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Finite Element Analysis and Ambient Vibration Test of the Arch Type Steel Highway Bridges

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ABSTRACT

In this paper, it is aimed to determine the dynamic characteristics of highway bridges using finite element analyses and ambient vibration tests. A modern steel highway bridge which has arch type structural system with 216 m total length and located in the Ayvacık county of Samsun, Turkey is selected as an application. Because of the fact that the bridge connects the villages which are separated with Suat Uğurlu Dam Lake, it has a major logistical importance for this region. The construction of the bridge is completed in 2009 and opened the traffic. An analytical modal analysis is performed on the developed 3D finite element model of the highway bridge to provide the analytical frequencies and mode shapes. The experimental measurements are carried out by ambient vibration tests under traffic loads. Vibration data are gathered from bridge deck. Measurement time, frequency span and effective mode number are determined by consider similar studies and literature. Enhanced Frequency Domain Decomposition method in the frequency domain and Stochastic Subspace Identification method in the time domain are used for the output only modal identification and dynamic characteristics such as natural frequencies, mode shapes and damping ratios are determined, experimentally. At the end of the study, analytically and experimentally identified dynamic characteristics are compared with each other. A good agreement is found between mode shapes, but some difference in natural frequencies.

INTRODUCTION

The dynamic response of a highway bridge under dynamic loads, such as wind, earthquake or traffic, is very complex and requires special studies. Using of experimental measurement tests is advisable to determine the structural properties at the time of opening and during the life time of the bridge. It allows us to compare the dynamic characteristics assumed in the design with those of experimental tests. Also, any changes in the structural performance and detecting any damage to the structure can be determined [1].

There are two basically different methods available to experimentally identify the dynamic system parameters of a structure: Experimental Modal Analysis and Operational Modal Analysis. In the Experimental Modal Analysis, the structure is excited by known input force (such as impulse hammers, drop weights and electrodynamics shakers) and response of the structure is measured. In the Operational Modal Analysis (OMA), the structure is excited by unknown input force (ambient vibrations such as traffic load, wind and wave) and response of the structure is measured. Some heavy forced excitations become very expensive and sometimes may cause the possible damage to the structure. But, ambient excitations such as traffic, wave, wind, earthquake and their combination are environmental or natural excitations. Therefore, the system identification techniques through ambient vibration measurements become very attractive [2,3].

In the literature, there are some researches on experimental measurements of highway bridges [4-8]. However, there is no enough studies about the comparison of analytical and experimental dynamic characteristics of arch type steel highway bridges. So, this paper aims to determine the dynamic characteristics of a modern steel highway bridge which has arch type structural system using finite element analysis and OMA.

DESCRIPTION OF THE BRIDGE

Eynel Bridge is selected for the application example in this paper. The investigated arch type steel highway bridge is located in Black Sea region of Turkey, and has a main arch span of 186 m. It connects to the villages near two sides of Suat Uğurlu Dam reservoir in city of Samsun. This bridge was originally designed and constructed by Prokon Engineering and Consultancy, Inc. [9]. The construction of the bridge started in 2007 and it was opened to traffic in 2009. Figure 1 shows the some views of the Eynel Highway Bridge.

Figure 1 Some views of Eynel Highway Bridge [9]

The bridge is upper-deck steel bridge which has arch type carriage system with a total length of 216 m. The structural system of the bridge consists of the steel arch ribs, vertical and lateral load carrying systems, columns, and the deck system. The span of arch rib is 186 m and it has box-type section. The height and width of the section is 2.4 m and 12 m, respectively. 12 vertical columns (6 on one side) transmit loads from the deck to the arch ribs. The deck is 12 m wide and 10 cm constant thickness. Along its whole length, the arch ribs and deck are stiffened by horizontal brace members. General arrangement drawing of the entire bridge are shown in Figure 2.

