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Ambient vibration testing of Berta Highway Bridge with post-tension tendons

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Abstract. The aim of this study is to determine the dynamic characteristics of long reinforced concrete highway bridges with post-tension tendons using analytical and experimental methods. It is known that the deck length and height of bridges are affected the dynamic characteristics considerably. For this purpose, Berta Bridge constructed in deep valley, in Artvin, Turkey, is selected as an application. The Bridge has two piers with height of 109.245 m and 85.193 m, and the total length of deck is 340.0 m. Analytical and experimental studies are carried out on Berta Bridge which was built in accordance with the balanced cantilever method. Finite Element Method (FEM) and Operational Modal Analysis (OMA) which considers ambient vibration data were used in analytical and experimental studies, respectively. Finite element model of the bridge is created by using SAP2000 program to obtain analytical dynamic characteristics such as the natural frequencies and mode shapes. The ambient vibration tests are performed using Operational Modal Analysis under wind and human loads. Enhanced Frequency Domain Decomposition (EFDD) and Stochastic Subspace Identification (SSI) methods are used to obtain experimental dynamic characteristics like natural frequencies, mode shapes and damping ratios. At the end of the study, analytical and experimental dynamic characteristic are compared with each other and the finite element model of the bridge was updated considering the material properties and boundary conditions. It is emphasized that Operational Modal Analysis method based on the ambient vibrations can be used safely to determine the dynamic characteristics, to update the finite element models, and to monitor the structural health of long reinforced concrete highway bridges constructed with the balanced cantilever method.

Keywords: operational modal analysis; dynamic characteristics; balanced cantilever concrete bridges; finite element model updating; structural health monitoring of bridge

1. Introduction

Highway bridges are important engineering structures. Determination of natural frequencies, mode shapes and damping ratios which are the dynamic characteristics are very important to

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assess the current condition of the bridges. Nowadays, analytical and experimental methods are used to obtain dynamic characteristics. Analytical modelling is often carried out using the Finite Element Method (FEM) and the experimental modeling is performed using the Operational Modal Analysis (OMA) in which only the response is measured using ambient vibrations such as the wind, human walking or traffic. Operational Modal Analysis method is preferred during experimental testing of structures because it is cheap, fast and is non destructive.

In the literature, there are many studies related to finite element modelling, finite element model updating and experimental measurements of highway bridges. Maeck *et al*. (2001) studied damage identification of Z24 Highway Bridge by the finite element model updating technique using vibration monitoring. Brownjohn *et al*. (2003) studied assessment of highway bridges by dynamic testing and the finite element model updating. Feng *et al*. (2004) applied a neural network based system identification technique to a highway bridge using experimental measurements under ambient vibrations such as traffic loads. El-Borgi *et al*. (2005) investigated the modal parameter identification and model updating of Boujnah Reinforced Concrete Bridge.

Kwasniewski *et al*. (2006) presented an experimental study for a preselected typical highway bridge. Static and dynamic field tests were performed on a two-lane concrete highway bridge. Bozdağ *et al*. (2006) determined the analytical and experimental dynamic characteristics of new Galata Bridge located in Istanbul, Turkey. Chen (2006) and Guan (2006) studied the vibration-based structural health monitoring of highway bridges.

Karbhari (2007) investigated the long-term structural health monitoring of FRP composite highway bridges using vibration-based monitoring techniques. Conte *et al*. (2008) carried out dynamic field tests on the Alfred Zampa Memorial Bridge located 32 km northeast of San Francisco on interstate Highway I-80. Siringoringo and Fujino (2008), presented a schematic data analysis and evaluation of system identification procedures to obtain the dynamic characteristics of the Hakucho Suspension Bridge which is located at the entrance of Muroran Gulf in Hokkaido Prefecture, in the northern part of Japan using ambient response.

Liu *et al*. (2009) investigated finite element analyses, field measurements using ambient vibration tests and seismic evaluation of a three-span highway bridge subjected to a virtual ground motion. Bayraktar *et al*. (2009) determined the dynamic characteristics of Kömürhan Highway Bridge located on Elazığ-Malatya highway in Turkey using finite element analyses and ambient vibration tests. Brownjohn *et al*. (2010), carried out several purposes that included the evaluation of the current technology for instrumentation and system identification and the generation of an experimental dataset of modal properties to be used for validation and updating of finite element models for scenario simulation and structural health monitoring in their study. Humber Bridge located in England was selected for these purposes.

Wang *et al*. (2010), studied on a two-phase progressive FE model updating approach is developed and the baseline model for the Runyang Suspension Bridge (RSB) which is the longest bridge in China with a main span of 1490 m based on the approach is obtained using the ambient vibration test data. Benedettini and Gentile (2011), obtained the vertical dynamic characteristics of the bridge which crosses the river Oglio between the municipalities of Bordolano and Quinzano by using a traditional data acquisition system with servo-accelerometers, the identification of local natural frequencies of the stay cables using an innovative radar vibrometer and the theoretical study, vibration modes were determined using a 3D finite element model of the bridge and the information obtained from the field tests, combined with a classical system identification technique. Magalhães *et al*. (2012), stressed the usefulness of operational modal analysis in the context of Structural Health Monitoring systems.

Gentile and Saisi (2011), determined results of the experimental modal analysis performed on the historic Paderno Bridge (1889) which has an arch span of 150 m, total length of 266 m between the abutments and about 2600 tons of wrought iron were used in its construction over the Adda River. The dynamic tests, are performed in operational conditions (i.e., under traffic and wind-induced excitation). Altunışık *et al*. (2011) determined the dynamic characteristics of Gülburnu Highway Bridge located on Giresun-Espiye state highway in Turkey using finite element analyses and ambient vibration tests.

The aim of this study is to determine the dynamic characteristics of long reinforced concrete highway bridges with post-tension tendons and height piers which are constructed with balanced cantilever method using ambient vibration data. It is known that the deck length and height of bridges are affected the dynamic characteristics considerably. For this purpose, Berta Bridge constructed in deep valley, in Artvin, Turkey, is selected as an application. The Bridge has two piers with height of 109.245 m and 85.193 m, and the total length of deck is 340.0 m. Three dimensional finite element model of the bridge is created using SAP2000 (2008) and analytical dynamic characteristics were determined. OMA is used to determine the experimental dynamic characteristics of Berta Bridge and the experimental dynamic characteristics are extracted using the Enhanced Frequency Domain Decomposition and Stochastic Subspace Identification methods. Finite element model of the bridge is updated considering the material properties, the boundary conditions and other variations to eliminate the differences between the analytical and the experimental dynamic characteristics.

2. Formulation

In this study, two well-known identification techniques of ambient vibration test, which are Enhanced Frequency Domain Decomposition (EFDD) in the frequency domain and Stochastic Subspace Identification (SSI) in the time domain, are used used to extract dynamic characteristics of Berta Bridge. The basic formulations of EFDD and SSI techniques are given in below.

2.1 Enhanced Frequency Decomposition Domain (EFDD) method

In EFDD method, the relationship between the unknown input and the measured responses can be expressed as (Ren *et al*. 2004, Jacobsen *et al*. 2006, Bendat and Piersol 2004)

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

where G_{xx} is the rxr Power Spectral Density (PSD) matrix of the input, r is the number of inputs, G_{yy} is the mxm PSD matrix of the responses, m is the number of responses, $H(\omega)$ is the mxr Frequency Response Function (FRF) matrix, and * and superscript T denote complex conjugate and transpose, respectively. Solution of the Eq. (1) is given detail in the literature (Peeters and De Roeck 2000, Raineiri *et al*. 2007).

