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Finite element model updating of Kömürhan highway bridge based on experimental measurements

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Abstract. The updated finite element model of Kömürhan Highway Bridge on the Fırat River located on the 51st km of Elazığ-Malatya highway is obtained by using analytical and experimental results. The 2D and 3D finite element model of the bridge is created by using SAP2000 structural analyses software, and the dynamic characteristics of the bridge are determined analytically. The experimental measurements are carried out by Operational Modal Analysis Method under traffic induced vibrations and the dynamic characteristics are obtained experimentally. The vibration data are gathered from the both box girder and the deck of the bridge, separately. Due to the expansion joint in the middle of the bridge, special measurement points are selected when experimental test setups constitute. Measurement duration, frequency span and effective mode number are determined by considering similar studies in literature. The Peak Picking method in the frequency domain is used in the modal identification. At the end of the study, analytical and experimental dynamic characteristic are compared with each other and the finite element model of the bridge is updated by changing some uncertain parameters such as material properties and boundary conditions. Maximum differences between the natural frequencies are reduced from 10% to 2%, and a good agreement is found between natural frequencies and mode shapes after model updating.

Keywords: ambient vibration; finite element model updating; highway bridge; operational modal analysis; peak picking method.

1. Introduction

Determination of the dynamic characteristics such as natural frequencies, mode shapes and damping ratios using modal testing is very important to obtain current behaviour of the engineering structures. Modal testing has been conducted on bridges since the late 19th century (Salawu and Williams 1995).

Modal testing is one of the most popular and simple techniques for studying the behaviour of a structure through a number of natural frequencies and mode shapes. Modal testing includes an excitation source and response measurement. Response signals usually attained as acceleration, velocities and displacements. Various methods, including time and frequency domain, are available for extracting modal information from the dynamic response of a structure and corresponding input excitation. Types of excitation are usually ambient vibrations and forced vibrations. The ambient vibration are originated from wind, wave, traffic input. Forced vibration includes impact hammer and hydraulic shakers. The process of establishing the characteristics of a system from an experimental

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model is known as system identification.

Modal testing was applied on a lot of different highway bridge by many researchers in the literature to determine the dynamic characteristics. Conte *et al*. (2008) studied about dynamic field tests of Alfred Zampa Memorial Bridge located 32 km northeast of San Francisco on interstate Highway I-80. The dynamic field tests were conducted just before the bridge opening to traffic. To determine the dynamic characteristics both ambient vibration tests and forced vibration tests were used. Stochastic Subspace Identification method in the time domain was used for output-only modal identification. Guan *et al.* (2007) investigated the long-term structural health monitoring of FRP composite Highway Bridges using vibration-based monitoring techniques. Ambient vibration techniques were used, and the modal parameters are extracted from measured bridge response. The finite element model updating technique was used to provide an improved baseline model. The updated model was used for simulation of damage effects. Ashebo *et al.* (2007) carried out field measurements of box girder continuous bridge to evaluate dynamic loads. Experimental procedure, data acquisition system, calibration test, modal analysis and load distribution in a transversal direction were given in detail. A three-axle heavy truck was used to calibrate the field measurements. Chen (2006) and Guan (2006) studied the vibration-based structural health monitoring of highway bridges. Ambient vibration tests under environmental excitations and forced vibration tests by shaking table were used to extract the dynamic characteristics. Bozdağ *et al*. (2006) determined the analytical and experimental dynamic characteristics of new Galata Bridge located in Istanbul, Turkey. Soon after it was taken into service, some very serious cracks and deformations were noticed on the flaps of the bridge in 1998. So, the results of experimental stress and vibration analysis after the restoration were presented. Moreover, the natural frequencies and mode shapes were obtained by finite element method, and the results are compared with experiment measurements. El-Borgi *et al.* (2005) investigated the modal parameter identification and model updating of Boujnah Reinforced Concrete Bridge. Ambient vibration tests were conducted on the bridge using a data acquisition system with nine force-balance accelerometers. The Enhanced Frequency Domain Decomposition technique was applied to extract the dynamic characteristics. Finite element model was updated in order to obtain a reasonable correlation between experimental and analytical modal parameters. Material properties such as modulus of elasticity, elastic bearing stiffness and foundation spring stiffness were selected as updating parameters. Also, modal testing, structural condition assessment, health monitoring and damage identification of highway bridges were studied by other researchers (Wang 2008, Lu *et al*. 2008, Huang and Yang 2008, Bayraktar *et al*. 2007, Jaishi 2005, Patjawit and Kanok-Nukulchai 2005, Wang 2005, Teughels and De Roeck 2004, Zhao and DeWolf 2002, Maeck *et al*. 2001).

Fig. 1 Some views of Kömürhan Bridge

The finite element model updating of the Kömürhan Bridge using analytical and experimental results is aimed in this study. Kömürhan Highway Bridge is located on the 51st km of Elazığ-Malatya highway. Construction of the bridge started in 1983 and completed in 1986. Kömürhan Bridge has a reinforced concrete box girder structural system and constructed by balanced cantilever method. Some views of Kömürhan Bridge are given in Fig. 1.

2. Description of Kömürhan Highway Bridge

The bridge deck consists of a main span with 135 m length and two side span with 76 m length each. The total bridge length is 287 m and the width of the bridge is 11.50 m. 1340 ton building iron, 143 ton prestress steel and 11000 m^3 concrete were used in the construction of the bridge. The structural system of Kömürhan highway bridge consists of deck, columns, side support and expansion joint. Schematic representation of Kömürhan bridge including plan and evaluation is given in Fig. 2.

2.1 Bridge deck

The bridge's deck has a 287 m total span and 11.50 m width. The traffic on the bridge deck is going on two lines (one going and the other turning). Deck of the bridge was constructed with balanced cantilever and prestress box beam method.

