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Analytical and experimental modal analyses of a highway bridge model

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Abstract. In this study, analytical and experimental modal analyses of a scaled bridge model are carried out to extract the dynamic characteristics such as natural frequency, mode shapes and damping ratios. For this purpose, a scaled bridge model is constructed in laboratory conditions. Three dimensional finite element model of the bridge is constituted and dynamic characteristics are determined, analytically. To identify the dynamic characteristics experimentally; Experimental Modal Analyses (ambient and forced vibration tests) are conducted to the bridge model. In the ambient vibration tests, natural excitations are provided and the response of the bridge model is measured. Sensitivity accelerometers are placed to collect signals from the measurements. The signals collected from the tests are processed by Operational Modal Analysis; and the dynamic characteristics of the bridge model are estimated using Enhanced Frequency Domain Decomposition and Stochastic Subspace Identification methods. In the forced vibration tests, excitation of the bridge model is induced by an impact hammer and the frequency response functions are obtained. From the finite element analyses, a total of 8 natural frequencies are attained between 28.33 and 313.5 Hz. Considering the first eight mode shapes, these modes can be classified into longitudinal, transverse and vertical modes. It is seen that the dynamic characteristics obtained from the ambient and forced vibration tests are close to each other. It can be stated that the both of Enhanced Frequency Domain Decomposition and Stochastic Subspace Identification methods are very useful to identify the dynamic characteristics of the bridge model. The first eight natural frequencies are obtained from experimental measurements between 25.00-299.5 Hz. In addition, the dynamic characteristics obtained from the finite element analyses have a good correlation with experimental frequencies and mode shapes. The MAC values obtained between 90-100% and 80-100% using experimental results and experimental-analytical results, respectively.

Keywords: ambient vibration; bridge model; dynamic characteristic; enhanced frequency domain decomposition; finite element model; operational modal analysis; stochastic subspace identification

1. Introduction

Structural modeling is an integral part of the design process and it offers a mechanism to study the behavior of a structure in an environment that cannot be tested very easily. In cases of practical

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and complex structures, modeling is often carried out using the finite element method. The accuracy of the model depends on a number of factors including the element type and size, geometry information, material properties, and boundary conditions. There are some uncertainties associated with many of these factors, and the structural model often differs from the actual structure. Thus, it is imperative that the finite element analyses results should be correlated with the actual structure using experimental tests (Bagchi 2005).

There are basically two different methods available to experimentally identify the dynamic characteristics of a structure: Ambient Vibration Testing and Forced Vibration Testing (Cantieni 2005). In Ambient Vibration Testing, the structure is excited by unknown input forces (natural vibrations such as wind, traffic and earthquake effects) and responses of the structure are measured. In Forced Vibration Testing, the structure is excited by known input forces (such as impulse hammer, and electrodynamics shaker) and responses of the structure are measured. Some heavy forced excitations become very expensive and sometimes may cause the possible damage to the structure. However, ambient excitations such as traffic, wave and wind effects are environmental and natural (Roeck 2000).

Last two decade, some researchers have investigated to structural behavior of bridges using Experimental Modal Analyses method. In these studies it is highlighted that the physical conditions are hard and test become too expensive (Bayraktar *et al*. 2007, Reynders and Roeck 2008, Bayraktar *et al*. 2009, Liu *et al*. 2009, Whelan *et al*. 2009, Altunışık 2010, Altunışık *et al*. 2010, Bayraktar *et al*. 2010a, Bayraktar *et al*. 2010b, Altunışık *et al*. 2011a, Altunışık *et al*. 2011b). Therefore, such kind of conditions made the researchers to construct laboratory bridge models to investigate the structural behavior, experimentally (Zapico *et al*. 2003, Ren *et al*. 2008, Dönmez and Karakan 2009, Sanayei and DiCarlo 2009).

In this study, dynamic characteristics of a scaled reinforced concrete box girder bridge are determined by finite element analysis and Experimental Modal Analyses (ambient and forced vibration tests) using Enhanced Frequency Domain Decomposition (EFDD) and Stochastic Subspace Identification (SSI) methods. For this purpose, a bridge model with length of 6 m constructed in the laboratory conditions, and experimental measurement tests are performed for different configurations.

2. Formulation

2.1 Formulation of ambient vibration testing

Ambient excitation does not lend itself to Frequency Response Function (FRFs) or Impulse Response Function (IRFs) calculations because the input force is not measured in an ambient vibration test. Therefore, a modal identification procedure is needed to base itself on output-only data (Ren *et al*. 2004). There are several modal parameter identification methods available. In this study, Enhanced Frequency Domain Decomposition (EFDD) and Stochastic Subspace Identification (SSI) methods were used to extract dynamic characteristics of the model bridge.