2.2 Stochastic Subspace Identification (SSI) method

Stochastic Subspace Identification (SSI) is an output-only method that directly works with time data without the need to convert time domain measurements to auto-correlations or to frequency spectra. The method is especially suitable for operational modal parameter identification, and the literature provides a detailed technical overview (Van Overschee and De Moor 1996, Peeters and De Roeck 1999, Peeters 2000). The model of vibrating structures can be defined by a set of linear, constant coefficient and second-order differential equations

$$M\ddot{U}(t) + C_2\dot{U}(t) + KU(t) = F(t) = B_2u(t) \tag{2}$$

where M, C_2, K are the mass, damping and stiffness matrices, $F(t)$ is the excitation force, and $U(t)$ is the displacement vector depending on time t. Observe that the force vector $F(t)$ is factorized into a matrix B_2 describing the inputs in space and a vector $u(t)$. Solution of the Eq. (2) is given in detail in the literature (Ewins 1984, Yu and Ren 2005).

3. Description of Berta Bridge

Berta Bridge was selected as an application. Berta Bridge was constructed between 22 + 494.098 and 22 + 764.098 km of Artvin-Erzurum highway, Turkey. Construction of the bridge started in 2008 and was completed in 2011. Before the construction of the Berta Bridge, transportation in its region was provided historical Berta Bridge (Fig. 1). After Deriner Dam which is located 5 km upstream of Artvin and which has been constructed to protect for energy and high-water is completed, historical Berta Bridge is going to submerge. For this purpose, the new Berta Bridge is constructed above the level of the top elevation of the dam reservoir. Some views of Berta Bridge are given in Fig. 2.

Berta Bridge was constructed in accordance with the balanced cantilever method. This method is the best and the optimum method for the passing of large and long valleys with reinforced concrete highway bridges using maximum span and minimum columns. The balanced cantilever segmental construction has long been known as one of the most efficient methods due to the fact that the method does not need any formwork to build a bridge. In this method, firstly, columns and

(a) (b)

Fig. 1 Some views of historical Berta Bridge

(a) (b)

Fig. 2 Some views of Berta Bridge

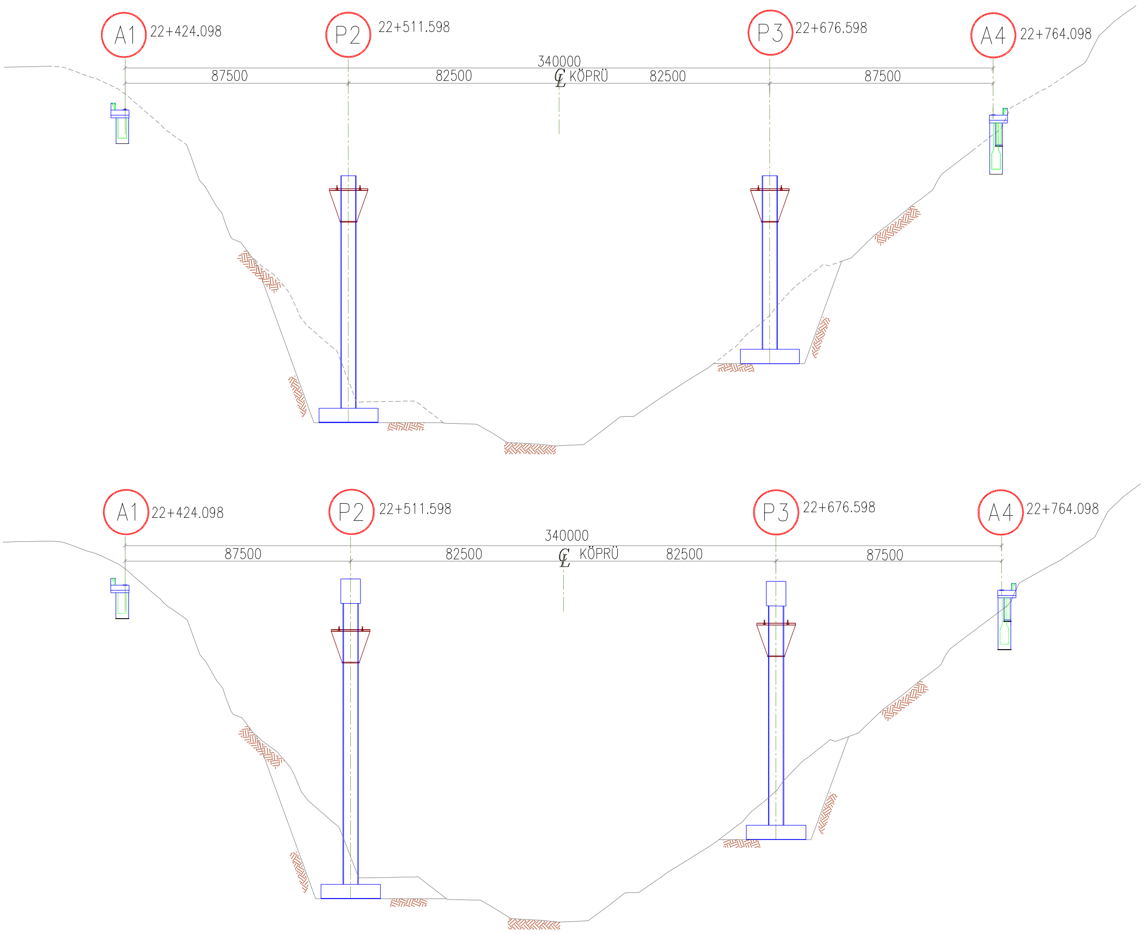


Fig. 3 Schematic drawing of balanced cantilever construction (DOLSAR 2007)

