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Manual model updating of highway bridges under operational condition

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Abstract. Finite element model updating is very effective procedure to determine the uncertainty parameters in structural model and minimize the differences between experimentally and numerically identified dynamic characteristics. This procedure can be practiced with manual and automatic model updating procedures. The manual model updating involves manual changes of geometry and analyses parameters by trial and error, guided by engineering judgement. Besides, the automated updating is performed by constructing a series of loops based on optimization procedures. This paper addresses the ambient vibration based finite element model updating of long span reinforced concrete highway bridges using manual model updating procedure. Birecik Highway Bridge located on the 81^{st}km of Şanlıurfa-Gaziantep state highway over Fırat River in Turkey is selected as a case study. The structural carrier system of the bridge consists of two main parts: *Arch and Beam Compartments*. In this part of the paper, the arch compartment is investigated. Three dimensional finite element model of the arch compartment of the bridge is constructed using SAP2000 software to determine the dynamic characteristics, numerically. Operational Modal Analysis method is used to extract dynamic characteristics using Enhanced Frequency Domain Decomposition method. Numerically and experimentally identified dynamic characteristics are compared with each other and finite element model of the arch compartment of the bridge is updated manually by changing some uncertain parameters such as section properties, damages, boundary conditions and material properties to reduce the difference between the results. It is demonstrated that the ambient vibration measurements are enough to identify the most significant modes of long span highway bridges. Maximum differences between the natural frequencies are reduced averagely from %49.1 to %0.6 by model updating. Also, a good harmony is found between mode shapes after finite element model updating.

Keywords: ambient vibration test; enhanced frequency domain decomposition; finite element model; highway bridge; manual model updating; operational modal analysis

1. Introduction

Among all types of civil engineering structures, long span highway bridges attract the greatest interest for studies of structural performance by the academic researchers (Brownjohn, Magalhaes *et al.* 2010). Dynamic characteristics are of immense importance in determining the current structural performance. Generally, these properties are determined numerically using the finite element analyses (Bayraktar, Altunışık *et al.* 2009). During numerical studies, material properties, boundary conditions and section areas accepted in the design can change due to various reasons such as; workers' mistakes during construction, different load cases which are not considered in the design and which the structure may be exposed to in the course of time, contributing to a reduction in structural resistance. Therefore, it is suggested here, that the, dynamic characteristics of structures need to be based on and be determined by experimental methods.

Operational Modal Analyses method is widely used to determine the experimental dynamic characteristics. This is especially true for long span highway bridges under operational condition using experimental measurements. Essentially, it is performed by just measuring the structural response under ambient excitation with the main objective of estimating the dynamic characteristics. The methods available to perform the identification of dynamic characteristics of systems based on their response to ambient excitation are usually classified as frequency domain or time domain methods (Magalhaes and Cunha 2011).

It is a widely accepted fact that natural frequencies and mode shapes obtained from field testing do not coincide with those of the numerical model. The problem of how to modify the numerical model from the dynamic measurements is known as the model updating in structural dynamics (Altunışık, Bayraktar *et al.* 2011). This procedure can be practiced with manual and automatic model updating procedures. The manual model updating involves manual changes of geometry and analyses parameters by trial and error, guided by engineering judgement. Besides, the automated updating is performed by constructing a series of loops based on optimization procedures. The main purpose of the model updating procedure is to minimize the differences between the numerically and experimentally determined dynamic characteristics by changing some uncertainty parameters such as material properties or

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boundary conditions.

In the literature, there have been some studies relating to finite element modeling and experimental measurements of highway bridges: Ubertini, Gentile *et al.* (2013) studied the automated modal identification of engineering structures in operational conditions. This procedure is also applied to bridge structures for case studies. Whelan, Gangone *et al.* (2009), performed finite element analyses using real-time wireless vibration monitoring of an integral abutment highway bridge under operational condition. Magalhaes, Caetano *et al.* (2012) carried out ambient and free vibration tests of the Millau Viaduct, the tallest vehicular bridge in the world, its total length being 2460m and its pylon rising at 343 m above the river level. Real, Sanchez *et al.* (2012) conducted the experimental modal analysis of railway concrete sleepers with cracks. Lauzon and DeWolf (2006) studied the ambient vibration monitoring of a highway bridge undergoing a destructive test. In this study, structural responses of a highway bridge during the passage of a small truck were measured using a number of sensors. Gentile (2006) performed the dynamic-based assessment of a reinforced concrete arch bridge using Peak Picking and the Enhanced Frequency Domain Decomposition techniques. Yang, Bail *et al.* (2012) obtained the dynamic characteristics of Qingshui River Bridge using finite element analysis and ambient vibration test. In the experimental measurements, both the ambient vibration testing and the vehicle impact testing were carried out on a concrete multi-girder bridge. Also, the up-to-date articles can be available about the structural identification, finite element modelling, experimental measurements and model updating of bridge structures (Zhu, Xu *et al.* 2015, Dubbs and Moon 2016, Polanco, May *et al.* 2016). As can be seen from the literature mentioned above, studies of finite element analyses, experimental measurements and manual finite element model updating of long span highway bridges are insufficient.