The deck consists of 56 segments. All of the segments are nearly 5 m length. Height of the box girder is 9.35 m on the main columns, but it decreases parabolically to 3.5 m at the side supports and 3.0 m at the expansion joint. The dimensions of the box girder are given in Fig. 3.

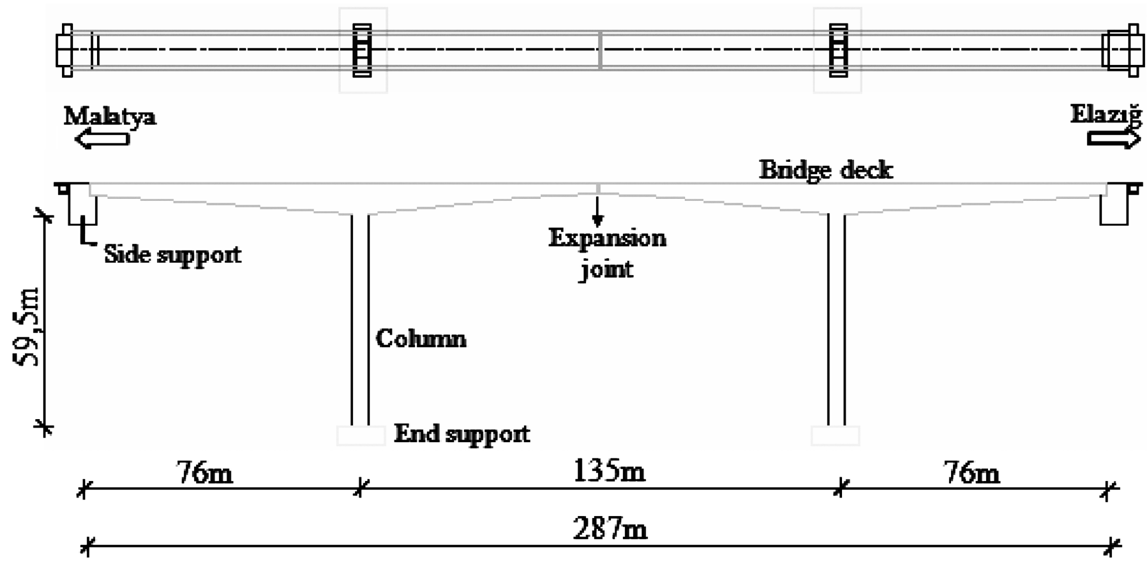


Fig. 2 Schematic representation of Kömürhan Bridge including plan and evaluation

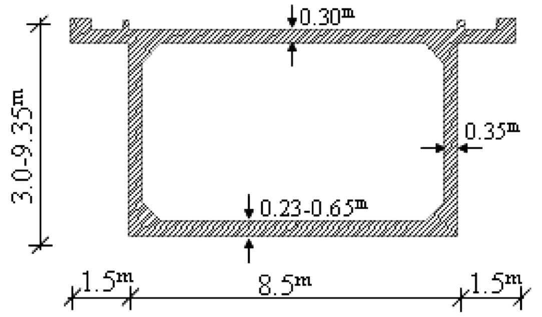


Fig. 3 Dimensions of box girder

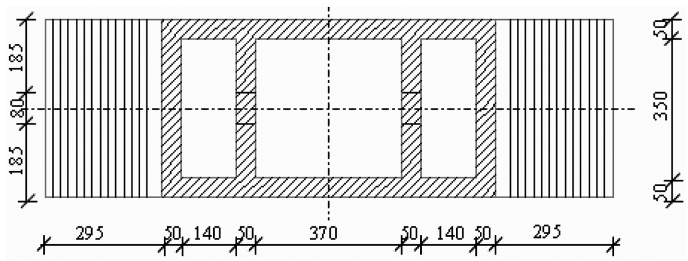


Fig. 4 The views of variable section of the main columns (dimensions in cm)

2.2 Side supports and main columns

The side supports of Kömürhan Highway Bridge are fixed by 60 unit Ø 36 anchor rods to hard rock. The length of the anchor rods in Elazığ and Malatya part are 25 m and 40 m, respectively. Also, 80 unit tensile rods are used to anchor the deck at concrete wall of side supports. Length of these rods in Elazığ and Malatya parts are 4.7 m and 3.7 m, respectively.

There are two main columns of 59.50 m height. They have variable section with three divisions. Width of the section decreases linearly from 14.40 m at the foundation to 8.50 m at the top of the column. To maintain the hydrostatic balance, transition of water at the column hulls and walls is permitted. The variable column sections are given in Fig. 4.

2.3 Expansion joint

To combine deck cantilevers, an expansion joint is constituted in the main span of the bridge. It consists of two IPB 600 steel beams. In this way, the edge of the cantilever at the main span is free, and the expansion caused heat and traffic load is allowed. Also, equivalent motion of the deck in the vertical direction is provided by developing a connection between two ends for vertical loads. Each of the beams is fixed by four pinned supports (two at top and two at bottom) in Elazığ part and two roller support (one at top and one at bottom) which has vertical load capacity in Malatya part of the bridge. Therefore, steel beam in Elazığ part is fully fixed by blocking the rotation and motion freedom. Rotations and horizontal motions are allowed in Malatya part; thereby a joint mechanism is formed. Also, transverse motion is prevented by side wedges. The view of the expansion joint can be seen in Fig. 5.