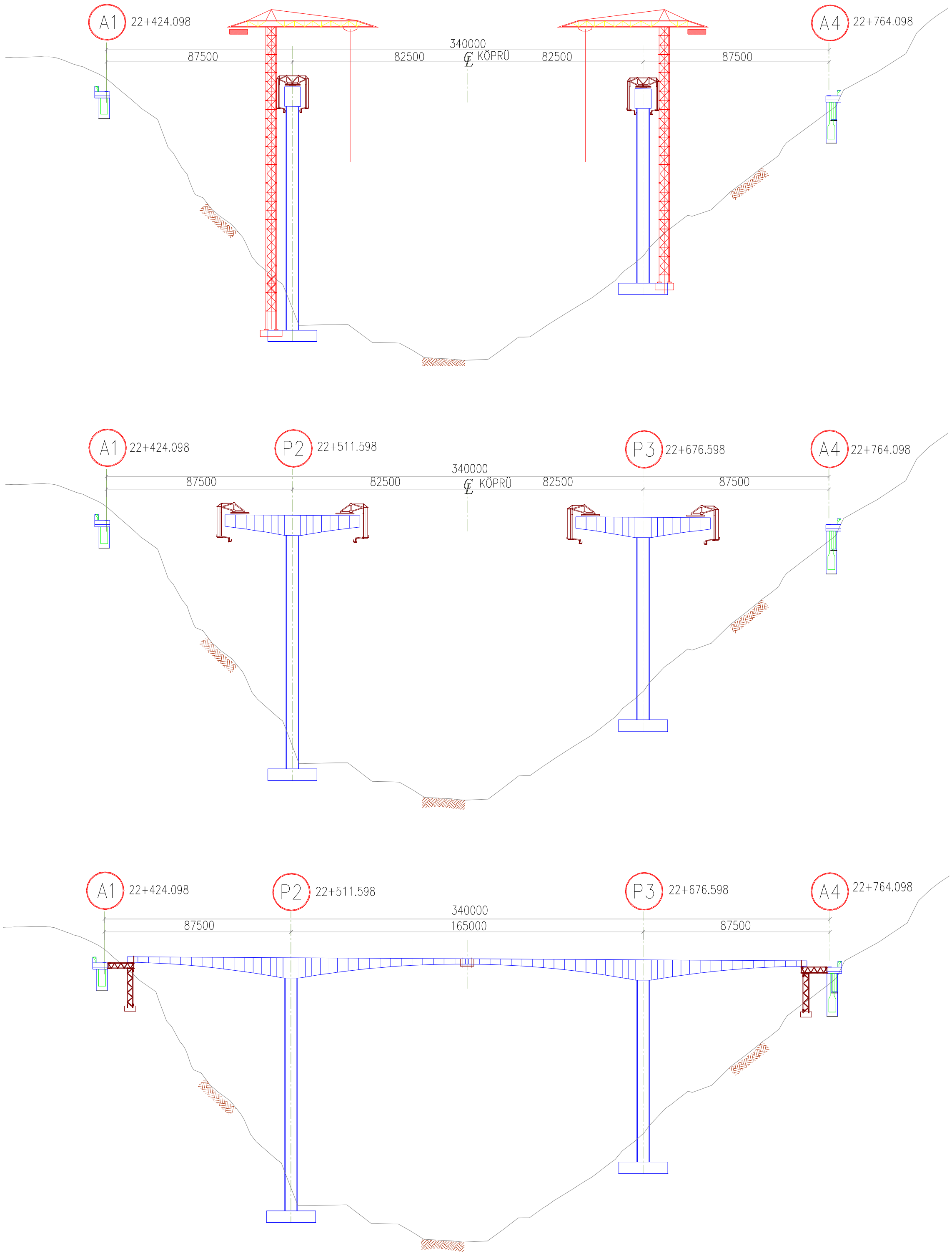


Fig. 3 Continued

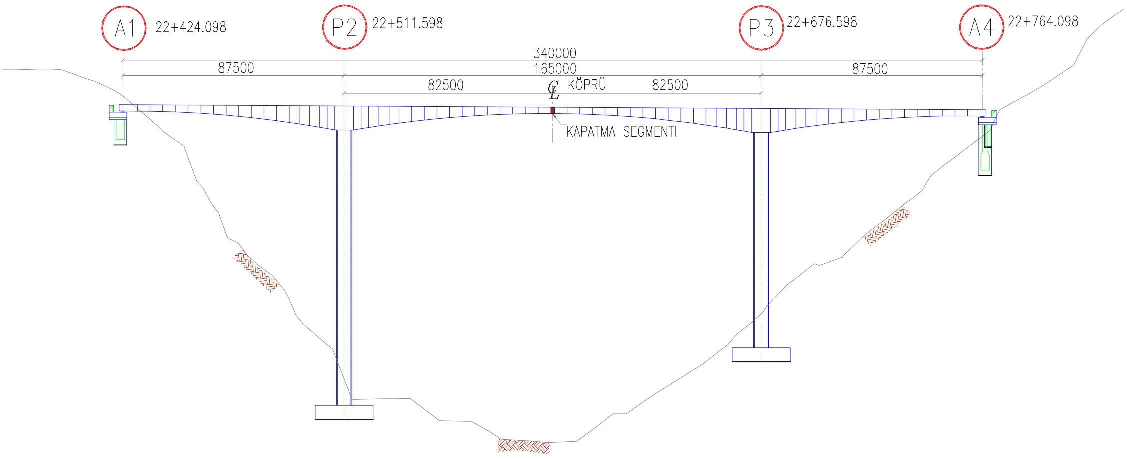


Fig. 3 Continued

small part of bridge deck are constructed over substructure using suitable formwork. Then, segments (3-5 m length) are erected on opposite sides of each column to balance the loads by using a movable form carrier. After the concreting, prestress tendons are inserted in the segments and stressed with post-tension. The prestressing tendons are arranged according to the moment diagram of a cantilever, with a high concentration above the column. Towards the mid span or the abutment, the number of tendons gradually decreases. Finally, form carrier is moved to the next position and a new cycle starts. This sequence is completed in a week and going on until bridge decks meet at mid span. At the mid span, closure segment is established to complete one span. The construction process of each segment is repeated until the bridge is completed (Altunışık *et al*.

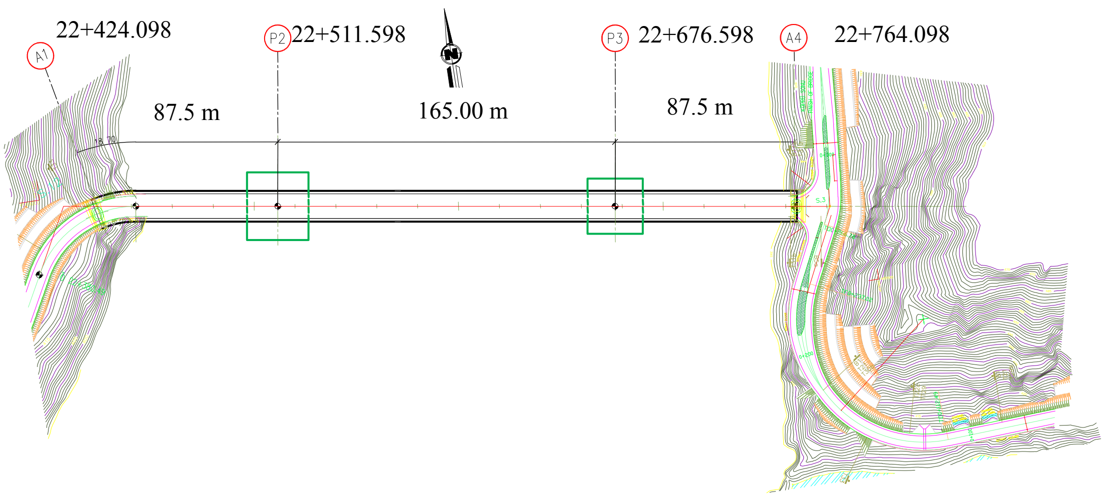


Fig. 4 The Berta Bridge's plan and longitudinal section (DOLSAR 2007)