2. Enhanced Frequency Domain Decomposition (EFDD) method

The EFDD method is an extension of the FDD method which is a basic technique that is easy to use. In this method, modes are simply picked locating the peaks in Singular Value Decomposition plots calculated from the spectral density spectra of the responses. As FDD method is based on using a single frequency line from the Fast Fourier Transform analysis, the accuracy of the estimated natural frequency depends on the FFT resolution and no modal damping is calculated. However, EFDD gives an improved estimation of both the natural frequencies and the mode shapes and also includes damping. More detail information can be found about the EFDD method and its theoretical background in the literature (Felber 1993, Peeters 2000, Bendat and Piersol 2004, Ren, Zhao *et al.* 2004, Jacobsen, Andersen *et al.* 2006, Rainieri, Fabbrocino *et al.* 2007).

3. Birecik highway bridge-arch compartment

The Birecik Highway Bridge is located on the 81stkm of Şanlıurfa-Gaziantep state highway over Fırat River in Turkey. It has a major logistical importance due to its positon of being the only bridge in this part of Fırat. The construction of the bridge was started in June 1951 and the bridge was opened to traffic in April 1956. It is the longest concrete highway bridge of Turkey considering the date of its construction.

The total length of the bridge is 720 m and its width is 10 m. The structural carrier system of the bridge consists of two main parts: *Arch and Beam Compartments*. The Arch compartment of the bridge consists of five arches each of which has a 55 m main span. This part of the paper will be focusing on the arch compartment. The bridge arches have rigid connectivity at the middle spans and side supports. But, the right and left side of the middle points of the slabs are constructed using joints. The columns, beams, arches, decks and foundations were constructed as reinforced concrete. The total length of the arch compartment is 300m. Some views of the general appearance, joints and support types of Birecik Highway Bridge-Arch Compartment are given in Figs. 1(a)-1(c).

4. Finite element analysis

Three dimensional finite element model of the bridge-*arch compartment* is constructed using building survey drawings by SAP2000 software (SAP2000 2015). Arches, columns and beams are modeled by frame elements having three translational DOFs and three rotational DOFs at each node. Also, the deck and side walls are modeled by shell elements. Expansion joints are modeled using restricted boundary conditions and rigidity springs.

To determine the material and soil properties, some samples were taken from the main structural elements and geotechnical investigation were carried out. According to the laboratory studies and prepared reports, the considered material properties id presented in Table 1.

Experimental measurements on each bridge arch were separately conducted in order to determine the structural behavior of the arches within the shortest time span and to compare the numerical results with experimental results for model updating. The experimental measurements proved that, the frequency span of bridge arches paralleled each other. Consequently, the initial finite element model of the bridge arch compartment was constituted for one bridge arch only.

Experimental measurements applied to other bridge arches and to all bridge models were obtained to be considered for the improvements to be made on the arches. The arch-foundation interaction points were assumed to be rigid and fully fixed in the initial finite element model. Expansion joints between each arch were modeled using spring and link elements which had longitudinal, transverse and vertical displacements stiffness. Fig. 2 shows the three dimensional initial finite element model of the bridge arch.

The first five mode shapes obtained from numerical solutions of the bridge is given in Fig. 3. From the modal analysis, a total of five natural frequencies which range between 3.940-9.530Hz, are attained numerically. The numerical mode shapes can be classified into vertical and transverse modes.