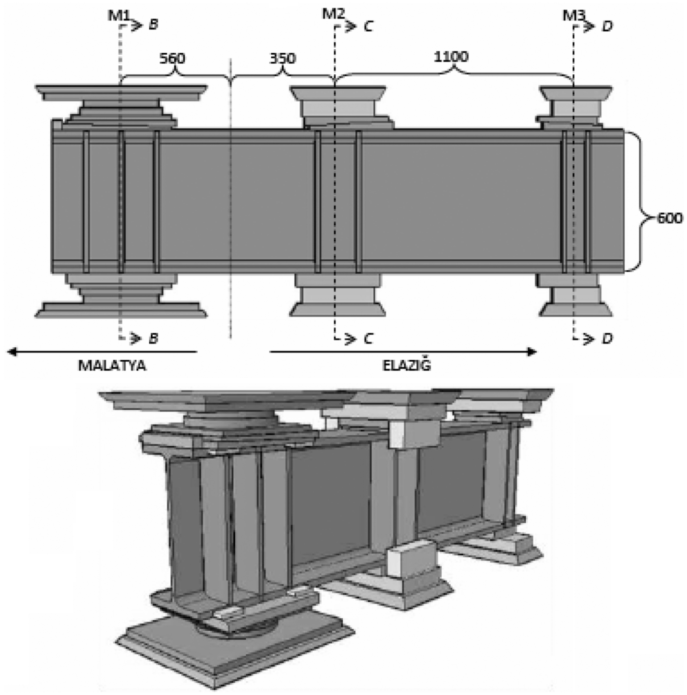


Fig. 5 Schematic view of the expansion joint mechanism (dimensions as mm)

3. Finite element modelling

Finite element model of the Kömürhan Bridge is created in SAP2000 structural analyses software (SAP2000 1998) considering design criteria given below;

· Bridge deck and columns are modelled using frame elements, and they consist of 56 and 10 segments, respectively. In the 2D finite element model, the section properties of each segment are calculated and assigned to frame elements. Also, rigid frame elements are used in the distance connections. In the 3D finite element model, nonprismatic section definition option is used to obtain variable sections directly.

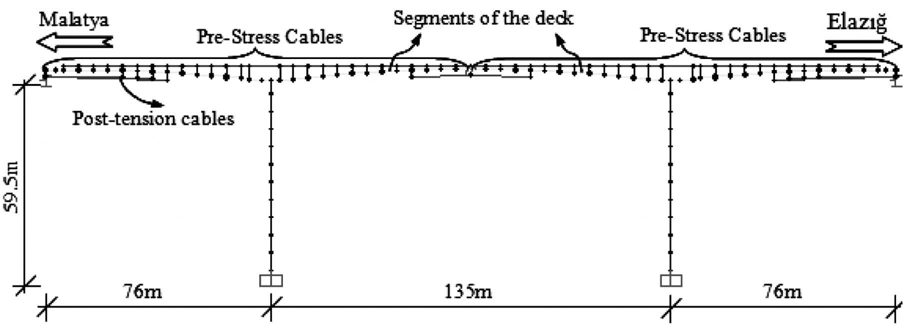
· Post-tension cables are modelled using frame elements constrained to rotation and fixed to end of the each segments. Post-tension loads are considered as strain.

· Boundary conditions of ends of the deck and columns are defined using very rigid springs and restraints.

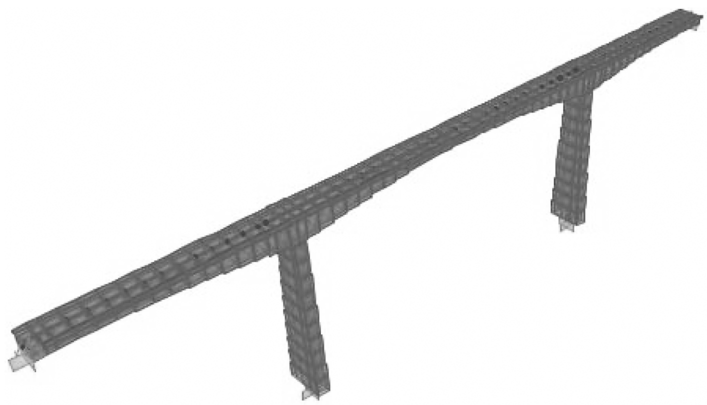
· The expansion joint in the middle of the bridge is modelled by spring element to allow movement in the longitudinal directions.

Table 1 Material properties used in the analytical model

Materials	Elasticity modulus (MPa)	Poisson ratios	Weight per unit volume (kg/m^3)
Deck	42500	0.2	2500
Columns	42500	0.2	2500
Pre-stress elements	195000	0	0
Rigid elements	1.0E9	0.3	0



(a) 2D finite element model



(b) 3D finite element model

Fig. 6 2D and 3D finite element models of the Kömürhan Bridge

Material properties used in the analyses are taken as in Table 1. The 2D and 3D finite element model of the Kömürhan Bridge considering design criteria mentioned in the above are given in Fig. 6. The first ten mode shapes obtained from the analytical analyses of the Kömürhan Bridge is given in Fig. 7.

In the 2D and 3D modal analyses of the bridge, some kinds of load cases are considered;

· **Dead Load:** Weight of all elements. They are calculated from the finite element software directly.

·**Additional Mass:** Weight of the asphalt, cobble, pipeline and its supports, scarecrow. 35 kN/m distributed load is added to each segment considering 8-10 cm asphalt.

4. Ambient vibration test

The responses of the Kömürhan Bridge are measured by using B&K 4506 type tri-axial and B&K 4507 type uni-axial accelerometers. The signals are acquired by 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, OMA (OMA 2006), is used.