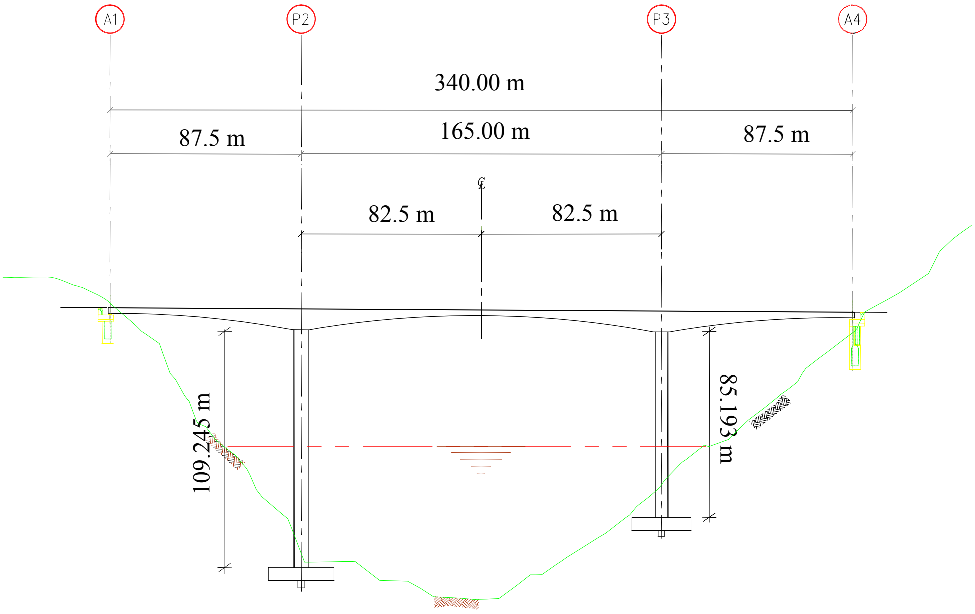


Fig. 4 Continued

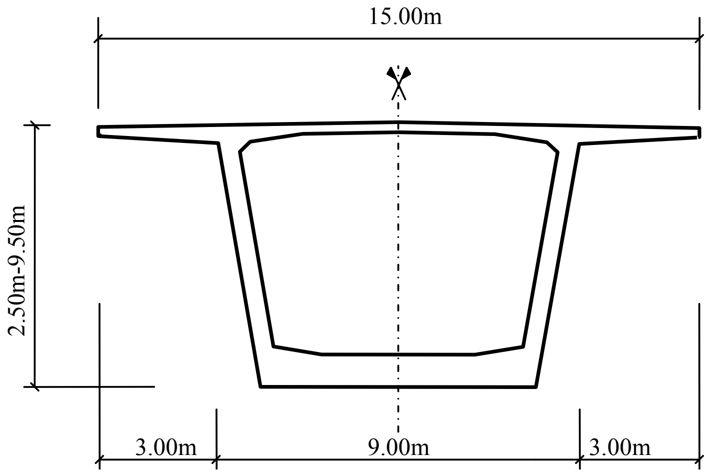


Fig. 5 Dimensions of box girder cross section

2011, Turan 2012). Fig. 3 schematically shows the balanced cantilever method, in which segments are symmetrically added to the columns.

3.1 Berta Bridge's deck

Berta Bridge has a continuous post-tensioned concrete single deck which has a box girder cross section. The bridge deck consists of a main span of 165.00 m and two side spans of 87.50 m each.

The total bridge length is 340.00 m and width of the bridge is 15.00 m. Deck of the bridge was constructed with the balanced cantilever and prestress box beam method. The load carrying system of the bridge consists of the deck, the two piers and the two abutments. The plan and the longitudinal section of the bridge are given in Fig. 4.

The deck consists of 76 segments. All of the segments have nearly 5 m length. The cross-sections of the segments are variable along the bridge length. The maximum depth is 9.5 m on the columns, but it decreases parabolically to 2.50 m at the side supports and center of the bridge. The thickness of the bottom slab changes parabolically from 0.25 m in to 1.40 m. The top slab thickness of 0.25 m that is constant all over the structure. Fig. 5 shows the dimensions of the box girder cross section.

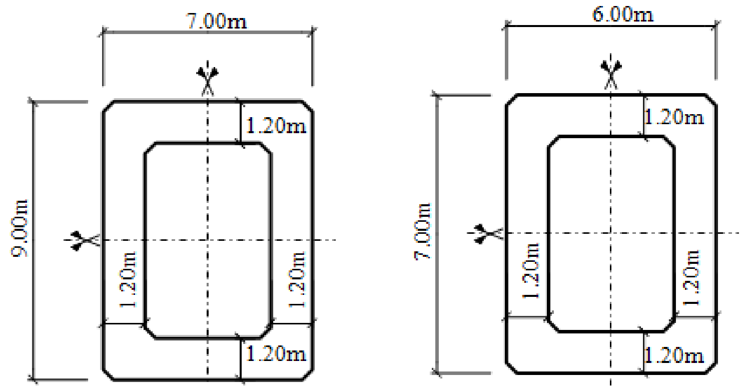


Fig. 6 Sectional views of piers

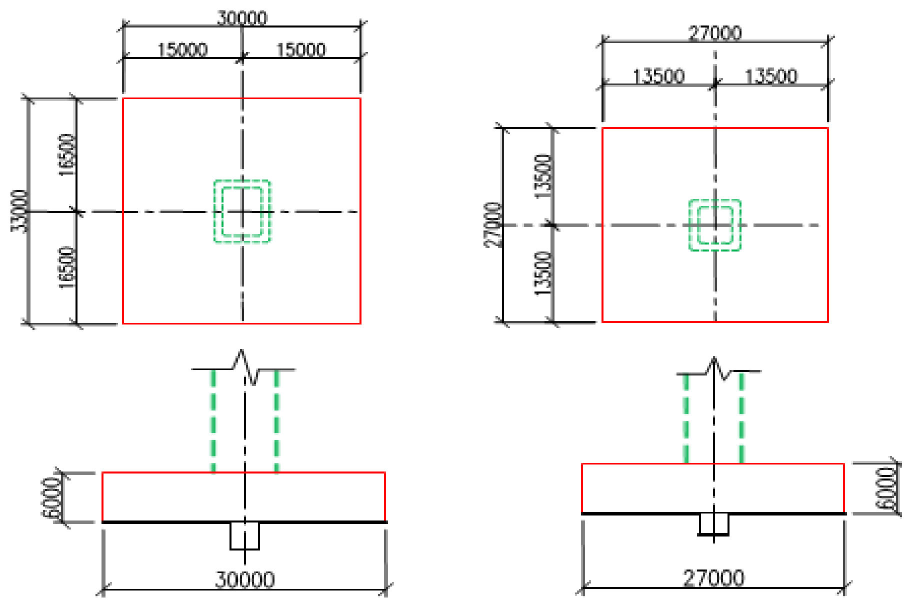


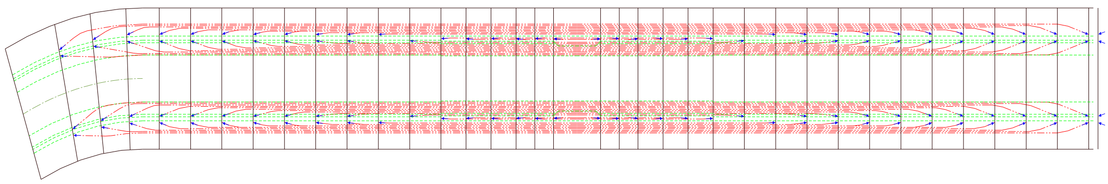
Fig. 7 Dimensions of foundation (DOLSAR 2007)

3.2 Bridge's Piers and foundation

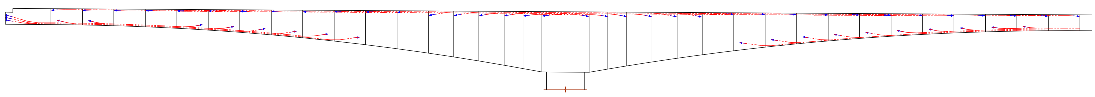
Berta Bridge has two piers, one with a height of 109.245 m at 22 + 511.598 km and the other 85.193 m at 22 + 676.598 km. Piers have 9.00 × 7.00 m^2 and 7.00 × 6.00 m^2 cross section areas, respectively. Each pier is located on individual footing which has 6.00 m height. Bridge's foundations have 33.00 × 30.00 m^2 and 27.00 × 27.00 m^2 cross section areas, respectively. The concrete compressive strength in the foundation is 40 MPa. In the foundation, S420 reinforcement steel is used. The dimensions of the piers and the foundations are shown in Figs. 6 and 7, respectively.

4. Finite element analyses and analytical dynamic characteristics

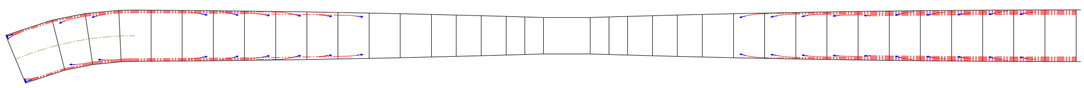
Three dimensional finite element model of the bridge is created using SAP2000 (2008) software to obtain dynamic characteristics (natural frequencies and mode shapes) analytically. The finite element model of the bridge is built using the criteria given below.