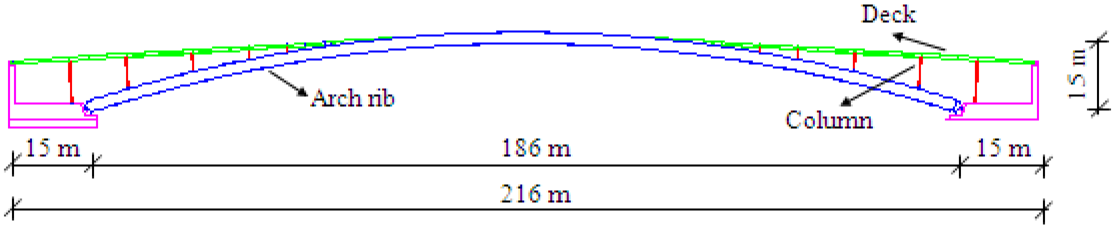


Figure 2 General arrangements drawing of the bridge [9]

FINITE ELEMENT MODELING

Three dimensional finite element model of the Eynel Highway Bridge is constructed using the SAP2000 software [10]. The curve, which defines the axis of the arch, is designed in accordance with the form referred to as the chain curve. In this way, the occurrence of the moment is restricted under the dead load. Also, it is aimed that the arch structural system carries the axial forces.

The selected highway bridge 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:

- In the finite element model of the bridge, the fictitious elements are used to determine the torsional and M22 moment effects which are consist of asymmetrical load cases. These elements are defined on the axis through the gravity center of uniform and linear loads. Also, these elements are modelled as massless,
- In the finite element model of the bridge deck, diagonal fictitious elements are used to reflect the rigid diaphragm effect of the concrete,
- Fictitious elements are modelled as two ends hinged and one end axial sliding,
- Rigid link elements are modelled as two ends rigid to ensure the torsional moments in the carrier system elements. The elements have an great bending rigidity.

To determine the length of the rigid element, it is aimed that fictitious elements are located the gravity center of the loads. Three dimensional finite element model of Eynel Highway Bridge is given in Figure 3. The values of the material properties used in analyses of the highway bridge are given in Table 1.

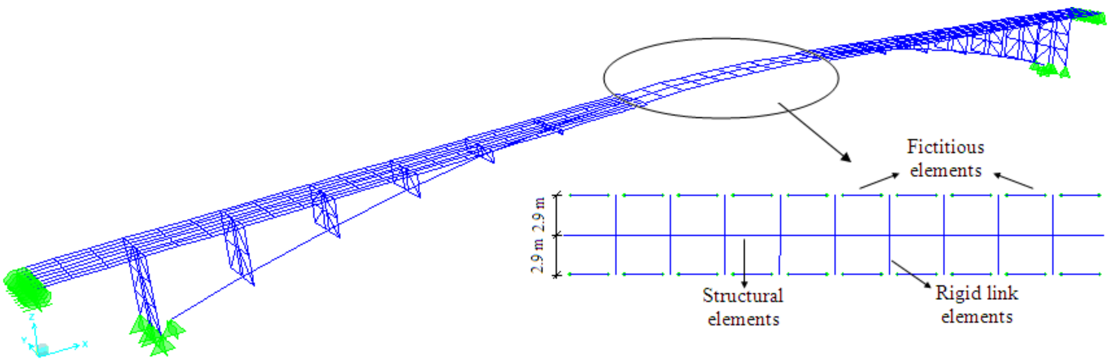
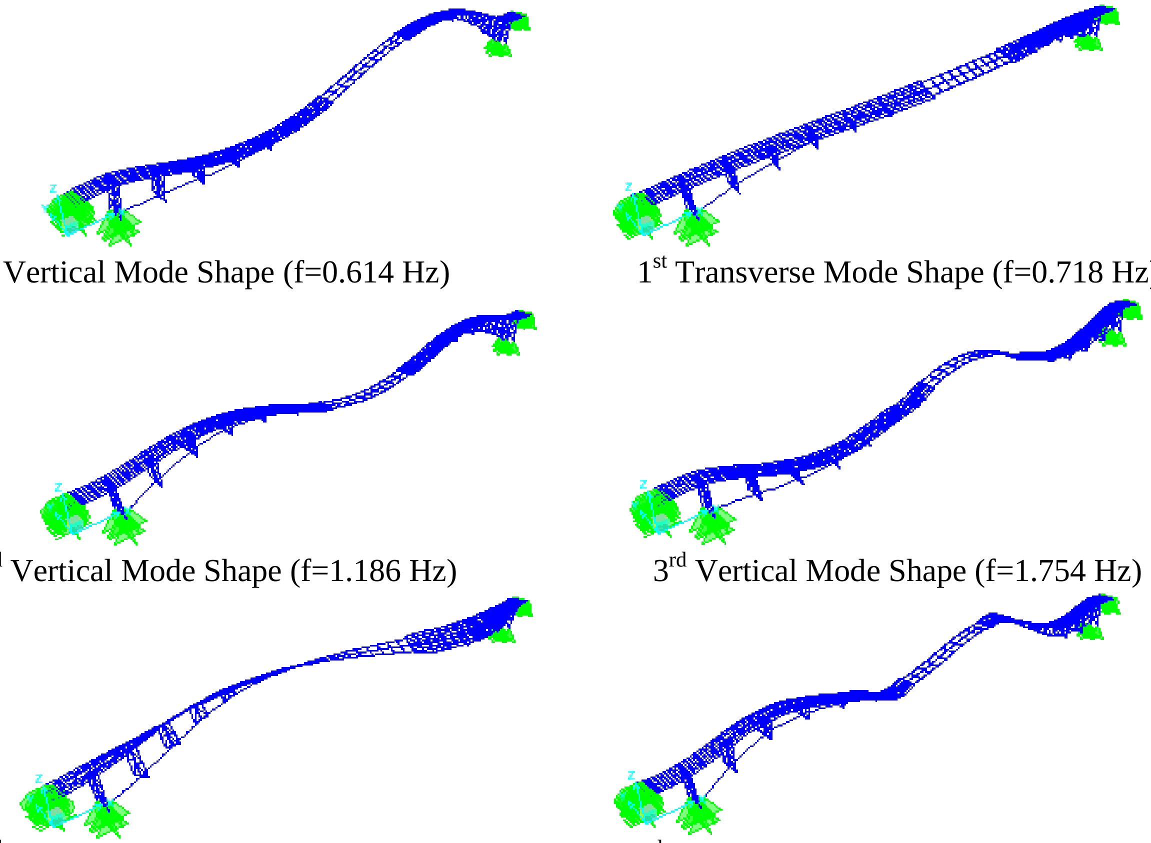