During the test in February 2008, normal traffic over the bridge was used as a source of ambient vibration. Six ambient vibration modal tests were carried out during the period between on February 25th and February 27th, 2008. The first five setups are performed in the box girder, and the other is done

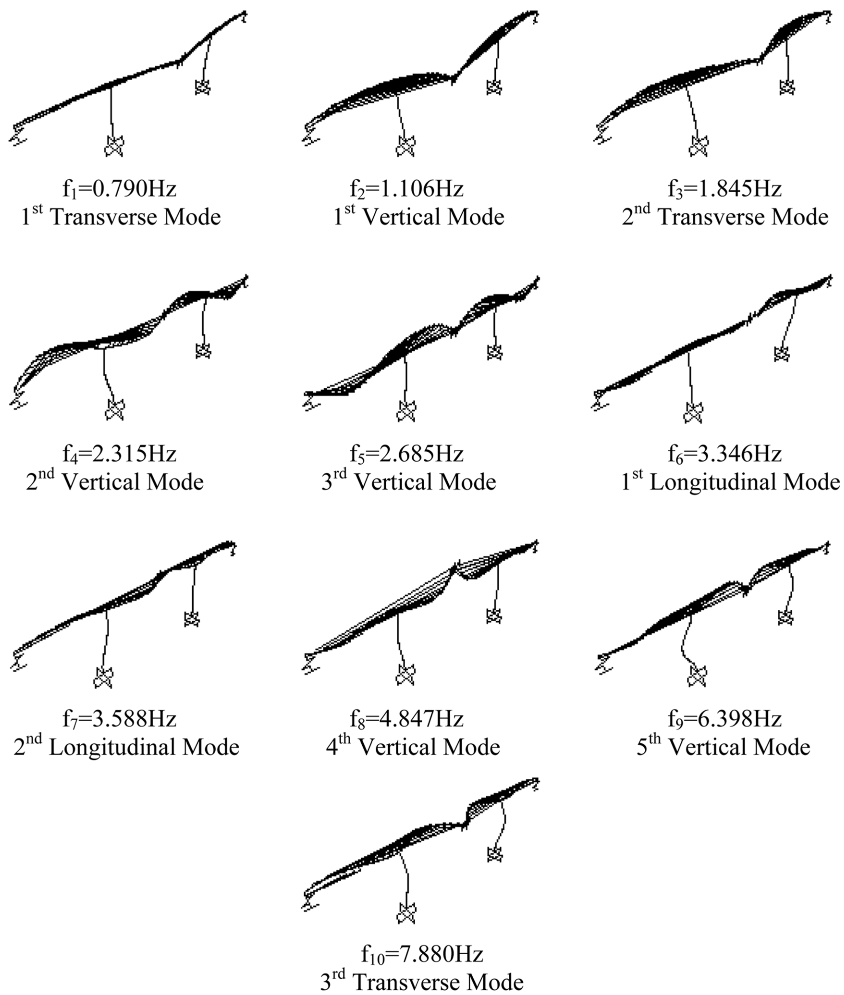


Fig. 7 Analytically identified the first ten mode shapes

on the bridge deck. Due to the limited availability of sensors and data acquisition equipment, only 9 sensor locations for each test setup could be used to monitor the bridge responses simultaneously. For each setup, 4 tri-axial accelerometers in vertical, lateral and longitudinal directions and one uni-axial accelerometer in vertical direction were used. Among these accelerometers, uni-axial was used as reference accelerometer, and its location unchanged throughout the test. The rest of the 4 accelerometers were used as roving accelerometers and were moved in order to cover all sensor locations. Reason of selected measurement points are explained in below;

- **First Test Setup:** When the expansion joint mechanism in the middle of the bridge is considered, Kömürhan Bridge can divide into two symmetrical parts as Elazığ and Malatya. So, it is thought that dynamic characteristics of these parts should be determined and compare with each other. Therefore, Elazığ part of the bridge is measured from the box girder along the one way.
- **Second Test Setup:** In the second test setup, Malatya part of the bridge is measured from the box girder along the one way. Accelerometers are placed at the symmetry point of first setup to compare

the dynamic characteristics of Elazığ and Malatya parts with each other.

- **Third Test Setup:** Elazığ and Malatya parts of the bridge are measured in the first two measurements. Transverse effects are not determined because of the fact that the first and second measurements are conducted along the one way. So, the third measurement is performed on reciprocal points in the box girder of Elazığ part.
- **Fourth Test Setup:** In the fourth test setup, Malatya part of the bridge is measured on reciprocal points in the box girder to obtain transverse effects more influentially. Accelerometers are placed at the symmetry point of third setup to compare the dynamic characteristics of Elazığ and Malatya parts.
- **Fifth Test Setup:** Elazığ and Malatya parts of the bridge are measured by different configurations in the first four measurements. In the fifth measurement, the bridge is measured from one end to the each other end in the box girder.
- **Sixth Test Setup:** First fifth test setup is carried out in the box girder of the bridge. The sixth test setup is performed on the deck, and only main span between two columns is measured along the one way.

Measurement locations on the 2D schematic view of the bridge are given in Fig. 8. It can be seen from Fig. 8 that the first five measurements are performed in the box girder and the sixth measurement is conducted on the bridge deck. Table 2 summarizes details of six group of measurement together with accelerometer locations.

Singular values of spectral density matrices of all test setups attained from vibration signals using PP method and mode shapes are shown in Figs. 9 and 10, respectively.

The dynamic characteristics of the Kömürhan Bridge obtained from analytical modal analysis and experimental measurements are given in Table 3.

