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Experimental identification of box girder bridge model under undamaged and damaged conditions considering time effect

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Abstract. In this paper, it is aimed to evaluate the structural behavior of box girder bridge model under undamaged and damaged conditions considering time effect between June 2009 and February 2015 using ambient vibration tests. For this purpose, a scaled bridge model is constructed and experimental measurements are performed to determine the damage and time effect on dynamic characteristics such as natural frequencies, mode shapes and damping ratios. In the ambient vibration tests, natural excitations are provided and the response of the bridge model is measured. 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. Measurement time, frequency span and effective mode number are selected by considering similar studies found in the literature. To expose the damage and time effect on dynamic characteristics, four experimental measurement cases are considered between 2009 and 2015. The first measurement case is conducted on June 2009 under undamaged conditions. The second and third measurement cases are performed on October 2010 under undamaged and damaged conditions to emerge the damage and time effect, respectively. The fourth measurement tests are carried out on February 2015 to display the time effect on the dynamic characteristics considering same damage condition in third measurements. At the end of the study, experimentally identified dynamic characteristics are compared with each other to investigate the damage and time effects. 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. Maximum differences obtained as 11.98% and 112.24% between Case 1 and Case 2, 10.30% and 26.24% between Case 2 and Case 3, 12.36% and 401.50% between Case 3 and Case 4 for natural frequencies and damping ratios, respectively. It is seen that damages and environmental conditions affect the structural behavior of concrete bridges, substantially. Also, time dependent environmental conditions such as temperature, humidity and ageing are as important as cracks and damages.

Keywords: ambient vibration; bridge model; damage effect; dynamic characteristic; enhanced frequency domain decomposition; operational modal analysis; stochastic subspace identification; time effect

1. Introduction

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The reinforced concrete highway bridges are subject to different time dependent environmental conditions such as over design traffic loads, accident, fire, temperature, humidity, water effect, excitation amplitude and ageing. The dynamic characteristics are often sensitive to changing these effects, which will cause changes in the structural response. Therefore, to determine the real performance of structures for bridges, it is of paramount importance to characterize normal variability of the dynamic characteristics due to time dependent environmental effects (Bayraktar *et al*. 2014; Altunışık *et al*. 2015).

Beside the environmental effects, one of the most important parameters is damages and cracks for changing of dynamic characteristics. If a structure is damaged, the structural behavior is changed depending on location and size of damage. The changes come up in the natural frequencies, mode shapes and modal damping ratios that are the dynamic characteristics of structures. Natural frequencies and mode shapes are key parameters for studying the structural dynamic behavior; they are often treated as constants for undamaged structures (Türker and Bayraktar 2014).

There are two basically different methods available to experimentally identify the dynamic system parameters of a structure: Experimental Modal Analysis (EMA) and Operational Modal Analysis (OMA). In the EMA, 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 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.

Last two decades, some researchers have investigated to damage effect on the structural behavior of bridges using experimental measurement tests (Lee and Yun 2006; Zhang 2007; Ventura and Carvajal 2011; Bahlous *et al*. 2013; Tondreau and Deraemaeker 2014). Also, some papers are presented about the damage effect on the behavior of bridges by using finite element analysis (Alos-Moya *et al*. 2014; Caterino *et al*. 2014; Wang *et al*. 2014). Beside these studies, some papers are published about the crack and damage effect on the response of other engineering structures such as buildings, dams, masonry and steel structures, vaults, towers and silos using experimental and analytical methods (Gentile and Saisi 2007; Ramos *et al*. 2010; Shiradhonkar and Shrikhande 2011; Çalık *et al*. 2014).