Figure 3 Three dimensional finite element model of Eynel Highway Bridge

Table 1 Material Properties Used in Analyses of the Highway Bridge

Elements	Material Properties		
	Modulus of Elasticity (N/m2)	Poisson's Ratio (-)	Mass per unit Volume (kg/m3)
Carrier System Elements	2.062E11	0.3	7850
Fictitious Elements	2.000E11	0.3	-

Natural frequencies and corresponding vibration modes are important dynamic properties and have significant effect on the dynamic performance of structures. A total of six natural analytical frequencies of the highway bridge are attained which range between 0.614 and 2.386 Hz. The six analytical vibration modes of the highway bridge as a whole are shown in Figure 4.



1st Vertical Mode Shape (f=0.614 Hz) — 1st Transverse Mode Shape (f=0.718 Hz)

2nd Vertical Mode Shape (f=1.186 Hz) — 3rd Vertical Mode Shape (f=1.754 Hz)

2nd Transverse Mode Shape (f=1.940 Hz) — 4th Vertical Mode Shape (f=2.386 Hz)

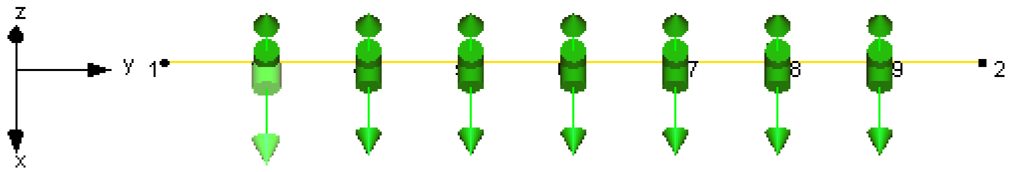
Figure 6 Analytically identified the first six mode shapes of the highway bridge