2.1.1 Enhanced frequency domain decomposition (EFDD) method

Enhanced Frequency Domain Decomposition method is an extension to Frequency Domain Decomposition (FDD) method, which is a basic method that is extremely easy to use. In the method, modes are simply picked locating the peaks in Singular Value Decomposition plots (SVD) 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 (FFT), the accuracy of the estimated natural frequency depends on the FFT resolution and no modal damping is calculated. However, EFDD method gives an improved estimation of both the natural frequencies, the mode shapes and includes the damping ratios (Jacobsen *et al.* 2006).

In EFDD method, the single degree of freedom (SDOF) Power Spectral Density (PSD) function, identified around a peak of resonance, is taken back to the time domain using the Inverse Discrete Fourier Transform (IDFT). The natural frequency is obtained by determining the number of zero-crossing as a function of time, and the damping by the logarithmic decrement of the corresponding SDOF normalized auto correlation function (Jacobsen *et al.* 2006). In EFDD method, the relationship between the unknown input and the measured responses can be expressed as (Brincker *et al.* 2000, Bendat and Piersol 2004)

$$\left[G_{\mathbf{yy}}(j\omega)\right]=\left[H(j\omega)\right]^{*}\left[G_{\mathbf{xx}}(j\omega)\right]\left[H(j\omega)\right]^{T} \tag{1}$$

where $G_{\mathbf{xx}(jw)}$ is the rxr Power Spectral Density (PSD) matrix of the input, r is the number of inputs, $G_{\mathbf{yy}(jw)}$ is the mxm PSD matrix of the responses, m is the number of responses, $H(jw)$ is the mxr Frequency Response Function (FRF) matrix, and * and superscript T denote complex conjugate and transpose, respectively.

2.1.2 Stochastic subspace identification (SSI) method

Stochastic Subspace Identification (SSI) is an output-only time domain method that directly works with time data, without the need to convert them to correlations or spectra. The method is especially suitable for operational modal parameter identification, but it is an incredibly difficult procedure to explain in detail in a short way for civil engineers (Juang 1994, Van Overschee and DeMoor 1996, Peeters 2000). The model of vibration structures can be defined by a set of linear, constant coefficient and second order differential equations as given below (Peeters and DeRoeck 1999)

$$M\ddot{U}(t)+C_{*}\dot{U}(t)+KU(t)=F(t)=B_{*}u(t) \tag{2}$$

where M, C_*, K are the mass, damping and stiffness matrices, $F(t)$ is the excitation force, and $U(t)$ is the displacement vector at continuous time t. The force vector $F(t)$ is factorized into a matrix B_* describing the inputs in space and a vector $U(t)$. Although Eq. (2) represents quite closely the true behavior of a vibrating structure, it is not directly used in SSI methods. So, the equation of dynamic equilibrium (2) will be converted to a more suitable form: the discrete-time stochastic state-space model (Ewins 1984, Peeters and DeRoeck 1999, Yu and Ren 2005).

2.2 Formulation of forced vibration testing

In the Forced Vibration Testing (FVT), the structure is artificially excited with a forcing function in a point i and its response $Y_k(t)$ to this excitation is measured together with the forcing signal $X_i(t)$. Transformation of these time signals into the frequency domain and calculation of all Frequency Response Functions (FRF) H_{ik} between the response and the forcing function time signals yields the FRF matrix, also referred to as Transfer Matrix, $H(iw)$ (Schwarz and Richardson 1999, Cantieni 2004). The relationship between the input and the measured responses can be expressed as

$$H_{ik}(iw) = \frac{X_i(w)}{Y_k(w)} \tag{3}$$

3. Description of the scaled bridge model

The model bridge constructed in the laboratory condition is reinforced concrete box girder structures. The bridge deck consists of a main span of 3 m and two side span of 1.5 m each. The structural system of the model bridge consists of deck, piers and foundation. The total length of bridge deck is 6 m and width of bridge deck is 60 cm. There are two piers, each have 80 cm height and 20 × 40 cm^2 cross section areas. Piers are footing on the raft foundation to ensure the fixed boundary condition. Each raft foundation has the dimension of 1 × 1 m^2 and 30 cm depth. Basic configuration of the model bridge is shown in Fig. 1.

The superstructure of the bridge model is a continuous single cell box girder. The bridge's deck has a 6 m total span and 60 cm total width. The cross-section of the deck is constant along to the bridge length as 30 cm. The thickness of the top slab, bottom slab and web

The laboratory bridge model was constructed considering dimensions given in Figs. 1 and 2. In the construction of the model bridge, 1.5 m^3 concrete was used approximately. Model was constructed working fifteen days by four workers. Quantity of concrete components used in the model bridge is given in Table 1. Pictures from some construction stages and after construction of the model bridge are shown in Figs. 3 and 4.