(a) Plan of box girder top floor



(b) Front elevation



(c) Plan of box girder bottom floor

Fig. 8 General layout plan of the post-tension cables (DOLSAR 2007)

Table 1 Spring coefficients used in the initial analytical model

Boundary Conditions	Spring Parameters (kN/m)		
	Longitudinal	Transverse	Vertical
Right Abutment	100000	100000	-
Left Abutment	100000	100000	-

- Bridge deck and piers are modelled using frame elements which have 6 degrees of freedom. Each superstructure segments have variable height drawn according to the project data.
- While finite element model is created, 208 nodal points and 97 frame elements are used.
- Post-tension cables are modelled using frame elements constrained to rotation and fixed to the end of each segment. Post-tension loads are considered as strain. General layout plan of the post-tension cables are shown in Fig. 8.
- Each pier are divided to 10 finite elements and the superstructure segments are divided in to element which are of 0.5 m length.
- Abutments are modeled as springs which have significant rigidity. Thus, the vertical freedom of the abutments is taken exactly but the freedom of other directions is modelled such that the rotations aren't allowed. Spring coefficients used in the initial analyses are shown as in Table 1.

The material properties used in the analyses are taken as shown in Table 2. The three dimensional finite element model is shown in Fig. 9.

The first five mode shapes obtained from the initial analytical analyses of the Berta Bridge is given in Fig. 10. The analytical mode shapes can be classified as the vertical, the transverse and the longitudinal modes.

Table 2 Material properties used in the analytical model (DOLSAR 2007)

Material	Material properties			Concrete class
	Elasticity modulus (N/m^2)	Poisson ratios (-)	Weight per unit volume (kg/m^3)	
Deck	3.430E10	0.2	2450	C40
Piers	2.895E10	0.2	2450	C30
Foundations	2.895E10	0.2	2450	C30
Pre-stress elements	1.95E11	-	-	-

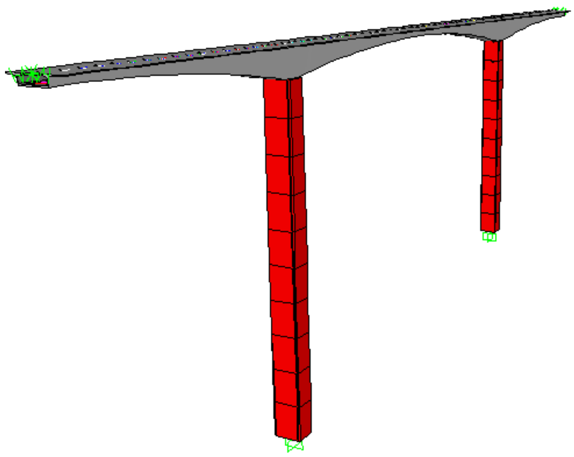
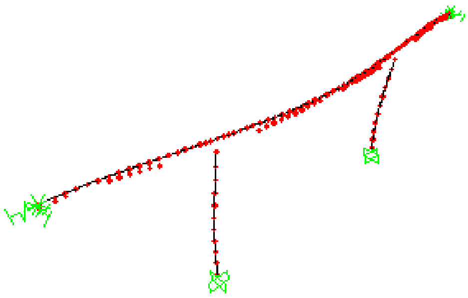
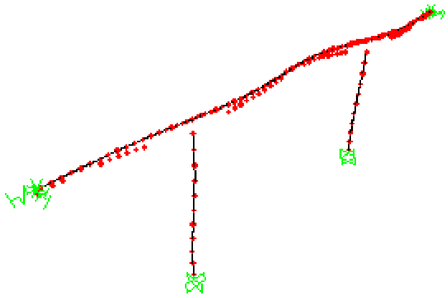


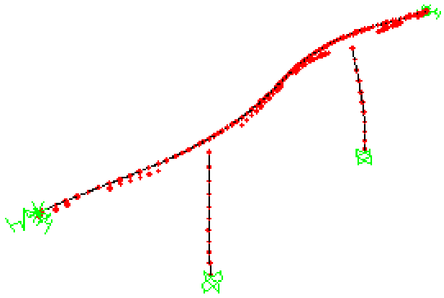
Fig. 9 Three-dimensional view of the finite element model of Berta Bridge



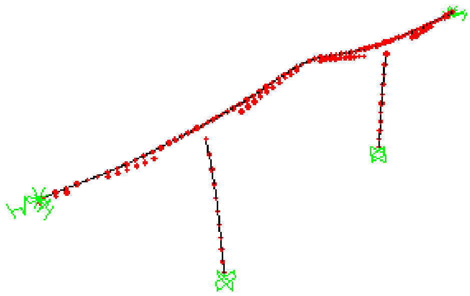
(a) Transversal (f_1 = 0.394 Hz)



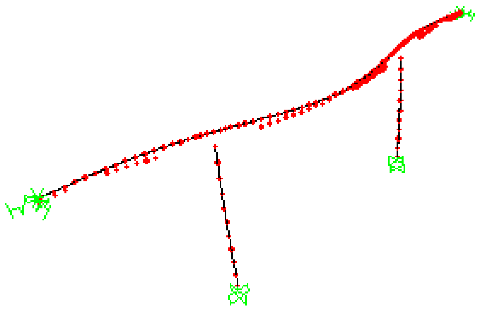
(b) Longitudinal (f_2 = 0.677 Hz)



(c) Transversal (f_3 = 0 .722 Hz)



(d) Vertical (f_4 = 0.954 Hz)



(e) Transversal (f_5 = 1.310 Hz)

Fig. 10 The first five mode shapes analytically identified

5. Ambient vibration tests and experimental dynamic characteristics

Finite element method is used to determine the dynamic characteristics but the method doesn’t inform about the real behaviour of structures due to uncertainties in models. There are inaccurate estimations of material and geometrical properties, poor approximation of boundary conditions and inadequate modelling of joints and nonlinearities, damping mechanisms, and coupling effects that are not taken into consideration in the finite-element model. Due to these reasons, the experimental methods are used to verify analytical dynamic characteristics. In this study, the ambient vibration test which is also called the Operational Modal Analysis (OMA) is performed to determine the natural frequencies, the mode shapes and the damping ratios of Berta Bridge.

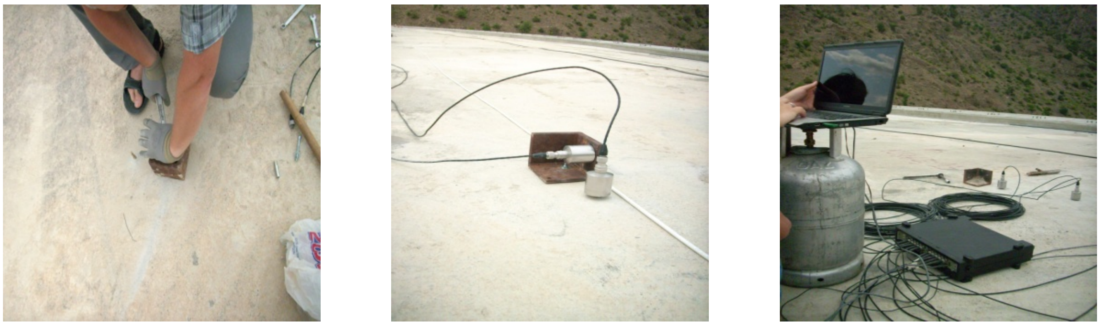


Fig. 11 Used equipment in measurements

In the ambient vibration tests, B&K 8340 type uni-axial, B&K 3560 data acquisition system with 17 channels, uni-axial signal cables and a laptop were used (Fig. 11). The minimum frequency span and the sensitivity of the accelerometers are 0.1–1500 Hz–10 V/g for B&K 8340, respectively. The signals are acquired in the B&K 3560 type data acquisition system and then transferred into the PULSE (2006) Lapshop software. To estimate parameters from the ambient vibration survey data, the Operational Modal Analysis (OMA 2006) software is used. The dynamic characteristics of Berta Bridge were extracted by EFDD and SSI methods. Measurements are performed in the range of 0-12.5 Hz and analyses in the range of 0-3.125 Hz. due to the fact that frequency span of bridge isn't known exactly. Measurement duration was 20 minutes.