Fig. 1 Some views of the Birecik Highway Bridge-Arch Compartment

Table 1 Material properties considered in finite element analyses

Elements	Material Properties		
	Modulus of Elasticity (N/m^2)	*Poisson Ratio (-)*	*Density (kg/m^3)*
Arch	3.2E10	0.2	2450
Deck	3.2E10	0.2	2450
Column	3.2E10	0.2	2450
Beam	3.2E10	0.2	2450
Foundation	3.2E10	0.2	2450
Rebar	2.0E11	0.3	7850

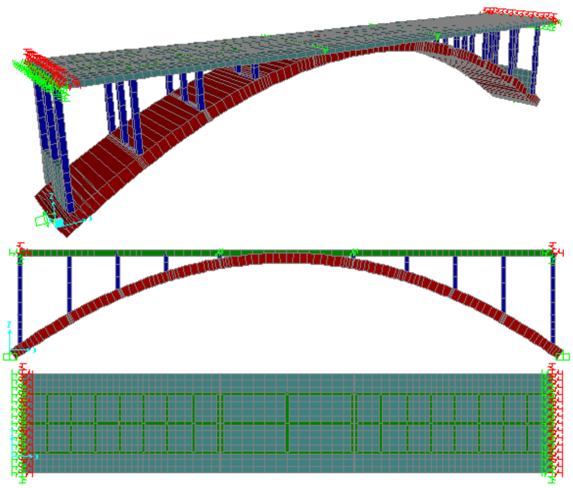


Fig. 2 Three dimensional initial finite element model of the bridge arch

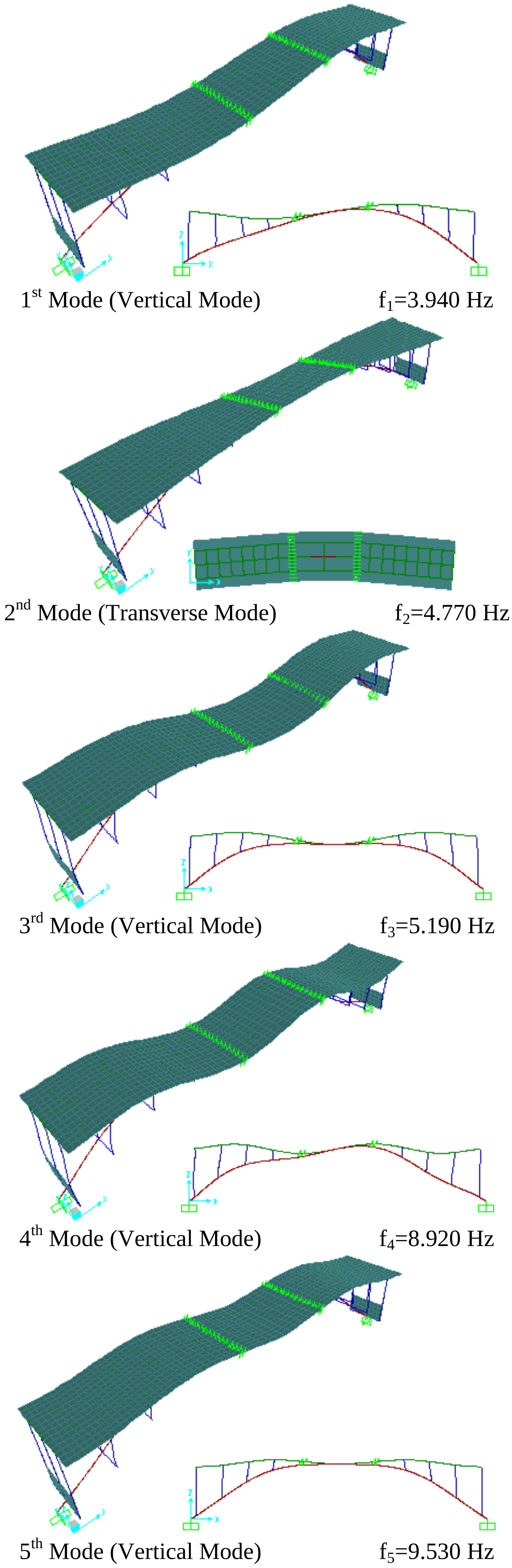


Fig. 3 The first five numerically identified mode shapes

5. Experimental measurements

The finite element method can produce a good representation of a true structure. However, the prediction from this method is not always accurate. Inaccuracies and errors in a finite element model may arise due to:

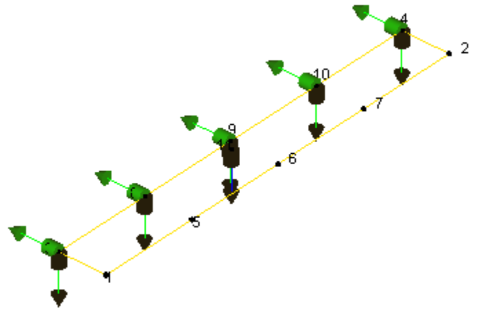
- Inaccurate estimation of material and geometric properties,
- Deterioration due to environmental hazards such as wind, earthquakes, and higher serviced loads after so many years of use,
- Poor approximation of boundary conditions and inadequate modeling of joints,
- Faulty assumptions in individual element shape functions and poor quality mesh,
- Nonlinearities, damping mechanisms, and coupling effects that are not taken into account in the model.

Experimental measurements are performed to increase the knowledge and understanding of the behavior of a structure. This is accomplished by observing the response of a structure to a set of known conditions. During the past few years, ambient vibration testing (Operational Modal Testing) has proved to be a valuable alternative to the classic forced vibration testing. Instead of artificial excitation devices, 'in operation modal testing' makes use of the freely available ambient excitation caused by natural sources on or near the test structure. Additionally, the test structure remains in its operating condition during the test.

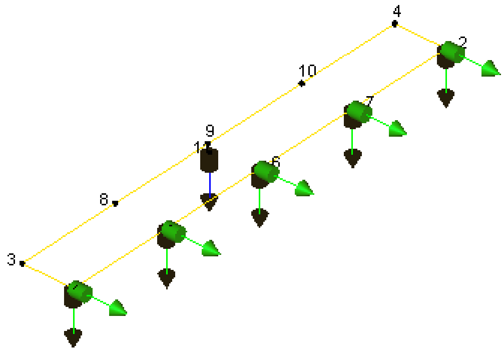
In the experimental measurements, the response of the arch is measured by using B&K 8340 type uni-axial accelerometers. The minimum frequency span and sensitivity of these accelerometers are 0.1-1000 Hz and 10 v/g. The signals are acquired in the B&K 3560 type data acquisition system and then transferred into the PULSE Lapshop software (PULSE 2006). For parameter estimation from the Ambient Vibration Survey data, the Operational Modal Analysis software is used (OMA 2006).

Normal traffic over the bridge was used as a source of ambient vibration during the tests. Since input force was not measured, the use of Operational Modal Analysis to identify modal parameters was indispensable. Three ambient vibration tests were carried out for one hour on the bridge deck. Due to the limited availability of accelerometers and data acquisition equipment, a maximum of 11 accelerometers for each test step could be monitored simultaneously. Among these accelerometers, a uni-axial was used as a reference accelerometer and its location remained unchanged throughout the test. The others were used as roving accelerometers and were moved in order to cover all accelerometer locations at the vertical and transverse directions. Explanation of the selected measurement points are given in Figs. 4(a)-4(c).

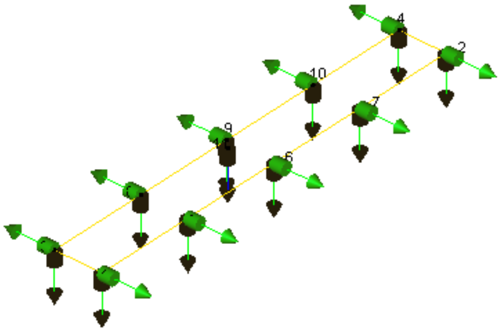
Singular values of spectral density matrices of the third test setup, attained from vibration signals using EFDD method, are shown in Fig. 5. The first five mode shapes, obtained from the experimental measurements, are given in Fig. 6. When the experimentally identified mode shapes are compared with each other, it can be observed that there is a good agreement between all results. With this in mind, only one measurement of a mode shape is given with detail in Fig. 6.