OPERATIONAL MODAL ANALYSIS

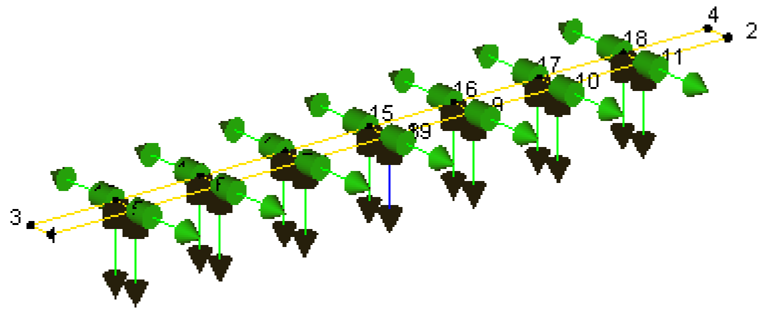
In the ambient vibration tests, B&K 3560 data acquisition system and B&K 8340 type uni-axial accelerometers were used. During the tests, frequency span was selected as 0-6.25 Hz. The measurements were performed along ten minutes, and excitations were provided from natural effects. Signals obtained from the tests were recorded and processed by the commercial software PULSE [11] and OMA [12]. The dynamic characteristics of the bridge were extracted by EFDD and SSI methods. Ambient vibration tests were conducted on the bridge using two test setups. During the first test, seven accelerometers were placed in the lateral direction on the bridge deck; and seven accelerometers were placed in the vertical direction on the bridge deck (Figure 7a). During the second test setup, 15 accelerometers were used. One of the accelerometers was used as the reference. In addition to the first test, the accelerometers were placed on the two sides of the bridge deck (Figure 7b).

EFDD Results

Singular Values of Spectral Density Matrices (SVSDM) are shown in Figures 8 and 9 for the first and second tests, respectively. The natural frequencies and damping ratios of Eynel Highway Bridge obtained from EFDD method are listed in Table 2. As seen in Table 2, the first six natural frequencies change between 0.779-2.674 Hz. The mode shapes of the bridge obtained from the first and second test setups appear in Figure 10. As seen in Figure 10, the mode shapes are vertical and transverse modes.



a). Location of accelerometers in the first test



b). Location of accelerometers in the second test

Figure 7 Accelerometers locations on the bridge deck during ambient vibration testing

