(Hz)	Damping ratios $\xi(\%)$
Translational	65.46	0.526
Bending	95.09	0.561
Torsional	130.55	0.368

Figure 12. Experimentally identified mode shapes of the masonry bridge model (a) Translational mode (b) Bending mode (c) Torsional mode

3.3. Comparisons in the dynamic behavior between reduced-scale and prototype bridges

The investigation of the similarity in the dynamic behavior of the prototype and model bridge consists of two steps. The first step involves comparing the natural frequencies corresponding to the translational, bending and torsional mode shapes obtained experimentally from the prototype and model bridge. This comparison was performed with the approaches presented in the similitude requirements. The second step includes the comparison of the corresponding mode shapes obtained from the prototype and the model bridge. This comparison was made by evaluating the MAC values and the compatibility of the mode shapes was examined.

Comparison of natural frequency values

In the similitude approach, taking into account the fact that the effect of gravity is neglected, Eq. 3 was used as the natural frequency relation between prototype and reduced-scale models. It is seen that the frequency scaling factors is related to the modulus of elasticity and unit weight of the prototype and model. Since the structure in this study is a historical bridge and the components of the structural system have different modulus of elasticity and unit weights, the approach in calculating corresponding values is explained below. Unit weight and modulus of elasticity of the systems was calculated from the geometric and material properties of the structural elements obtained from the calibrated FE model of both the prototype and the model bridge (Alpaslan, 2019) The volume, weights and unit weight calculations of structural components are shown in Table 4.

Table 4. Calculation of unit weight for the prototype and model

	Prototype			Model		
	Volume (m3)	Weight (kg)	Unit weight (kg/m3)	Volume (m3)	Weight (kg)	Unit weight (kg/m3)
Arch	52.143	99073	1900	0.82	1747	2131
Side walls	30.574	55034	1800	1.21	2517	2080
Slab	8.717	15691	1800	0.34	627	1843
Infill	105.94	144616	1365	4.84	7792	1610
Total	197.37	314414	1593	7.21	12683	1759

The approaches used in the calculation of the elasticity modulus of the composite materials were utilized. It is based on the calculation of the modulus of elasticity of the system related to the volumetric percentage ratios of the different system components with the different modulus of elasticity. In this study, elasticity modulus of prototype and model bridge systems were obtained by using Voigt and Reuss model. In the Voigt parallel phase model, it is assumed that there is a constant deformation on the composite material, that is, the elements demonstrate equal deformation. On the other hand, Reuss series phase model assumes constant stress on the composite material. The following equations are proposed for the calculation of modulus of elasticity of the system;

$$E_s = E_1 V_1 + E_2 V_2 + \dots E_n V_n \text{ (Voigt model)} \quad (5)$$

$$1/E_s = V_1/E_1 + V_2/E_2 + \dots + V_n/E_n \text{ (Reuss model)} \quad (6)$$

The modulus of elasticity values for prototype and model obtained from the equations are presented in Table 5.

The frequency scaling factors can be calculated from using these values as follows;

According to the Voigt approach;

$$\lambda_w = \frac{1}{\lambda_l} \sqrt{\frac{\lambda_E}{\lambda_\rho}} = \frac{1}{3} \sqrt{\frac{2095/2648}{1593/1759}} = 0.311$$

According to the Reuss approach;

Comparison of mode shapes

The second parameter in the investigation of similarity for the dynamic behavior between the prototype and model bridge is the natural mode shapes. The translational, bending and torsion modes obtained on the model bridge were compared with the corresponding mode shapes obtained on the prototype bridge. The MAC technique was used in the comparison. The MAC values and the MAC matrix obtained for the corresponding mode shapes are illustrated in Fig. 13. As can be understood from the figures, the mode shapes obtained between the bridge model and Sarpdere Bridge are in good harmony.

As a result of the experimental study performed on reduced-scale bridge model, the natural frequency values corresponding to translational, bending and torsion modes were obtained as 65.46 Hz, 95.09 Hz, and 130.55 Hz, respectively. Using the similitude requirements, these frequency values obtained from the reduced-scale model bridge are compared with the corresponding frequency values identified from the prototype bridge and it has resulted in that the differences in natural frequency values were found as 2% - 14% according to Voigt model and 10% - 25% according to Reuss model. The differences according to similitude requirements using the Voigt method appear to be significantly less than those obtained using the Reuss method. Moreover, the MAC values obtained in the comparison of the translational, bending and torsion modes of the model and prototype bridge were 0.93, 0.96 and 0.83, respectively.