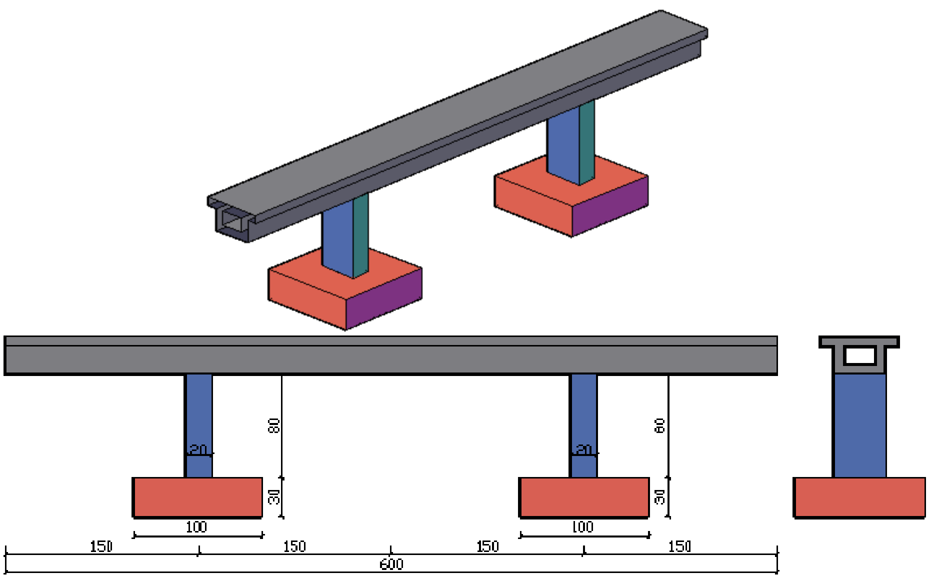


Fig. 1 Basic configuration of bridge model (all dimensions are in cm)

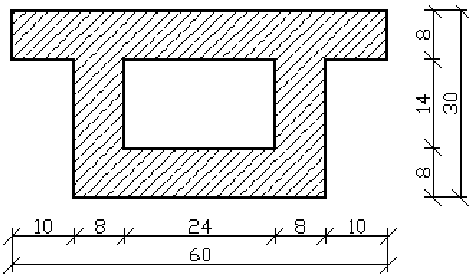


Fig. 2 Dimensions of box girder cross section (all dimensions are in cm)


Fig. 3 Pictures from some construction stages of the bridge model


Fig. 4 Some pictures of the bridge model after construction

Table 1 Quantity of concrete components used in the construction of the bridge model

Component	Foundation	Pier	Deck	
			Bottom slab web member	Top slab
Aggregate (8-16 mm)	558 kg/m^3	558 kg/m^3	558 kg/m^3	508 kg/m^3
Aggregate (4-8 mm)	465 kg/m^3	465 kg/m^3	465 kg/m^3	435 kg/m^3
Aggregate (0-4 mm)	837 kg/m^3	837 kg/m^3	837 kg/m^3	917 kg/m^3
Cement (C)	350 kg/m^3	350 kg/m^3	350 kg/m^3	350 kg/m^3
Water (W)	150 kg/m^3	150 kg/m^3	150 kg/m^3	150 kg/m^3
W/C	0.43	0.43	0.43	0.43
Admixture	3 kg/m^3	3 kg/m^3	3 kg/m^3	3 kg/m^3
Total	1417.80 kg	302.46	771.28	680.55