It can be easily seen that there are many papers about the structural identification, finite element analyses, damage detection applying different techniques and dynamic analyses of structures. But, there are no enough studies about the changing of dynamic characteristics with environmental condition effect by time. Some questions such as how to change the dynamic characteristics under undamaged and damage conditions at different times to display the damage effect using ambient vibration test remain unanswered in the literature. Also, there is not enough information about which parameter more effective such as damage or environmental condition with time on dynamic

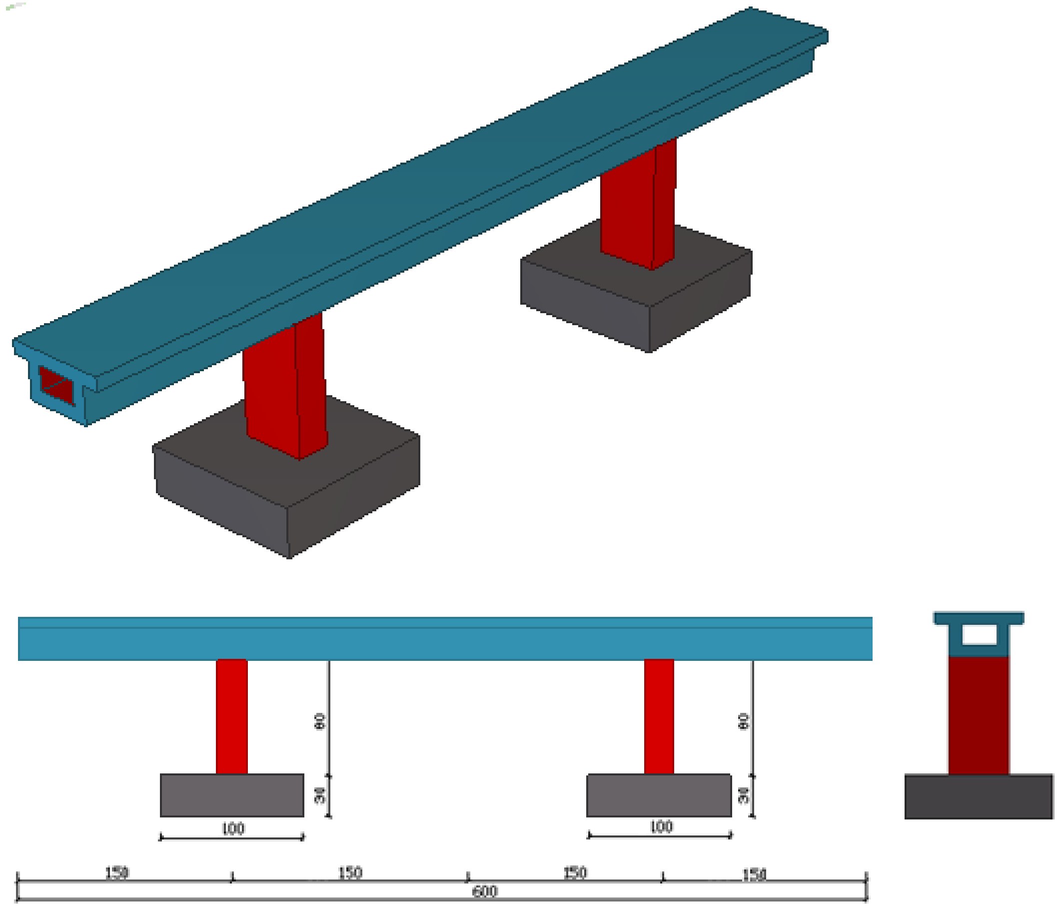


Fig. 1 Basic configuration of bridge model (all dimensions are in cm)

characteristics. For this reasons, in this paper, it is aimed to evaluate the structural behavior of box girder bridge model under undamaged and damaged conditions after nearly six years interval between June 2009 and February 2015 to expose the damage and environmental condition effects.

2. Description of the scaled bridge model

The bridge model, which has reinforced concrete box girder carrier system, consists of 3.0m main span and 1.5m two side spans. The total length and width of bridge deck is 6.0m and 60cm, respectively. When the structural dimensions of real concrete highway bridges constructed with balanced cantilever method are examined, it can be said that 1/50 scale factor is considered for deck length. But, when the same scale factor is selected, the box girder height and wall thickness are calculated as 0.02-0.10m. These values are very small for reinforced concrete models. So, the different scale factor is selected for box girder section. Each column has 80cm height and