Referenced measurement is carried out because the selected point numbers to take measurements are more than the number of channels in the data acquisition system and the available accelerometer numbers. Berta Bridge was divided into two symmetrical parts, Artvin and Erzurum, so that the dynamic characteristics of both parts are determined and compared with each other. After accelerometers are connected at station where are taken measurement on the bridge, adjustments of data acquisition system (selected frequencies span, formed connection of model and accelerometer, determined measurement duration etc.) is set and the measurements are taken. In the middle of bridge, one accelerometer was used as a reference accelerometer and its location was not changed throughout the tests. Other accelerometers were connected along to the bridge deck both vertically to obtain vertical modes of bridge and transversely to obtain transverse modes of bridge. Wind and human loads are considered an ambient vibration.

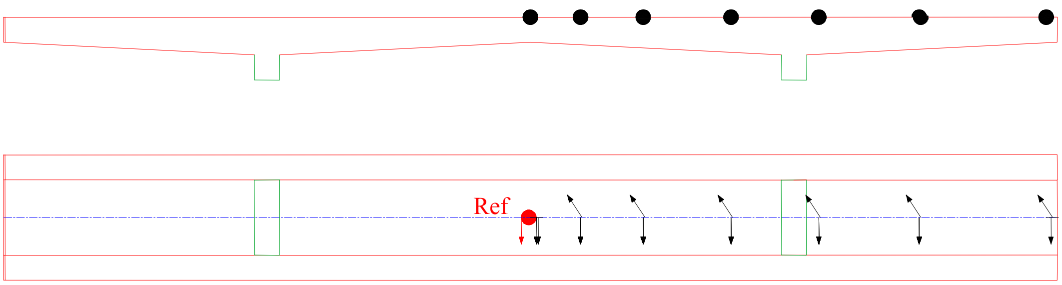
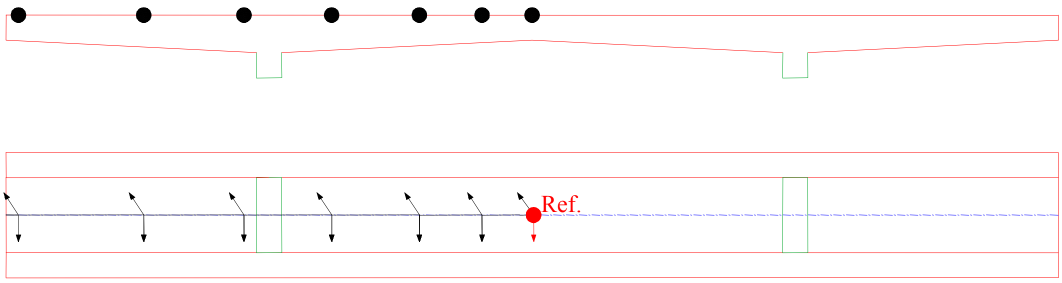


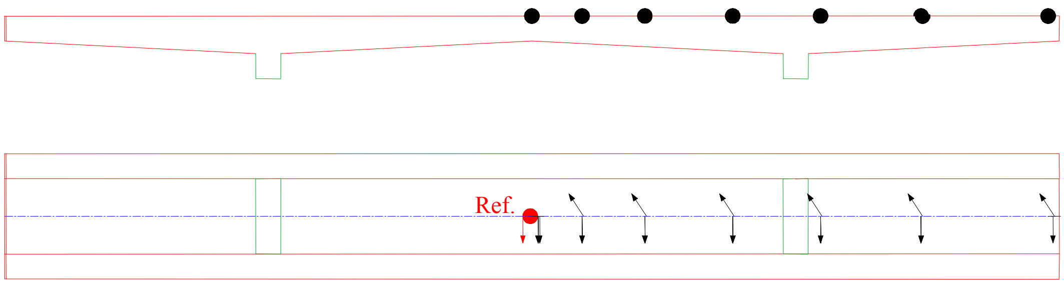
Fig. 12 Plan of accelerometer at the first test setup

In the first test setup, Erzurum part of the bridge was measured with a total of 13 accelerometers (reference excepted) on the deck of bridge. Middle point of bridge is a common point for both part of the bridge (Artvin-Erzurum) therefore; accelerometer at this point was placed at vertical direction in this setup (Fig. 12).

In the second test setup, Artvin part of the bridge was measured with a total of 14 accelerometers (one accelerometer is a reference) on the deck of bridge (Fig. 13). Accelerometers were placed in a symmetrical manner but the accelerometer at the center was placed at transverse direction in this setup (Fig. 13). Some photographs which are related to the measurement of the Berta Bridge are given Fig. 14.



(a)



(b)

Fig. 13 Plan of accelerometer at the second test setup

Fig. 14 Photographs from Berta Bridge

Fig. 14 Photographs from Berta Bridge

At the experimental measurements in this study, the Enhanced Frequency Domain Decomposition (EFDD) and the Stochastic Subspace Identification (SSI) methods were implemented in the Operational Modal Analysis (OMA) software and were used to obtain the dynamic characteristics of Berta Bridge. Obtained data from experimental measurement results were given by using of EFDD and SSI methods in below.

5.1 Enhanced Frequency Domain Decomposition (EFDD) method

The Operational Modal Analysis is carried out by using the EFDD method in the frequency domain. In the EFDD method, the dynamic characteristics are obtained from each vibration signal using the singular values as shown in Fig. 15.

The mode shapes obtained from the experimental measurements of the bridge is given in Fig. 16.

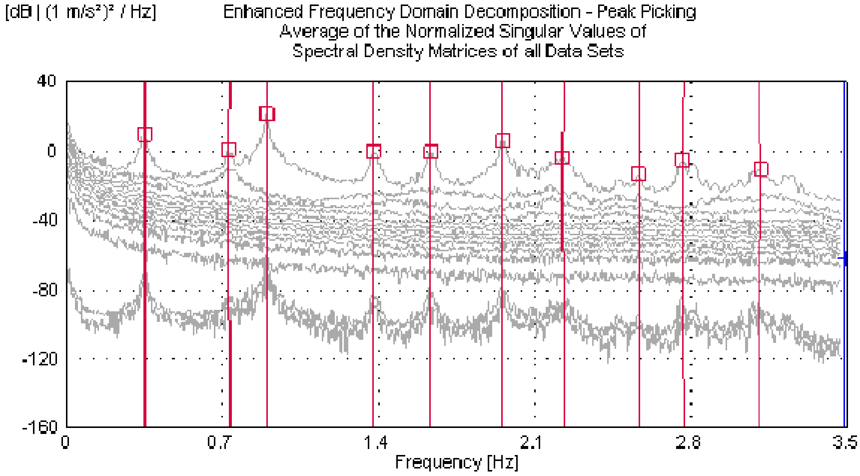
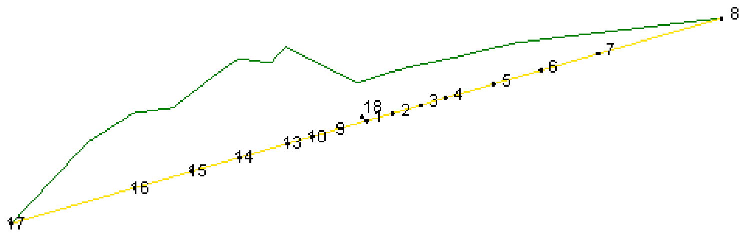
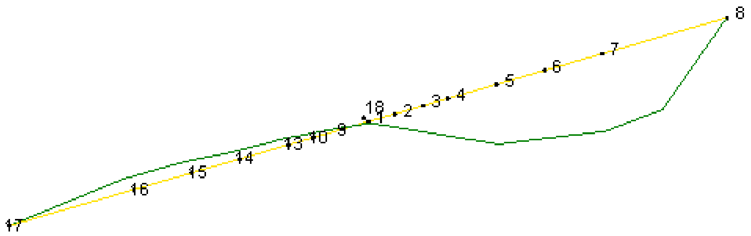