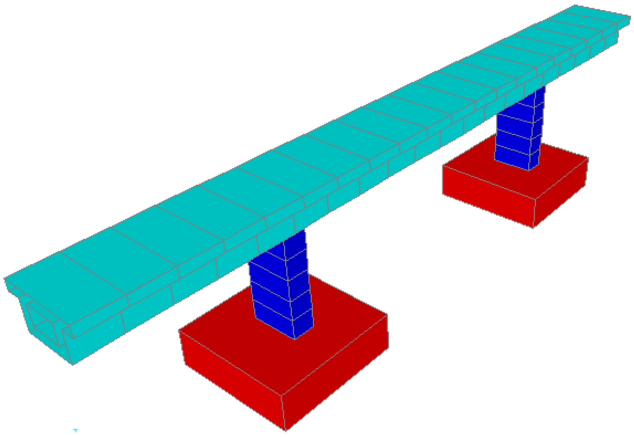


Fig. 5 Three dimensional finite element model of the bridge model

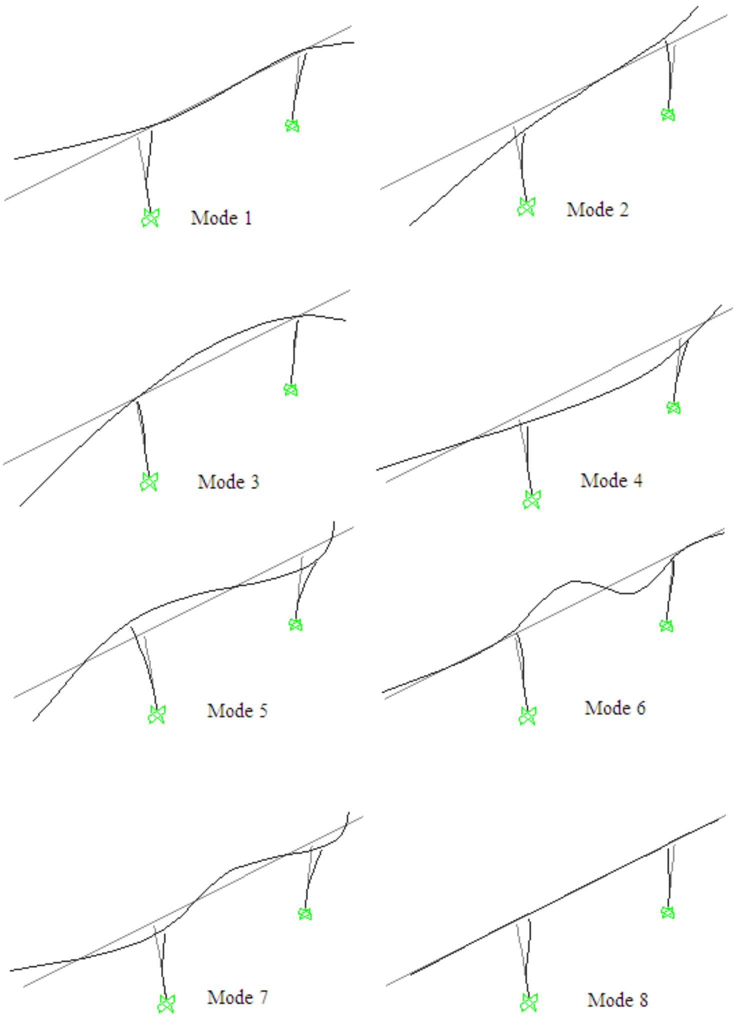


Fig. 6 Analytically identified mode shapes of the bridge model

Table 2 Material properties used in analyses of the bridge model

Finite element model	Material properties		
	Modulus of elasticity (N/m^2)	Poisson's ratio (-)	Mass per unit Vol. (kg/m^3)
Deck	2.85E10	0.2	2500
Column	3.00E10	0.2	2500
Foundation	3.00E10	0.2	2500

Table 3 First eight natural frequencies obtained from the finite element analyses

Mode	Frequency (Hz)	Period (s)	Mode shape
1	28.33	0.0353	1st Longitudinal
2	33.82	0.0296	1st Asym. Transverse
3	41.39	0.0242	1st Vertical
4	56.05	0.0178	1st Transverse
5	123.9	0.0081	2nd Vertical
6	232.7	0.0043	2nd Transverse
7	265.8	0.0038	3rd Transverse
8	313.5	0.0032	2nd Longitudinal

4. Finite element analyses

Three dimensional finite element model (Fig. 5) of the bridge model is constructed using the SAP2000 software (1998). The bridge model is modelled as a space frame structure with 3D prismatic beam elements which have two end nodes and each end node has six degrees of freedom: three translations along the global axes and three rotations about its axes. The key modelling assumptions are as follows: bridge deck and columns consist of 20 and 8 segments, respectively. In the three dimensional finite element model, nonprismatic section definition option is used to obtain cross sections more accurately; boundary conditions of ends of the bridge columns are defined as fixed. At the side spans, any boundary condition is defined to allow the movements in all directions. The values of the material properties used in analyses of the bridge model are given in Table 2.

Natural frequencies and corresponding vibration modes are important dynamic properties and have significant effect on the dynamic performance of structures. A total of 8 natural frequencies of the bridge model are attained which range between 28.33 and 313.5 Hz (Table 3). The eight vibration modes of the bridge model are shown in Fig. 6.