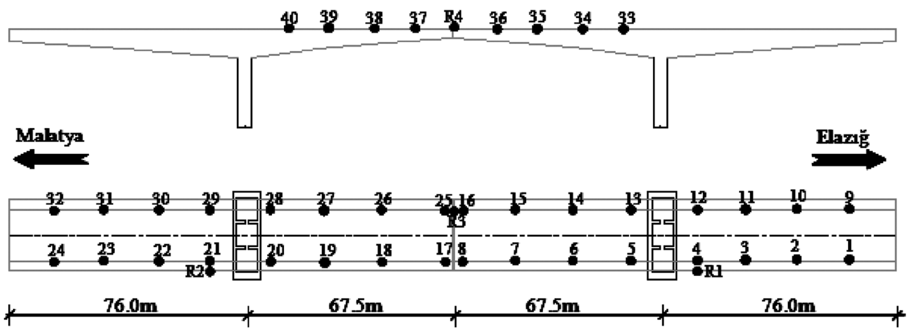
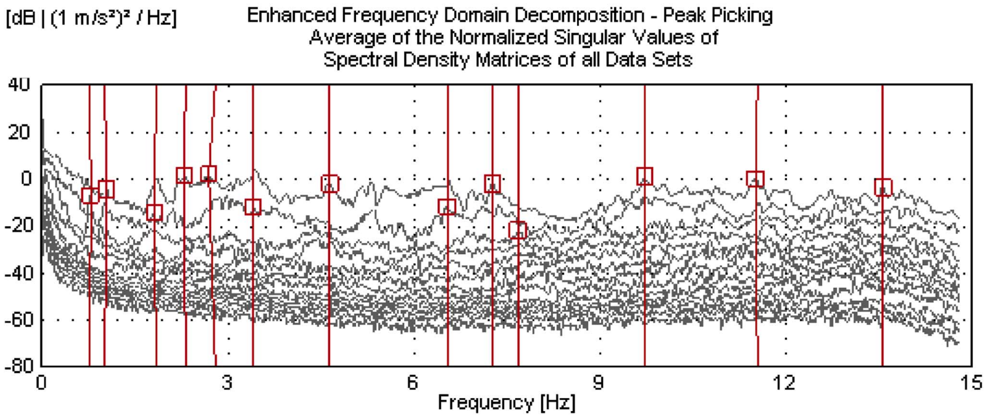


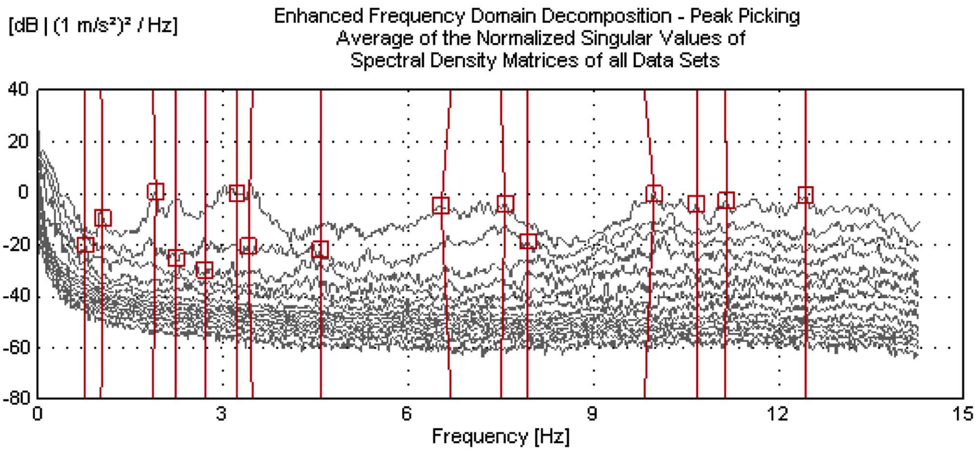
Fig. 8 Measurement locations in 2D schematic view

Table 2 Measurement test setup and accelerometer locations

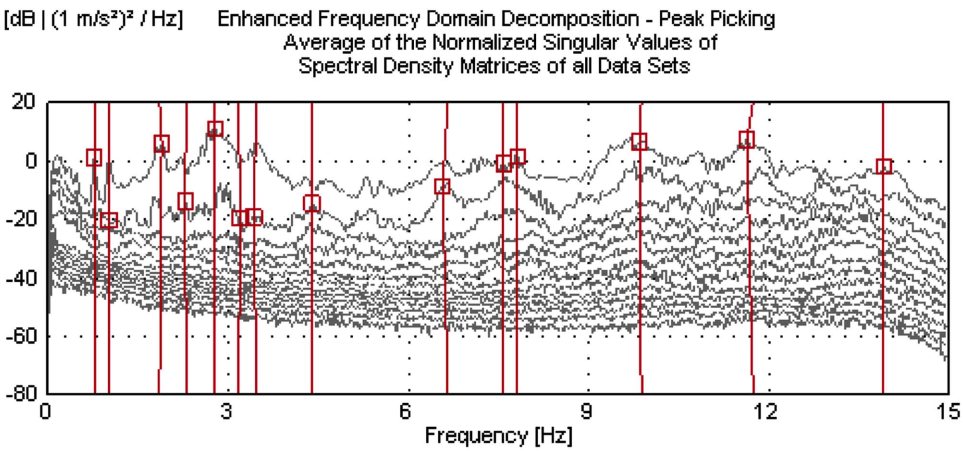
Test setup	Accelerometer		Measurement steps	References point
	Region	Points		
1st	In the box girder	1,2,3,4 and 5,6,7,8	Two Step	R1
2nd	In the box girder	17,18,19,20 and 21,22,23,24	Two Step	R2
3rd	In the box girder	1,3,9,11 and 5,7,13,15	Two Step	R1
4th	In the box girder	18,20,26,28 and 22,24,30,32	Two Step	R2
5th	In the box girder	3,4,11,12 and 6,7,14,15 18,18,26,27 and 21,22,29,30	Four Step	R3
6th	On the bridge deck	33,34,35,36 and 37,38,39,40	Two Step	R4