(a) First tests at the upstream direction



(b) Second test at the downstream direction



(c) Third test at the all directions

Fig. 4 The accelerometer locations for each experimental measurement

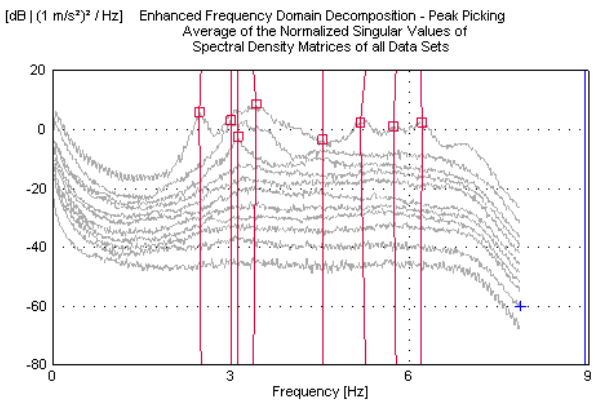
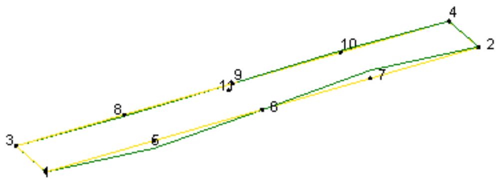
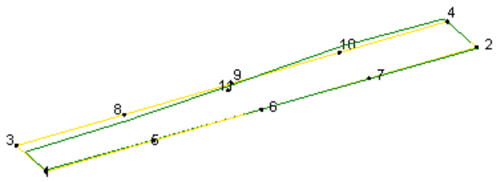


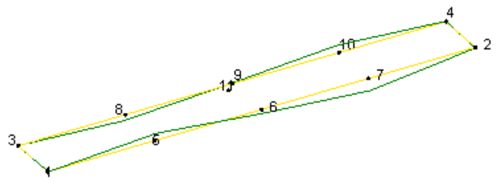
Fig. 5 Singular values of spectral density matrices



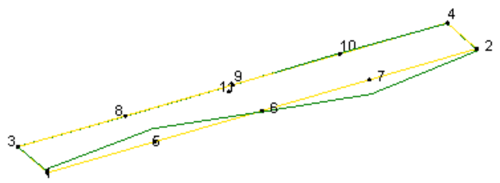
1^{st} Mode (Vertical Mode)



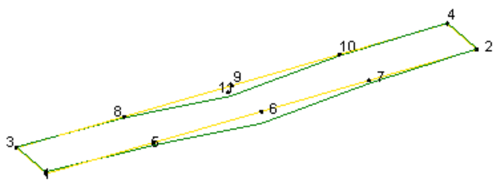
2^{nd} Mode (Transverse Mode)



3^{rd} Mode (Torsional Mode)



4^{th} Mode (Vertical Mode)



5^{th} Mode (Vertical Mode)

Fig. 6 The first five experimentally identified mode shapes

Table 2 Comparison of the numerical and experimental dynamic characteristics

Mod Number	Natural Frequency (Hz)		Differences (%)	Damping Ratios (%)
	Numerical	*Experimental*		
1	3.940	2.496	36.7	4.358
2	4.770	3.115	34.7	0.899
3	5.190	3.378	34.9	0.863
4	8.920	4.545	49.1	0.118
5	9.530	5.258	44.8	3.970

Numerically and experimentally identified dynamic characteristics of the bridge are given in Table 2. A comparison of Fig. 3, Fig. 6 and Table 2 reveals that there are some differences between the mode shapes and natural frequencies. The difference between the natural frequencies is measured between 34.7% and 49.1%.

6. Manual finite element model updating

When the numerically and experimentally identified dynamic characteristics are compared with each other, it becomes clear that there are some differences between mode shapes and natural frequencies. This makes it necessary to update the finite element model of the bridge by changing some uncertain parameters to eliminate these differences.

Some signs of deterioration were observed during field investigations on the bridge:

- Regional cracks at the arches and columns,
- Deteriorations at the supports and expansion joints,
- Foundation scouring,
- Moisture, humidity and water infiltration,
- Shell concrete failures due to the corrosions at some sections.

Some views of the deteriorations mentioned above can be seen in Figs. 7(a)-7(c). According to which the, structural properties of all damaged sections were manually reduced. Additionally, semi-rigid connections were designated at the foundations and expansion joints.

A comparison of the numerical and experimental dynamic characteristics of the bridge after finite element model updating is given in Table 3. According to this, the difference in the natural frequencies is reduced on average from 49.1% to 0.60% and a good agreement is found between natural frequencies and mode shapes after model updating.

In this paper, the manual model updating procedure is employed to reduce the differences between the numerically and experimentally identified dynamic characteristics. The manual model updating involves manual changes of geometry and analyses parameters by trial and error, guided by engineering judgement. So, the maximum differences are reduced to 14.4%. For more correlation, automated model updating procedure should be used. The aim of automated model updating procedure is to improve further correlation and minimize the differences between numerical and experimental dynamic characteristics considering more uncertain parameters. This method can be also used to determine the damage localization and structural health monitoring.