5. Experimental modal analyses

5.1 Ambient vibration tests

Ambient vibration tests were conducted to the bridge model to determine its natural frequencies, mode shapes and damping ratios. In the ambient vibration tests, B & K 3560 data acquisition system, B & K 4507 type uni-axial and B&K 4506 type three-axial accelerometers were used. 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 Operational Modal Analysis

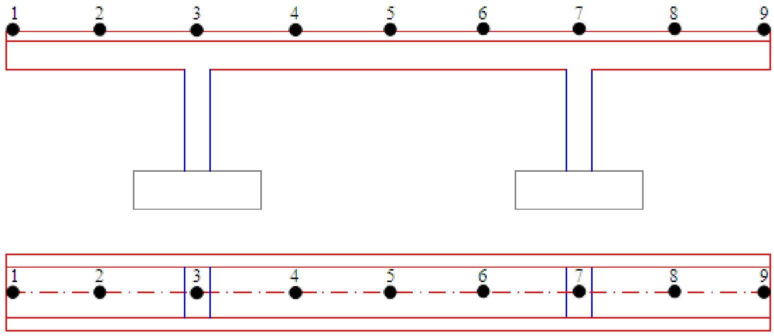
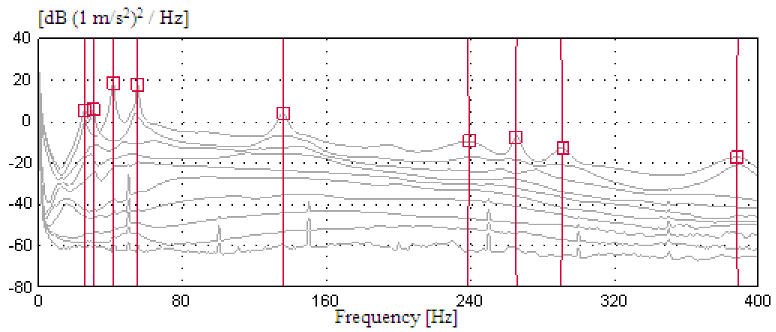
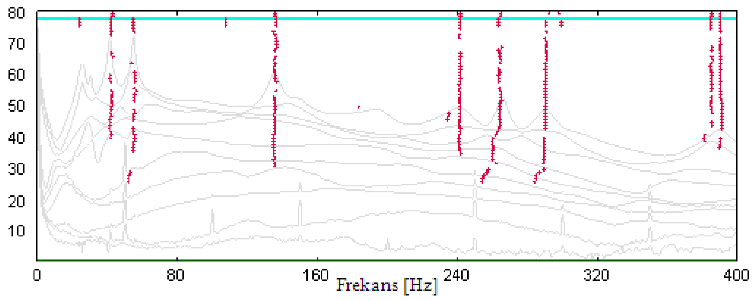


Fig. 7 Accelerometers locations on the 2D schematic view of the bridge model

Fig. 8 Some pictures from the measurements



(a) SVSDM of data set



(b) Stabilization diagram

Fig. 9 SVSDM of data set and stabilization diagram of estimated state space models attained from the fifth test

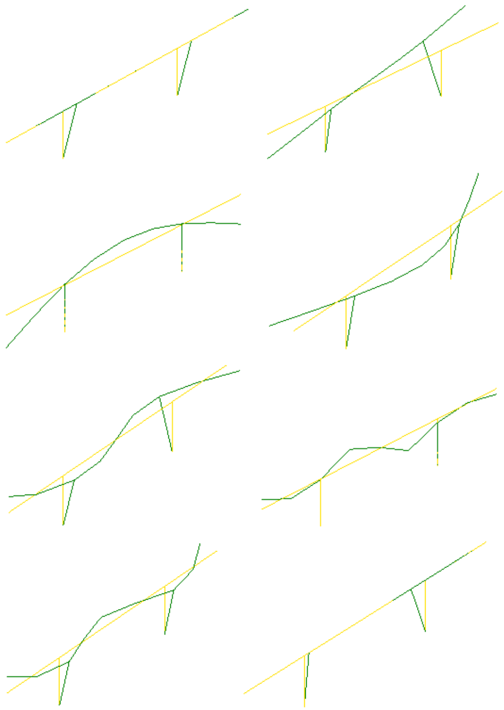


Fig. 10 Experimentally identified the first eight mode shapes using EFDD and SSI method

Table 4 Measurement tests setups and accelerometers locations

Tests	Accelerometers: Points	Direction: Vertical	Direction: Longitudinal	Direction: Transverse	Frequency span	Total duration	Step
1	1-9	✓	-	-	0-400Hz	5 min	1
2	1-9	-	-	✓	0-400Hz	5 min	1
3	1-9	-	✓	-	0-400Hz	5 min	1
4	1-9	-	✓	-	0-400Hz	15 min	3
	1-9	-	-	✓			
	1-9	✓	-	-			
5	1-3	✓	✓	✓	0-400Hz	15 min	3
	4-6	✓	✓	✓			
	7-9	✓	✓	✓			
6	4-6	✓	✓	✓	0-400Hz	5 min	1

Table 5 Natural frequencies and damping ratios attained from the experimental measurements of the bridge model using EFDD method