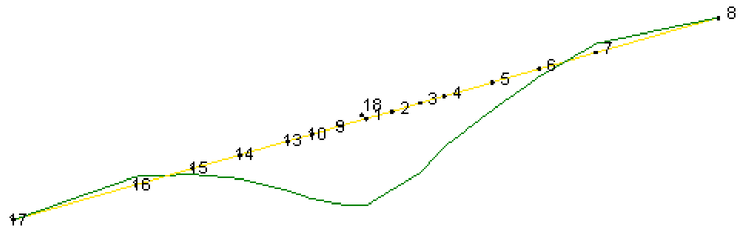
Fig. 15 Singular values of spectral density matrices



(a) (f_1 = 0.352 Hz) 1st Transverse mode

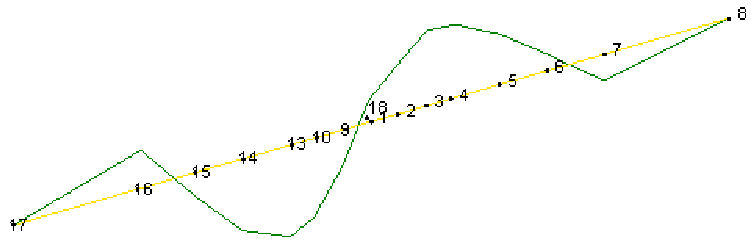


(b) (f_3 = 0.737 Hz) 2 nd Transverse mode



(c) (f_4 = 0.899 Hz) 1st Vertical mode

Fig. 16 Identified mode shapes using the EFDD method



(d) (f_5 = 1.382 Hz) 2nd Vertical mode

Fig. 16 Continued

5.2 Stochastic Subspace Identification (SSI) method

The Operational Modal Analysis is carried out using the SSI method in the time domain. In the SSI method, the dynamic characteristics are obtained from vibration signals using the singular values are shown in Fig. 17.

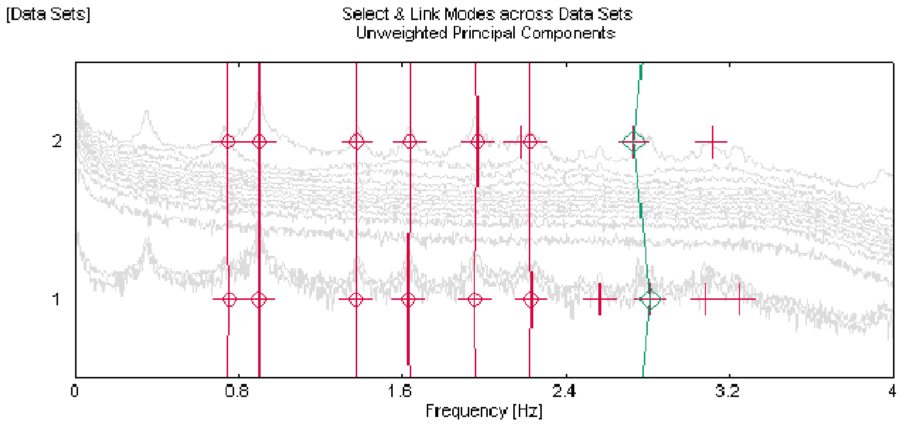
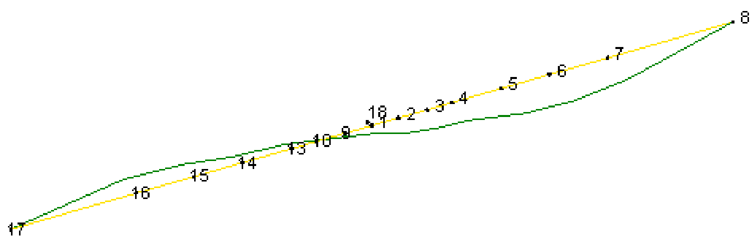
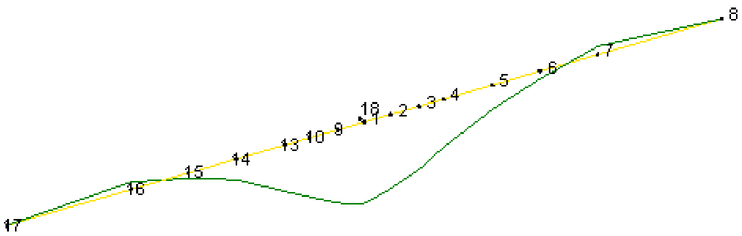


Fig. 17 Singular values of the spectral density matrices

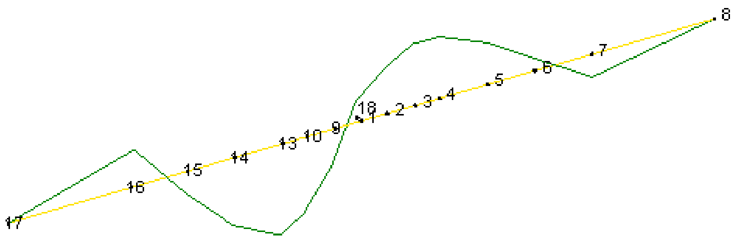


(a) (f_3 = 0.748 Hz) 3rd mode- transverse

Fig. 18 Identified mode shapes obtained using SSI method



(b) (f_4 = 0.900 Hz) 4th mode- vertical



(c) (f_5 =1.374 Hz) 5th mode - vertical

Fig. 18 Identified mode shapes obtained using SSI method

Table 3 Comparison of analytically and experimentally identified dynamic characteristics

Mode number	Analytical frequencies	EFDD Method		SSI Method	
		Frequency (Hz)	Damping ratio (%)	Frequency (Hz)	Damping ratio (%)
1	0.394	0.352	2.158	-------	-------
2	0.677	--------	0.260	-------	-------
3	0.722	0.737	0.571	0.748	1.639
4	0.954	0.899	0.688	0.900	0.369
5	1.310	1.382	0.678	1.374	0.974

The mode shapes obtained from the experimental measurements of the bridge are given in Fig. 18.

When Figs. 16 and 18 are investigated, the models using the EFDD and the SSI methods are very similar. Comparison of the dynamic characteristics of the Berta Bridge obtained from analytical modal analysis using SAP2000 (2008) software and the experimental measurements (EFDD and SSI) are given in Table 3. When Table 3 is examined, frequency values obtained are in agreement.

6. Finite element model updating

When the analytically and experimentally identified dynamic characteristics are compared with each other, it is apparent that there is good agreement between the mode shapes but some differences are observed between natural frequencies. Trial and error method which is one of the updating methods is used to update the bridge model. The finite element model of the bridge should be updated by changing the uncertain modelling parameters such as the material properties and the boundary conditions to eliminate and reduce these differences between the natural frequencies:

6.1 Updating of the material properties

The material properties are modified to eliminate these differences. The changes in the material properties (the modulus of elasticity and the density) for the updated finite element model are shown in Table 4.