(a) Singular values of first test setup

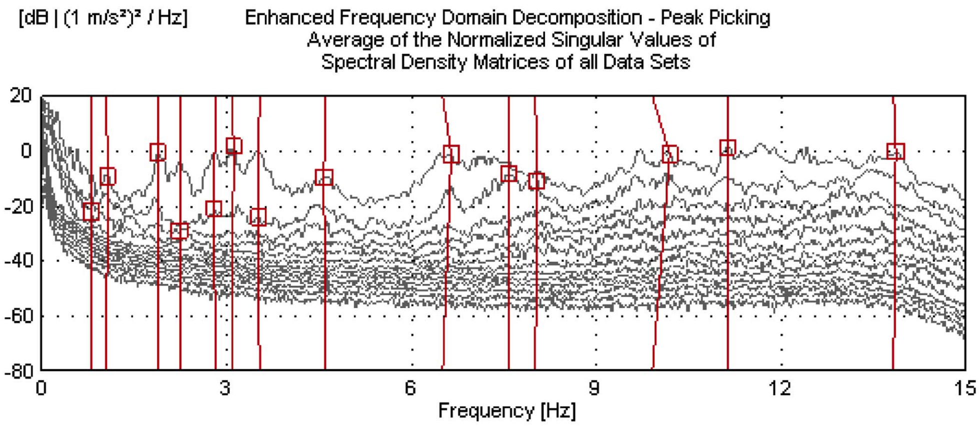


(b) Singular values of second test setup

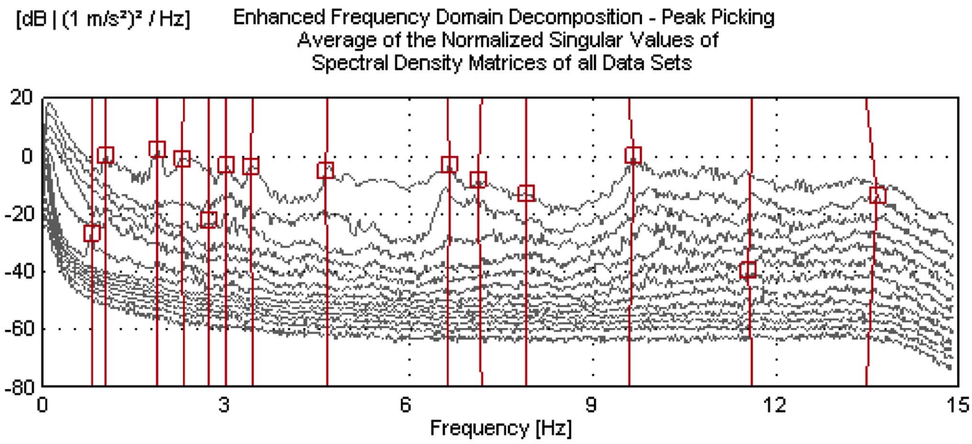


(c) Singular values of third test setup

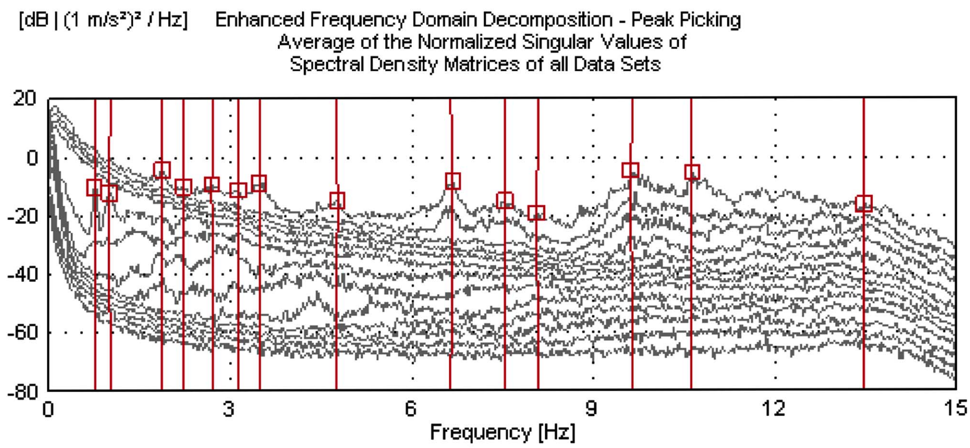
Fig. 9 Modal parameters attained from all test setup using PP method