The first five mode shapes obtained from numerical solutions after model updating are shown in Fig. 8. From the modal analysis, a total of five natural frequencies which range between 2.490-5.780 Hz is attained numerically. The numerical mode shapes can be classified into vertical, transverse and torsional modes. A good agreement is found between mode shapes after finite element model updating.

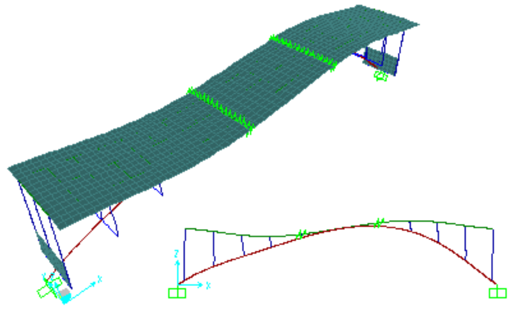
The arch compartment of the Birecik Highway Bridge consists of five arches. The regions between each arch were projected using expansion joint deck elements. The whole of the arch compartment of the bridge is constructed using updated finite element model of one arch. The finite element model of the Birecik Highway Bridge-*Arch Compartment* can be seen in Fig. 9. In this model, soil-structure interaction is taken into account to determine the static and dynamic behaviour of the bridge more accurately.

(a) Regional cracks at the arches and columns

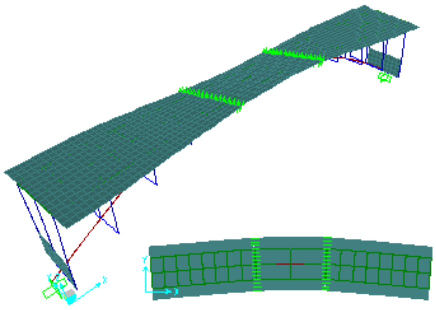
(b) Deteriorations and shell concrete failures

(c) Moisture, humidity and water infiltration

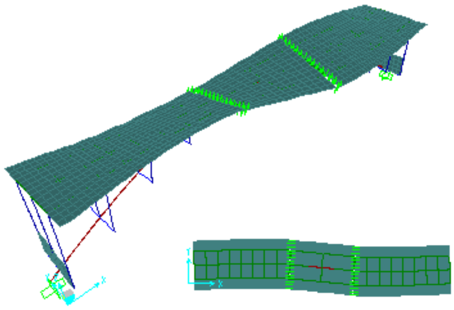
Fig. 7 Some views of the deteriorations obtained from the field investigation



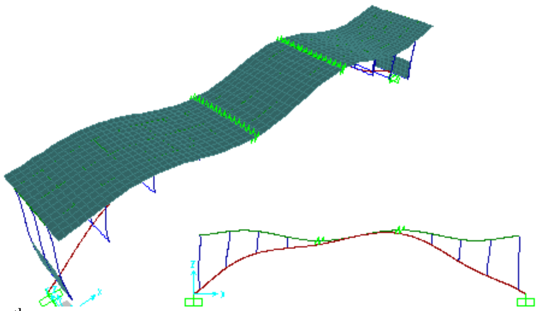
1^{st} Mode (Vertical Mode) f_1=2.490 Hz



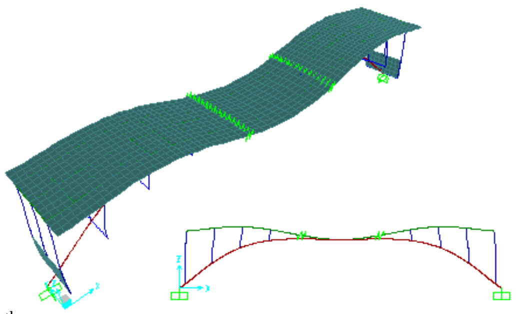
2^{nd} Mode (Transverse Mode) f_2=3.050 Hz