Modes	Ambient vibration tests-EFDD method											
	First test		Second test		Third test		Fourth test		Fifth test		Sixth test	
	Frequency (Hz)	DampingRatio (%)	Frequency (Hz)	DampingRatio (%)	Frequency (Hz)	DampingRatio (%)	Frequency (Hz)	DampingRatio (%)	Frequency (Hz)	DampingRatio (%)	Frequency (Hz)	DampingRatio (%)
1	25.32	2.488	25.84	4.008	27.30	4.263	25.79	4.659	25.34	2.363	25.36	2.295
2	31.51	1.402	31.13	2.987	32.45	2.532	30.50	3.720	30.17	3.514	30.44	2.392
3	41.47	1.472	41.90	0.941	42.25	1.368	41.50	1.159	41.40	1.406	41.46	1.392
4	52.18	5.631	54.91	1.004	51.37	1.265	54.34	1.695	55.01	1.043	55.09	0.963
5	139.0	2.315	135.4	2.184	133.9	2.302	138.0	0.239	135.5	1.996	135.8	1.721
6	235.0	5.715	241.7	2.423	240.0	2.693	240.5	2.620	238.1	3.232	236.2	1.855
7	264.8	0.492	265.1	0.673	265.0	0.783	266.0	0.944	265.6	0.761	265.4	0.813
8	295.5	1.420	297.0	1.112	288.8	1.856	291.0	2.661	290.4	1.253	290.9	0.626

Table 6 Natural frequencies and damping ratios attained from the experimental measurements of the bridge model using SSI method

Modes	Ambient vibration tests-SSI method											
	First test		Second test		Third test		Fourth test		Fifth test		Sixth test	
	Frequency (Hz)	DampingRatio (%)	Frequency (Hz)	DampingRatio (%)	Frequency (Hz)	DampingRatio (%)	Frequency (Hz)	DampingRatio (%)	Frequency (Hz)	DampingRatio (%)	Frequency (Hz)	DampingRatio (%)
1	25.30	2.500	26.77	5.225	27.00	4.350	26.50	4.250	26.00	2.600	26.00	2.320
2	31.70	1.870	34.92	2.534	31.90	2.400	31.19	3.500	30.50	2.800	30.80	1.950
3	41.40	3.351	41.90	1.315	49.04	1.720	42.00	1.430	41.50	1.520	43.91	1.650
4	51.00	5.631	54.66	0.697	55.78	1.414	54.70	1.820	55.00	1.715	54.01	1.914
5	138.2	4.125	135.3	1.947	136.0	0.539	138.5	0.895	138.0	0.912	134.7	1.359
6	235.0	5.020	243.2	3.175	241.1	4.504	238.0	2.714	241.0	2.670	236.9	4.700
7	265.8	0.799	265.4	0.800	265.2	0.872	265.0	0.810	265.0	0.785	265.6	0.821
8	299.5	2.857	297.3	0.914	290.5	1.698	290.0	1.420	290.0	0.985	292.9	0.715

software is used (OMA 2006). The dynamic characteristics of the model bridge were extracted by EFDD and SSI methods.

To determine the natural frequencies and damping ratios, the number and location of accelerometers is not important. The natural frequencies and damping ratios can be obtained only one accelerometer located on the any point of the deck. But to determine the mode shapes more accurately, the number and location of accelerometers is very important. In this paper, the first eight mode shapes are extracted from combination of six measurements. Vertical and transverse mode shapes were determined more accurately from first and second tests, respectively. Longitudinal mode shapes were determined more accurately from third and fifth tests.

Accelerometers locations on the model bridge are given in Fig. 7. Table 4 summarizes details of six groups of measurements. Some pictures from the measurements are shown in Fig. 8.

Singular Values of Spectral Density Matrices (SVSDM) of data set and Stabilization diagram of estimated state space models for fifth measurement are shown in Fig. 9. When the experimentally mode shapes obtained from all tests are compared with each other, it is seen that there is a good agreement between all results. Therefore, measurement mode shapes for one test setup are given in Fig. 10.

Natural frequencies and damping ratios obtained from the all test setup using EFDD and SSI methods are given in Tables 5 and 6.

5.2 Forced vibration tests (FVT)

In the forced vibration tests, B & K 3560 data acquisition system, B & K 4506-B003 type three-axial accelerometers and B & K 8210 type impact hammer were used. Linear averaging method was selected during the tests and number of the samples is taken as 5. Frequency span was chosen as between 0-400Hz. FRFs of the measurements were obtained from PULSE software. In the forced vibration tests, only the natural frequencies were determined due to optional tools were not found in the test equipment to determine mode shapes and damping ratios. Accelerometer location on the 3D view of the bridge and some pictures from the tests are shown in Figs. 11 and 12. Frequency responses functions for each accelerometer are shown in Fig. 13. The natural frequencies obtained from the forced vibration tests are given in Table 7.

Distribution of natural frequencies obtained from finite element analyses, ambient vibration tests (AVT) using EFDD and SSI methods, and forced vibration tests (FVT) are given in Fig. 14.