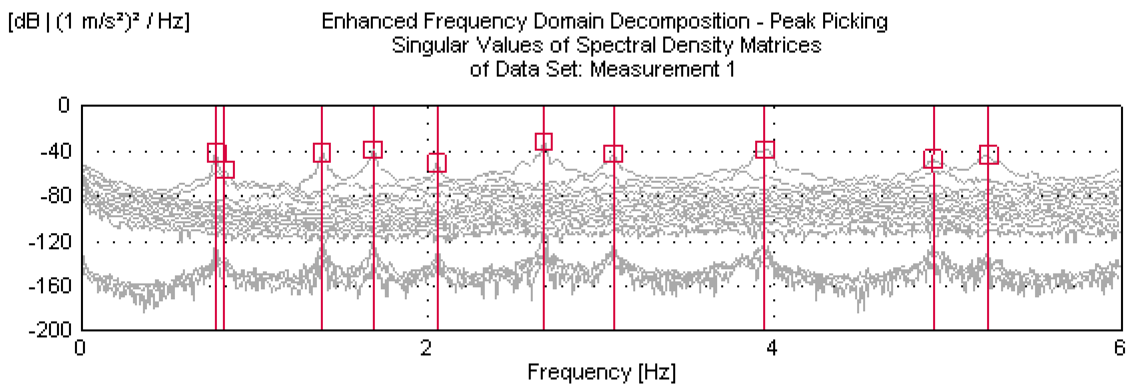


Figure 8 SVSDM for the first test

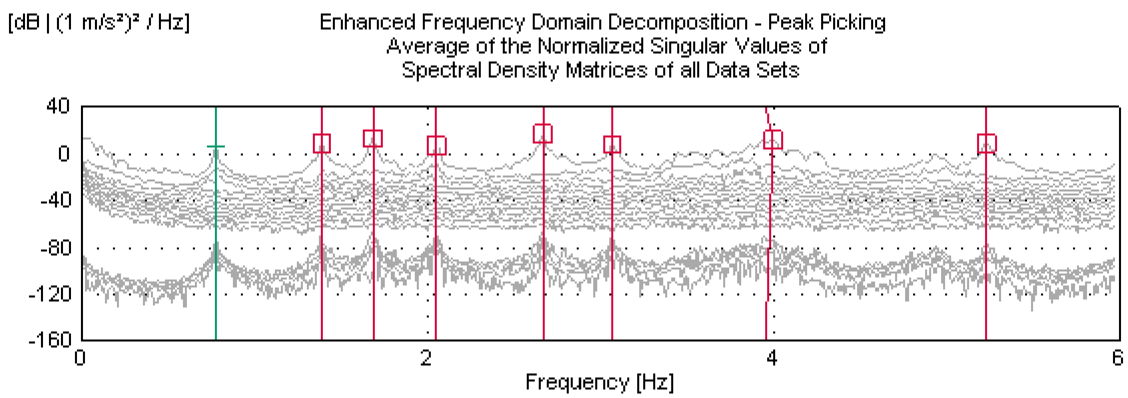


Figure 9 SVSDM for the second test

Table 2 Natural Frequencies and Damping Ratios of the Bridge using EFDD Method

Mode	First Measurement Test		Second Measurement Test	
	Frequency (Hz)	Damping Ratios (%)	Frequency (Hz)	Damping Ratios (%)
1	0.779	0.73	0.780	0.82
2	0.828	1.30	-	-
3	1.395	0.51	1.392	0.59
4	1.688	0.40	1.690	0.54
5	2.057	0.45	2.054	1.03
6	2.674	0.25	2.670	0.44

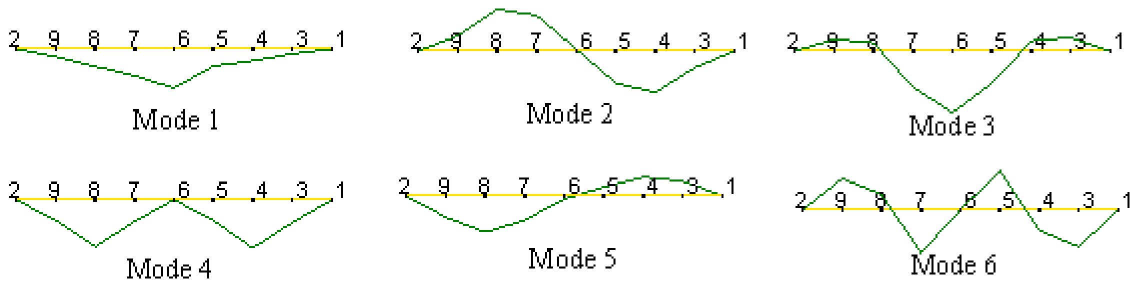


Figure 10 The mode shapes of the bridge obtained from the first test using EFDD method

SSI Results

Stabilization diagrams of estimated state space models for the two tests are given in Figures 11 and 12, respectively.

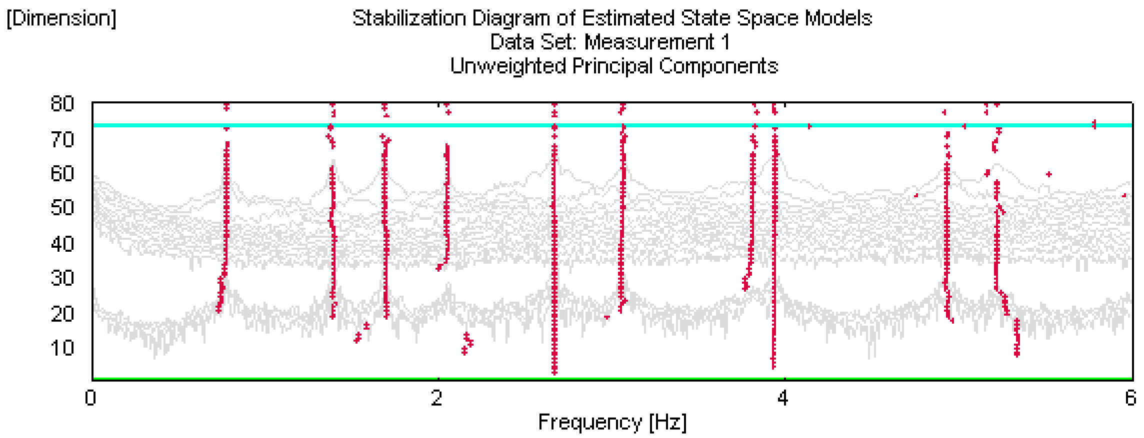
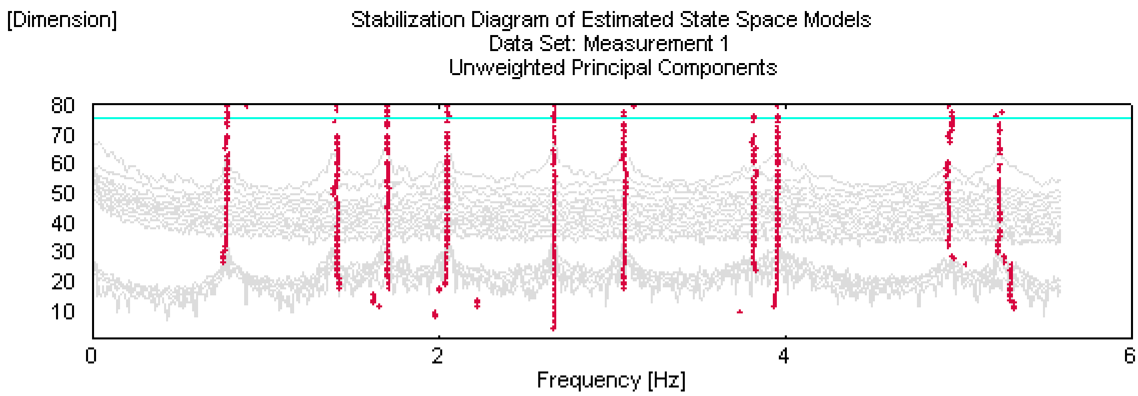