3^{rd} Mode (Torsional Mode) f_3=3.950 Hz



4^{th} Mode (Vertical Mode) f_4=4.300 Hz



5^{th} Mode (Vertical Mode) f_5=5.780Hz

Fig. 8 The first five numerically identified mode shapes after model updating

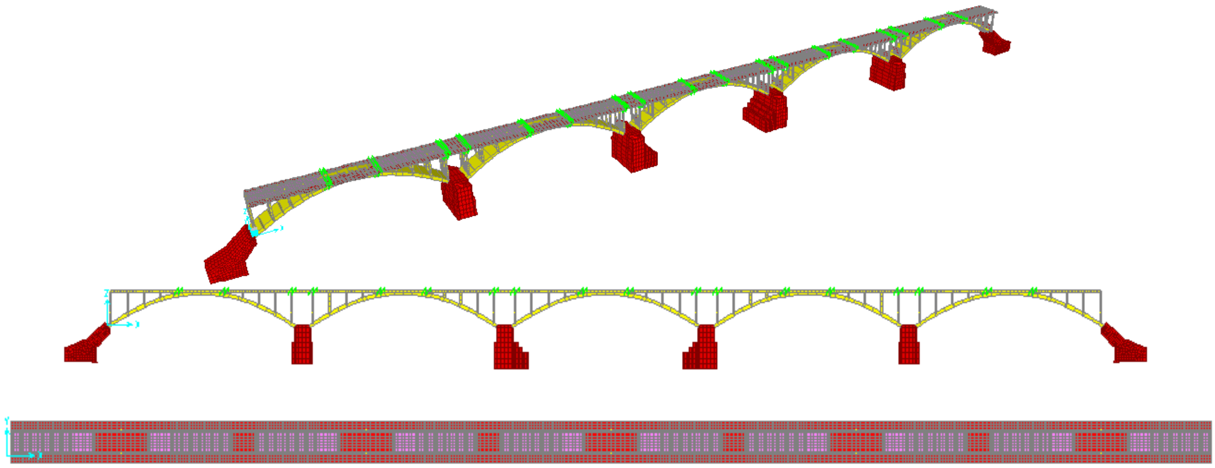


Fig. 9 Finite element model of the Birecik Highway Bridge-*Arch Compartment*

Table 3 Numerical and experimental dynamic characteristics after model updating

Mod Number	Natural Frequency (Hz)		Differences (%)	Damping Ratios (%)
	Numerical	*Experimental*		
1	2.490	2.496	0.60	4.358
2	3.050	3.115	2.08	0.899
3	3.950	3.378	14.4	0.863
4	4.300	4.545	5.39	0.118
5	5.780	5.258	9.09	3.970

7. Conclusions

This paper presents the ambient vibration based manual model updating of a long span reinforced concrete highway bridge. Birecik long span highway bridge located in Turkey is selected as an application. A comparison of the results from this study presents the following observations:

- Initial numerical natural frequencies of Birecik Highway Bridge-*Arch Compartment* were attained at ranges between 3.940 and 9.530 Hz for the first five modes. These can be classified into vertical modes in the z direction and transverse modes in the y direction.
- Three different measurement test setups were conducted for experimental measurements. The first five experimental modes were estimated between 2.496-5.258 Hz. These can be classified into vertical modes in the z direction, transverse modes in the y direction and torsional mode.
- A comparison among the numerically and experimentally identified dynamic characteristics of the bridge presents some differences between mode shapes and natural frequencies. The differences in the natural frequencies were obtained between 34.7% and 49.1%.
- Finite element model of the bridge was manually updated to eliminate these differences by changing some uncertain parameters such as regional cracks at the arches and columns, deteriorations at the supports and expansion joints, foundation scouring, moisture, humidity, water infiltration and shell concrete failures due to the corrosions at some sections.
- A good agreement was observed between mode shapes and natural frequencies after manuals model updating. The difference in the natural frequencies was reduced on average from 49.1% to 0.60%.

For more correlation, automated model updating procedure should be used to improve further correlation and minimize the differences considering more uncertain parameters. This method can be also used to determine the damage localization and structural health monitoring.

The arch compartment of the Birecik Highway Bridge consists of five arches. The regions between each arch were projected using expansion joint deck elements. The whole of the arch compartment of the bridge was constructed using the updated finite element model of one arch.

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References

Altunışık, A.C., Bayraktar, A., Sevim, B. and Ateş, Ş. (2011), "Ambient vibration based seismic evaluation of isolated Gülburnu highway bridge", *Soil Dyn. Earthq. Eng.*, **31**(11), 1496-1510.

Bayraktar, A., Altunışık, A.C., Sevim, B., Türker, T., Domaniç, A. and Taş, Y. (2009), "Vibration characteristics of kömürhan highway bridge constructed with balanced cantilever method", *J. Perform. Constr. Fac.*, **23**(2), 90-99.