Also, comparisons of natural frequencies are given in Table 8. Because of the fact that EFDD and SSI results are close to each other, only EFDD results are given for ambient vibration test

Table 7 Natural frequencies obtained from the forced vibration test

Forced vibration tests	Frequency (Hz)							
	1	2	3	4	5	6	7	8
Measurement-1	25.0	31.0	42.0	55.0	136.0	242.0	267.0	295.0

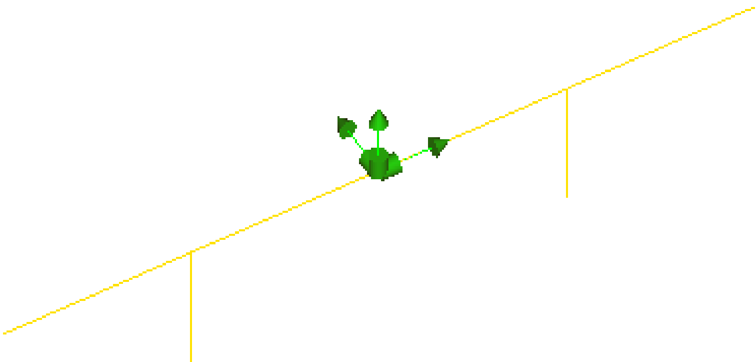


Fig. 11 Accelerometer location for the forced vibration test

Fig. 12 Some view from the forced vibration test

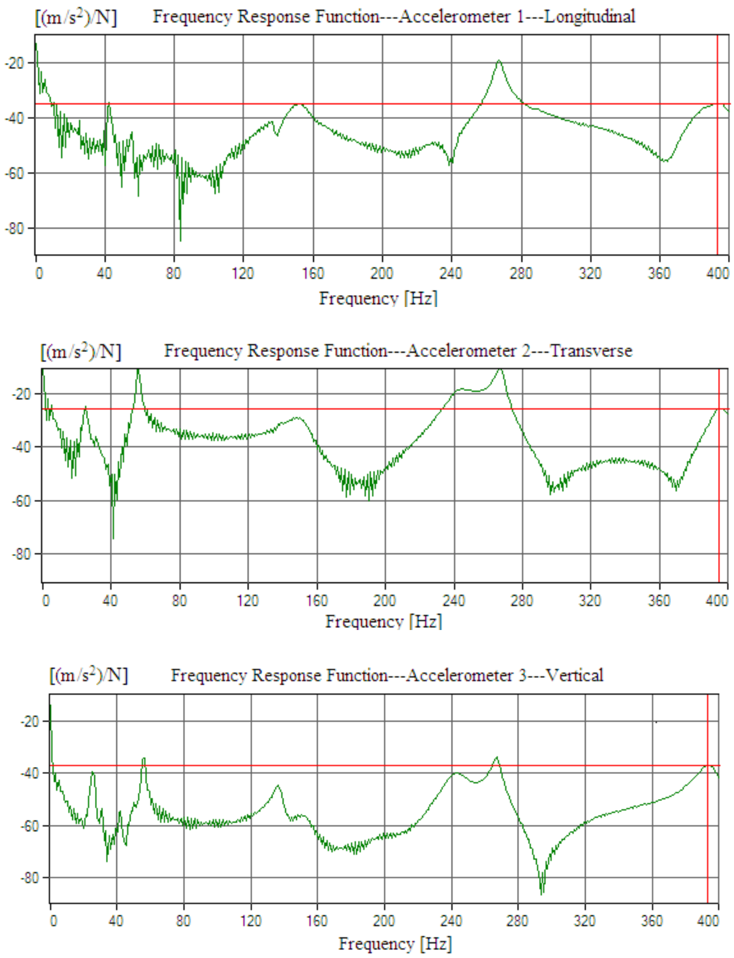


Fig. 13 Frequency responses functions for each component of accelerometer

results in Table 8. It is seen that there is a good agreement between all results. Modal Assurance Criteria (MAC) graphics plotted using finite element analyses and ambient vibration test results are shown in Fig. 15. It is seen from Fig. 15 that the MAC values are between 0.80-1.00. This shows that results are almost overlapped.