Table 5. Calculation of the modulus of elasticity of prototype and model

	Prototype				Model			
	Modulus of elasticity (MPa)	Volumetric Percentage	Modulus of elasticity (entire system) (MPa)		Modulus of elasticity (MPa)	Volumetric Percentage	Modulus of elasticity (entire system) (MPa)	
			Voigt	Reuss			Voigt	Reuss
Arch	3000	0.264			6355	0.114		

Sidewalls	2500	0.155			4569	0.168		
Slab	2500	0.044	2095	1903	4129	0.047	2648	1872
Infill	1500	0.537			1433	0.671		
Total	---	1			---	1		

The relationship between the natural frequencies between the prototype and the model bridge is calculated using the coefficients obtained by both methods.

$$\text{Natural Frequency of model} = (\text{Natural frequency of prototype}) / \lambda_{\omega} \quad (7)$$

Considering the similitude requirements, the natural frequency values corresponding to the translational, bending and torsional modes which supposed to be obtained experimentally from the model bridge are represented in Table 6.

Table 6. Expected natural frequency values from reduced-scale bridge model

Mode	Prototype (Hz)	Model (Hz)	Expected natural frequency values (Hz)			
			Voigt (Hz)	Error (%)	Reuss (Hz)	Error (%)
Translational	17.56	65.46	56.46	-13.75	49.74	-24.01
Bending	28.93	95.09	93.02	-2.18	81.95	-13.82
Torsional	41.23	130.55	132.57	-1.55	116.80	-10.53

Figure 13. MAC values of prototype and model
(a) MAC (b) MAC matrix

4. Conclusion

In this study, dynamic parameters of one-span Historic Sarpdere Bridge under environmental vibrations were obtained by using OMA method. Subsequently, 1/3 of the reduced-scale model of the historic bridge was constructed in the laboratory conditions. It was investigated whether the dynamic behavior of the reduced-scale bridge represents the dynamic behavior of the prototype bridge. These investigations were performed by comparing to the modal parameters

between prototype and reduced-scale bridge model in light of the similarity requirements.

As a result of the experimental study performed on reduced-scale bridge model, the natural frequency values corresponding to translational, bending and torsion modes were obtained as 65.46 Hz, 95.09 Hz and 130.55 Hz, respectively. When comparing the natural frequencies between reduced-scale model and prototype, the differences in natural frequency values were identified as 2% - 14% and 10% - 25% according to Voigt model and Reuss model, respectively, by performing the similitude requirements. It is appeared that more appropriate results were achieved by using Voigt model according to these comparisons. In addition, the MAC values obtained in the comparison of the translational, bending and torsional modes of the reduced-scale model and prototype were 0.93, 0.96 and 0.83, respectively. As a result of these two comparisons, it is understood that the dynamic behavior of the reduced-scale model bridge is similar to the dynamic behavior of the prototype bridge.

The application of reduced-scale modeling methodology has been resulted in to be useful and economical to understand the dynamic behavior of the structures. Scaling laws were derived for dynamic tests of structures by using similitude requirements and good correlation was obtained in experimental studies on prototype and model bridges. Therefore, it is understood that the reduced-scaled modeling technique can be used safely for dynamic analysis. Scaled modeling technique should be performed more frequently to determine the dynamic behavior of historical buildings. Reduced-scale modeling technique might be important to determine the presence and location of damages that may occur in historical buildings due to their cultural importance.

Symbols

$G_{xx}(j\omega)$	: Power Spectral Density (PSD) Matrix of the Input Signal
$G_{yy}(j\omega)$	: Power Spectral Density (PSD) Matrix of the Output Signal
$H(j\omega)$	: Frequency Response Function (FRF) Matrix
*	: Complex Conjugate
T	: Transpose
$\{\varphi\}_s$	: Test Modal Vector of Mode
$\{\varphi\}_t$	: Compatible Modal Vector of Mode
λ_i	: Scaling Factor Corresponding for i^{th} Physical Quantity
λ_E	: Young's Modulus Scaling Factors
λ_p	: Density Scaling Factors
λ_L	: Length Scaling Factors
E	: Modulus of Elasticity
V	: Volumetric Percentage Ratios of the Components

Acknowledgments

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.

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How to Cite This Article

Alpaslan, E., Karaca, Z., Investigation on Similarity between Dynamic Behavior of a Reduced-Scale One Span Historical Masonry Arch Bridge Model and Prototype Bridge, Civil Engineering Beyond Limits, 1(2021), 5-11. <https://doi.org/10.36937/cebel.2020.001.002>