Bendat, J.S. and Piersol, A.G. (2004), "Random data: Analysis and measurement procedures", John Wiley and Sons Inc., New Jersey, USA.

Brownjohn, J.M.W., Magalhaes, F., Caetano, E. and Cunha, A. (2010), "Ambient vibration re-testing and operational modal analysis of the Humber Bridge", *Eng. Struct.*, **32**(8), 2003-2018.

Dubbs, N.C. and Moon, F.L. (2016), "Assessment of long-span bridge performance issues through an iterative approach to ambient vibration-based structural identification", *J. Perform. Constr. Fac.*, **30**(5), 29-42.

Felber, A.J. (1993), "Development of Hybrid Bridge Evaluation System", PhD Thesis, University of British Columbia, Vancouver. (metinde atıf verilmemiş)

Gentile, C. (2006), "Modal and structural identification of a RC arch bridge", *Struct. Eng. Mech.*, **22**(1), 53-70.

Jacobsen, N.J., Andersen, P. and Brincker, R. (2006), "Using enhanced frequency domain decomposition as a robust technique to harmonic excitation in operational modal analysis", *Proceedings of the ISMA2006: International Conference on Noise & Vibration Engineering*, Leuven, Belgium, September.

Lauzon, R.G. and DeWolf, J.T. (2006), "Ambient vibration monitoring of a highway bridge undergoing a destructive test", *J. Bridge Eng. - ASCE*, **11**(5), 602-610.

Magalhaes, F., Caetano, E., Cunha, A., Flamand, O. and Grillaud, G. (2012), "Ambient and free vibration tests of the Millau Viaduct: Evaluation of alternative processing strategies", *Eng. Struct.*, **45**, 372-384.

Magalhaes, F. and Cunha, A. (2011), "Explaining operational modal analysis with data from an arch bridge", *Mech. Syst. Signal Pr.*, **25**(5), 1431-1450.

OMA (2006), Operational Modal Analysis, Release 4.0, Structural Vibration Solution A/S, Aalborg, Denmark.

Peeters, B. (2000), "System Identification and Damage Detection in Civil Engineering", PhD Thesis, K.U, Leuven, Heverlee.

Polanco, N.R., May, G. and Hernandez, E.M. (2016), "Finite element model updating of semi-composite bridge decks using operational acceleration measurements", *Eng. Struct.*, **126**, 264-277.

PULSE (2006), Labshop, Version 11.2.2., Brüel & Kjaer Sound and Vibration Measurement A/S. Naerum, Denmark.

Rainieri, C., Fabbrocino, G., Cosenza, E. and Manfredi, G. (2007), "Implementation of OMA procedures using labview: theory and application", *Proceedings of the 2nd International Operational Modal Analysis Conference*, Copenhagen, Denmark, 30 April-2 May.

Real, J.I., Sanchez,, M.E., Real, T., Sanchez, F.J. and Zamorano, C. (2012), "Experimental modal analysis of railway concrete sleepers with cracks", *Struct. Eng. Mech.*, **44**(1), 51-60.

Ren, W.X., Zhao, T. and Harik, I.E. (2004), "Experimental and analytical modal analysis of steel arch bridge", *J. Struct. Eng. - ASCE*, **130**(7), 1022-1031.

SAP2000 (2015), Computers and Structures Inc. Berkeley, California, USA.

Ubertini, F., Gentile, C. and Materazzi, A.L. (2013), "Automated modal identification in operational conditions and its application to bridges", *Eng. Struct.*, **46**, 264-278.

Whelan, M.J., Gangone, M.V., Janoyan, K.D. and Jha, R. (2009), "Real-time wireless vibration monitoring for operational modal analysis of an integral abutment highway bridge", *Eng. Struct.*, **31**(10), 2224-2235.

Yang, J.R., Bail, Y., Su, H.X. and Lai, Z.C. (2012), "Full-scale dynamic testing of Qingshui River Bridge", *Proceedings of the 2nd International Conference on Civil Engineering, Architecture and Building Materials*, Yantai, China, May.

Zhu, Q., Xu, Y.L. and Xiao, X. (2015), "Multiscale modeling and model updating of a cable-stayed bridge. I: Modeling and influence line analysis", *J. Bridge Eng. - ASCE*, **20**(10), 112-122.

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