Figure 11 Stabilization diagram of estimated state space models obtained from the first test



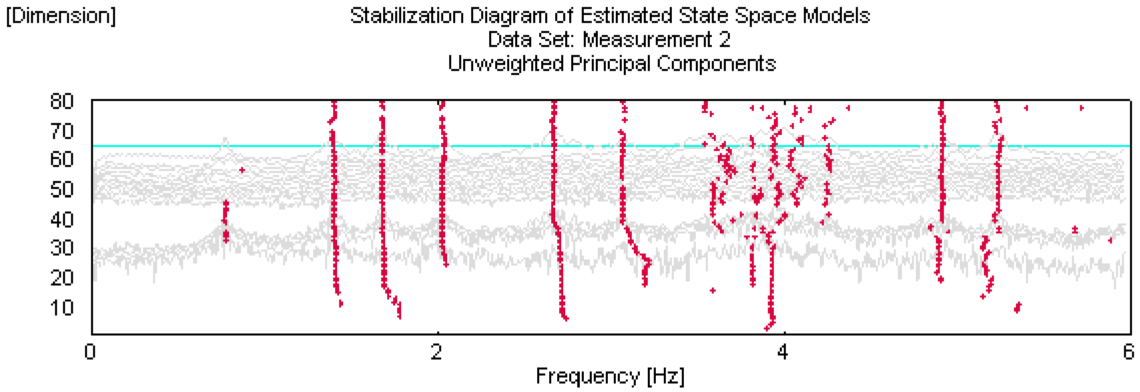


Figure 12 Stabilization diagram of estimated state space models obtained from the second test

The natural frequencies and damping ratios of Eynel Highway Bridge obtained from SSI method are listed in Table 3. As seen in Table 3, the first six natural frequencies change between 0.780-2.670 Hz.

Table 3 Natural Frequencies and Damping Ratios of the Bridge using SSI Method

Mode	First Measurement Test		Second Measurement Test	
	Frequency (Hz)	Damping Ratios (%)	Frequency (Hz)	Damping Ratios (%)
1	0.800	1.67	0.780	0.82
2	-	-	-	-
3	1.381	1.06	1.392	0.59
4	1.709	3.26	1.690	0.54
5	1.933	0.84	2.054	1.03
6	2.670	0.36	2.670	0.44

CONCLUSIONS

This paper describes analytical and experimental dynamic system identification of arch type steel highway bridges. Eynel Highway Bridge located in Samsun is selected as an application. The conclusions drawn from the study can be presented as below:

From the finite element model of the highway bridge, a total of six natural frequencies are attained analytically, which range between 0.614 and 2.386 Hz. Considering the first six mode shapes, these modes can be classified into vertical and transverse modes.

The natural frequencies and mode shapes obtained from EFDD and SSI methods for the first and second tests are generally close to each other. The first six natural frequencies are obtained between 0.779-2.674 Hz from both methods.

Vertical and transverse mode shapes are obtained for both EFDD and SSI methods.

The damping ratios are obtained between 0.25-3.26% for the two tests. The damping ratios obtained from the second tests results for EFDD and SSI are closed to each other; however, there are differences for the first test.

When comparing the analytical and experimental results, it was clearly seen that there are some differences between analytical and experimental natural frequencies and experimental natural frequencies are generally bigger than those of analytical. Also, there is not a good agreement between analytically and experimentally identified the first two modes.

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