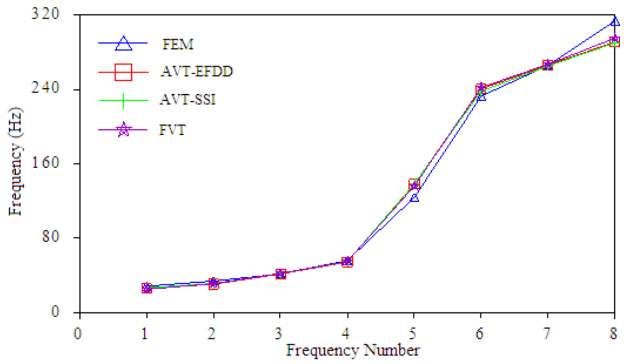


Fig. 14 Distribution of the analytically and experimentally identified natural frequencies

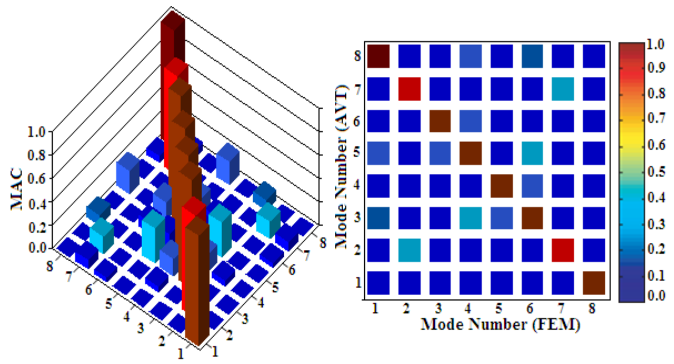


Fig. 15 MAC graphics using finite element analyses and ambient vibration test results

Table 8 Natural frequencies attained from the finite element analyses, ambient and forced vibration tests

Modes	First test			Second test			Third test			Fourth test			Fifth test			Sixth test		
	FEM	AVT	FVT	FEM	AVT	FVT	FEM	AVT	FVT	FEM	AVT	FVT	FEM	AVT	FVT	FEM	AVT	FVT
1	28.33	25.32	25.0	28.33	25.84	25.0	28.33	27.30	25.0	28.33	25.79	25.0	28.33	25.34	25.0	28.33	25.36	25.0
2	33.82	31.51	31.0	33.82	31.13	31.0	33.82	32.45	31.0	33.82	30.50	31.0	33.82	30.17	31.0	33.82	30.44	31.0
3	41.39	41.47	42.0	41.39	41.90	42.0	41.39	42.25	42.0	41.39	41.50	42.0	41.39	41.40	42.0	41.39	41.46	42.0
4	56.05	52.18	55.0	56.05	54.91	55.0	56.05	51.37	55.0	56.05	54.34	55.0	56.05	55.01	55.0	56.05	55.09	55.0
5	123.9	139.0	136.0	123.9	135.4	136.0	123.9	133.9	136.0	123.9	138.0	136.0	123.9	135.5	136.0	123.9	135.8	136.0
6	232.7	235.0	242.0	232.7	241.7	242.0	232.7	240.0	242.0	232.7	240.5	242.0	232.7	238.1	242.0	232.7	236.2	242.0
7	265.8	264.8	267.0	265.8	265.1	267.0	265.8	265.0	267.0	265.8	266.0	267.0	265.8	265.6	267.0	265.8	265.4	267.0
8	313.5	295.5	295.0	313.5	297.0	295.0	313.5	288.8	295.0	313.5	291.0	295.0	313.5	290.4	295.0	313.5	290.9	295.0

FEM: Finite Element Analyses; AVT: Ambient Vibration Tests; FVT: Forced Vibration Tests

6. Conclusions

In this study, analytical and experimental modal analyses of a scaled bridge model are carried out to extract the dynamic characteristics such as natural frequency, mode shapes and damping ratios. For this purpose, a bridge model is constructed in laboratory conditions. Three dimensional finite element model is constituted using SAP2000 software to determine the dynamic characteristics analytically. Ambient and forced vibration tests are conducted to obtain the experimental dynamic characteristics. The following observations can be made from the study:

•From the finite element model of the bridge model, a total of 8 natural frequencies are attained analytically, which range between 28.33 and 313.5 Hz. Considering the first eight mode shapes, these modes can be classified into longitudinal, transverse and vertical modes.

•The natural frequencies and mode shapes obtained from the all measurements using EFDD and SSI methods are almost close to each other.

•The first eight natural frequencies are obtained between 25.32-297.0 Hz for EFDD method and 25.30-299.5 Hz for SSI method.

•The mode shapes are obtained as longitudinal, transverse and vertical from EFDD and SSI methods, and there is a good agreement with the literature. Beside, the MAC values obtained using EFDD and SSI results change between 90-100%.

•The damping ratios are obtained as 1-5%, which are the compatible with the literature. On the other hand, the damping ratios obtained EFDD and SSI methods are different with each other. Also, there is not a suitable distribution for damping ratios along to first and last modes.

•In the forced vibration test, frequency responses functions are obtained and the first eight natural frequencies are extracted between 25.0-295.0 Hz. The frequencies obtained from the forced vibration tests are close to those of ambient vibrations.

•MAC values obtained using finite element analyses and ambient vibration test results change between 80-100%.

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