(d) Singular values of fourth test setup

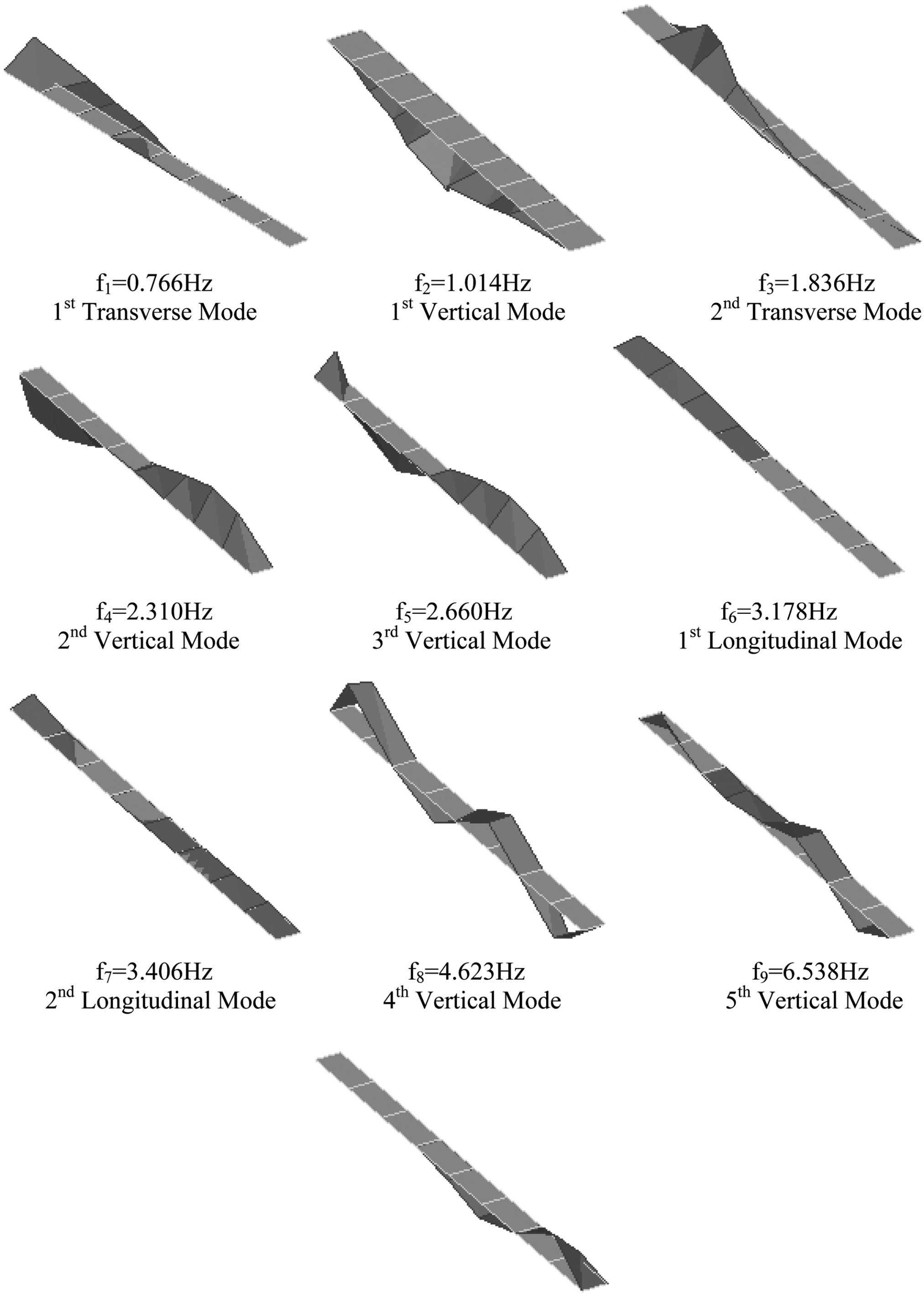


(e) Singular values of fifth test setup



(f) Singular values of sixth test setup

Fig. 9 continued



f_1=0.766Hz
1st Transverse Mode

f_2=1.014Hz
1st Vertical Mode

f_3=1.836Hz
2nd Transverse Mode

f_4=2.310Hz
2nd Vertical Mode

f_5=2.660Hz
3rd Vertical Mode

f_6=3.178Hz
1st Longitudinal Mode

f_7=3.406Hz
2nd Longitudinal Mode

f_8=4.623Hz
4th Vertical Mode

f_9=6.538Hz
5th Vertical Mode

f_{10}=7.272Hz
3rd Transverse Mode

Fig. 10 Experimentally identified first ten mode shapes

5. Finite element model updating

When the experimentally and analytically identified dynamic characteristics are compared with each other, some differences are found between both results. So, it is thought that finite element model of the bridge should be updated by changing uncertain modelling parameters such as material properties or boundary conditions in order to eliminate differences as much as possible. This process is customarily termed as model updating. The updating process typically consists of manual tuning and then automatic model updating using some specialised software. The manual tuning involves manual changes of the model geometry and modelling parameters by trial and error, guided by engineering judgement. The aim of this is to bring the numerical model closer to the experimental one. In this study, the manual tuning procedure is used for finite element model updating.

When the analytically and experimentally identified dynamic characteristics of the Kömürhan Highway Bridge are compared with each other, there is a good harmony between the mode shapes but some differences between natural frequencies. It can be seen from Table 3 that analytical frequencies are bigger than those of experimental. It is thought that these differences resulted from some uncertainties in the structural geometry, material properties and boundary conditions considered in the design phase of the bridge. So, the finite element model of the Kömürhan Highway Bridge must be updated using uncertain parameters to obtain current behaviour.

5.1 Updating of the material properties

To determine the material properties of the concrete using experimental methods, several samples were taken from the box girder and Schmidt hammer tests were performed. Samples were taken from the eight different segments at the bottom of the box girder (Fig. 11). Dimension of the samples are 15*30 cm. These samples were tested in different laboratories. Average strength of the samples was determined as 29 MPa and elasticity modulus is calculated as 32000 MPa for bridge deck concrete.

To determine the concrete strength using Schmidt hammer, the same segments and upper part of the bridge columns were measured. Average strength of the samples was determined as 30 MPa and

Table 3 Comparison of analytically and experimentally identified dynamic characteristics

Frequency number	Analytical frequencies (Hz)	Experimental frequencies (Hz)						Experimental damping ratios (%)
		Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	
1	0.790	0.766	0.766	0.766	0.797	0.788	0.764	1.961
2	1.106	1.014	1.020	1.016	1.049	1.027	1.010	3.211
3	1.845	1.836	1.861	1.851	1.894	1.850	1.862	2.170
4	2.315	2.310	2.230	2.290	2.234	2.291	2.219	1.329
5	2.685	2.660	2.714	2.773	2.807	2.703	2.710	2.141
6	3.346	3.178	3.211	3.162	3.090	3.001	3.118	1.937
7	3.588	3.406	3.467	3.465	3.528	3.440	3.491	1.750
8	4.847	4.623	4.575	4.595	4.586	4.665	4.754	1.826
9	6.398	6.538	6.690	6.651	6.421	6.612	6.636	1.236
10	7.880	7.272	7.494	7.571	7.587	7.176	7.528	0.962

Fig. 11 Taking of samples on the bottom of the bridge deck

Fig. 12 Some views of the measurements using Schmidt hammer

elasticity modulus was calculated as 32000 MPa for bridge deck. Also, average strength of the samples is determined as 34 MPa and elasticity modulus is calculated as 37500 MPa for bridge column. Some views from the measurements are given in Fig. 12. Results of the measurements are given in Tables 4 and 5.