6.2 Updating of the boundary conditions

In the initial finite element model of the Berta Bridge, the boundary conditions of the edge abutments are modelled using springs which have high stiffness. These springs are placed the transverse and longitudinal directions of bridge. In the updated finite element model, springs are

Table 4 Change in the material properties for the updated finite element model

(a) Change in the modulus of elasticity

Elements	Class	Modulus of elasticity (N/m^2)	
		Before model updating	After model updating
Deck	C40	3.430E10	3.6E10
Piers	C30	2.895E10	3.4E10
Foundation	C30	2.895E10	3.4E10

(b) Change in the density

Elements	Class	Density (kg/m^3)	
		Before model updating	After model updating
Deck	C40	2450	2500
Piers	C30	2450	2500
Foundation	C30	2450	2500

Table 5 Spring parameters for edge abutments

Spring parameters (kN/m)	Boundary conditions			
	Before abutment		Left abutment	
	Before model updating	After model updating	Before model updating	After model updating
Longitudinal	100000	400000	100000	400000
Transverse	100000	120000	100000	120000
Vertical	---	70000	---	70000

Table 6 Spring parameters for foundation

Boundary conditions	Spring Parameters (kN/m^3)		
	Longitudinal	Transverse	Vertical
Right foundation	20000	20000	20000
Left foundation	20000	20000	20000

modeled in the transverse, the longitudinal and the vertical directions of bridge and the displacements in these directions are permitted but are not free exactly. Also rotations aren't allowed in both directions.

Foundations are selected as another boundary condition. In the initial finite element model of the Berta Bridge, the foundations are modeled fixed. But, in the finite element model updating, the foundations are identified as shell element which have height of 6 m, cross sections of 33×30 m^2 and 27×27 m^2, respectively. And they are placed under the piers. Also, springs are placed under foundation all directions (transverse, longitudinal, vertical) to provide foundation-soil interaction and its value is selected as 20000 given in Table 6.

7. Comparison of the results of the finite element model updating

Three dimensional updated finite element model including all of the updating parameters is given Fig. 19.

The analytical mode shapes obtained from the updated finite element model match the experimental mode shapes well and they are given Fig. 20.

The analytical frequencies, the updated frequencies and the experimental frequencies of the Berta Bridge are given in Table 7, comparatively. While before the difference between initial analytical and experimental frequencies becomes 2-11%, after model updating the difference becomes 0.2-6%.

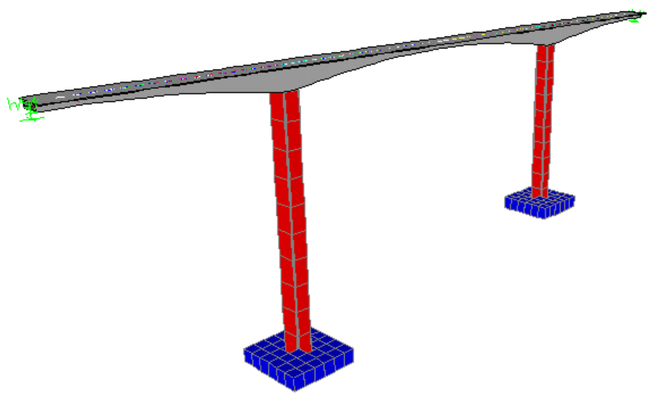
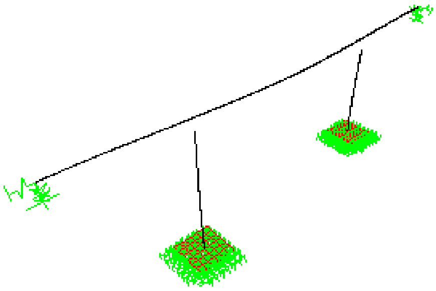
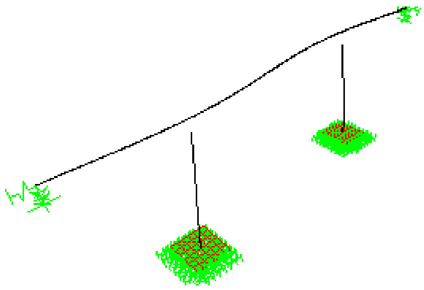


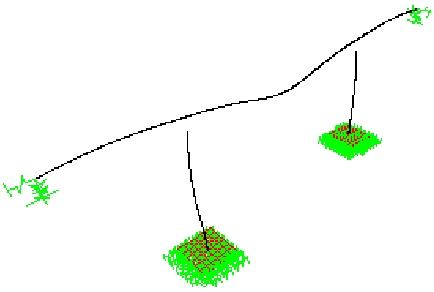
Fig. 19 Three dimensional updated finite element model



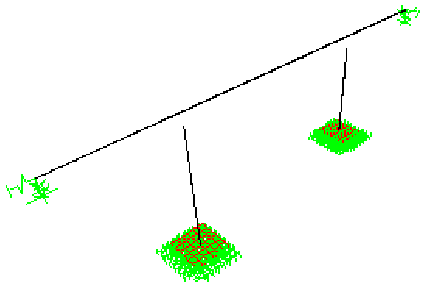
(a) Transverse (f_1 = 0.375 Hz)



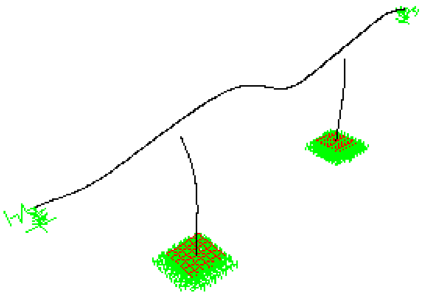
(b) Transverse (f_2 = 0.718 Hz)



(c) Vertical (f_3 = 0.897 Hz)



(d) Longitudinal (f_4 = 1.164 Hz)



(e) Vertical (f_5 = 1.350 Hz)

Fig. 20 The first five mode shapes obtained from the updated finite element model

Table 7 Differences between analytical and experimental dynamic characteristics

Mode	Initial analytical Frequencies (Hz)	Updated analytical Frequencies (Hz)	Experimental Frequencies (Hz)	Differences (%)	
				Before model updating	After model updating
1	0.394	0.375	0.352	11	6
2	0.677	0.718	0.737	---	3
3	0.722	0.897	0.899	2	0.2
4	0.954	1.164	------	6	---
5	1.310	1.350	1.382	3	2

8. Conclusions

The aim of this paper is determining the dynamic characteristics of long reinforced concrete highway bidges with height piers by using ambient vibration data. Berta Bridge which located on the Artvin-Erzurum highway is selected and the dynamic characteristics were determined using finite element analyses and ambient vibration tests. Three dimensional finite element model is constituted by using SAP2000 (2008) software and the analytical dynamic characteristics are determined. The experimental measurements are carried out by Operational Modal Analysis (OMA) under wind and human loads and experimental dynamic characteristics are determined. Finite element model of the bridge was updated by changing the design variables such as the material properties (modulus of elasticity and density) and the boundary conditions. The results of this study show that:

- The first five natural frequencies of the Berta Bridge are between 0.394-1.310 Hz from initial analytical modal analysis and 0.352-1.382 Hz from the ambient vibration test.
- The damping ratios vary between 2.158-0.688%.
- The mode shapes from finite element analyses and experimental measurement tests of Berta Bridge are in agreement with each other. The First and the third modes are the transverse, fourth and fifth modes are vertical. Also second analytical mode is obtained as a longitudinal mode. But, in the experimental measurements, corresponding longitudinal mode isn’t obtained due to any accelerometer isn’t put in longitudinal direction.
- When natural frequencies of the Berta Bridge are examined, it becomes apparent that there are differences among the frequencies. Therefore, to minimize the differences, the finite element model of the bridge was updated by adjusting the material properties and the boundary conditions. The differences between the frequencies decreased from 2-11% to 0.2-6%.
- As a result of decomposition of signals according to EFDD and SSI methods, similar dynamic characteristics are obtained. This shows that the EFDD and SSI methods are in agreement with each other.
- It is stated that the Operational Modal Analysis based on the ambient vibration data can be used safely for determining the dynamic characteristics of long reinforced concrete highway bridges with height piers.

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