Table 4 Measurement values obtained from Elazığ part of the bridge

Measurement	Rebound Value							
	Segment 0		Segment 12		Segment 22		Segment 27	
	Side	Side	Bottom	Side	Bottom	Side	Bottom	Side
1	54.0	58.0	36.0	54.0	40.0	46.0	43.0	44.0
2	56.0	58.0	38.0	56.0	43.0	46.0	43.0	44.0
3	58.0	58.0	40.0	56.0	43.0	47.0	43.0	45.0
4	58.0	58.0	40.0	56.0	43.0	50.0	43.0	46.0
5	59.0	58.0	40.0	56.0	44.0	50.0	44.0	46.0
6	60.0	58.0	42.0	56.0	44.0	50.0	44.0	46.0
7	60.0	58.0	44.0	58.0	45.0	51.0	46.0	46.0
8	60.0	58.0	44.0	58.0	48.0	52.0	46.0	46.0
9	60.0	60.0	48.0	60.0	50.0	52.0	47.0	48.0
10	60.0	60.0	48.0	60.0	52.0	54.0	50.0	48.0

Table 5 Measurement values obtained from Malatya part of the bridge

Measurement	Rebound Value							
	Segment 0		Segment 12		Segment 22		Segment 27	
	Side	Side	Bottom	Side	Bottom	Side	Bottom	Side
1	54.0	58.0	36.0	54.0	40.0	46.0	43.0	44.0
2	56.0	58.0	38.0	56.0	43.0	46.0	43.0	44.0
3	58.0	58.0	40.0	56.0	43.0	47.0	43.0	45.0
4	58.0	58.0	40.0	56.0	43.0	50.0	43.0	46.0
5	59.0	58.0	40.0	56.0	44.0	50.0	44.0	46.0
6	60.0	58.0	42.0	56.0	44.0	50.0	44.0	46.0
7	60.0	58.0	44.0	58.0	45.0	51.0	46.0	46.0
8	60.0	58.0	44.0	58.0	48.0	52.0	46.0	46.0
9	60.0	60.0	48.0	60.0	50.0	52.0	47.0	48.0
10	60.0	60.0	48.0	60.0	52.0	54.0	50.0	48.0

According to the samples and average ratio of steel, weight per unit volume of the bridge column and deck are determined as 2400 kg/m^3 and 2300 kg/m^3, respectively.

5.2 Updating of the boundary conditions

In the initial finite element model of Kömürhan Highway Bridge, boundary conditions of Elazığ and Malatya abutments are modelled using linear elastic link elements. Properties of the link elements are calculated and added the finite element program. However, it is thought that these abutments must be characterized by multi linear elastic link elements which display different response in the tensile and compressive loading. So, in the finite element model updating, multi linear elastic link elements are used. In the initial finite element model, the expansion joint in the middle of the bridge is modeled by spring element to allow movement in the longitudinal directions. The base of the bridge column is fixed. These boundary conditions are not changed in the model updating.

5.3 Updating of the other structural properties

Besides boundary conditions, some additional modifications are made to obtain the updated finite element model of Kömürhan Highway Bridge as below;

· The diagonal rigid elements along the height of the box girder on the main columns are used in the finite element model. Properties of these elements such as areas, rigidities, inertia moments and masses are calculated and added to both side of the "Segment 0" for the main columns.

· Weight of the reinforced concrete walls at the abutments and both side of expansion joint are calculated as 1117 kN and 150 kN, respectively, and added to the relevance points in the finite element model.

Comparison of the analytical and experimental dynamic characteristics of Kömürhan Highway Bridge after finite element model updating is given in Table 6. According to Table 6, there is a good harmony between natural frequencies after model updating. Also, good agreement is found between analytically and experimentally identified mode shapes.

Table 6 Analytical and experimental dynamic characteristics after model updating

Analytical frequencies (Hz)	Updated analytical frequencies (Hz)	Experimental frequencies (Hz)					
		Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6
0.790	0.760	0.766	0.766	0.766	0.797	0.788	0.764
1.106	1.032	1.014	1.020	1.016	1.049	1.027	1.010
1.845	1.815	1.836	1.861	1.851	1.894	1.850	1.862
2.315	2.214	2.230	2.230	2.290	2.234	2.291	2.219
2.685	2.551	2.660	2.714	2.773	2.807	2.703	2.710
3.346	3.238	3.178	3.211	3.162	3.090	3.001	3.118
3.588	3.439	3.406	3.467	3.465	3.528	3.440	3.491
4.847	4.480	4.623	4.575	4.595	4.586	4.665	4.754
6.398	6.370	6.538	6.690	6.651	6.421	6.612	6.636
7.880	7.392	7.272	7.494	7.571	7.587	7.176	7.528

6. Conclusions

In this paper, it is aimed to compare the analytically and experimentally identified dynamic characteristics and to obtain updated finite element model of the Kömürhan Highway Bridge located on the Elazığ-Malatya highway. The analytical finite element model is constituted by using SAP2000 software. The experimental measurements are carried out by Operational Modal Analysis under traffic loads. Comparing the results of the study, following observations can be made:

· The first ten natural frequencies range between 0-8 Hz. The first ten mode shapes can be classified into vertical, transverse and longitudinal modes.

· There is a good agreement between the results of the four test setup.

· When the comparing of finite element and experimental results, it is seen that there is a good harmony between mode shapes, but little differences between natural frequencies. The differences are eliminated by updating material properties, boundary conditions and other structural properties.

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