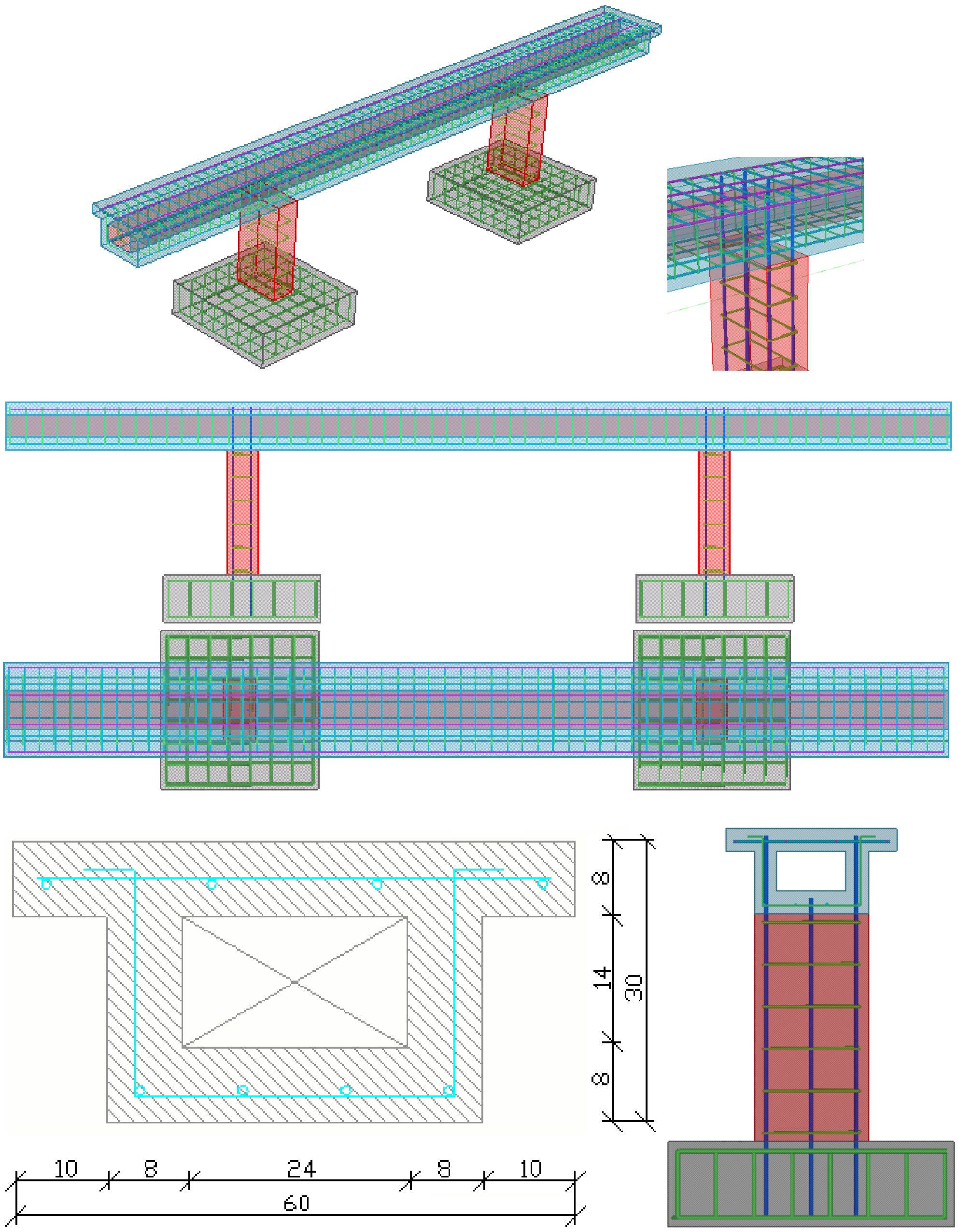


Fig. 2 Steel reinforcement details for each structural element (all dimensions are in cm)

$20 \times 40 cm^2$ cross section areas. 1/50 scale factor is considered for columns. Piers are footing on the raft foundation (dimension of $1 \times 1 m^2$ and 30cm depth) to ensure the fixed boundary condition as

Fig. 3 Some views of the bridge model

Fig. 4 Some view from the samples and compression tests

possible (Altunışık 2010). Fig. 1 shows the basic configuration of the bridge model. The superstructure of the bridge is a continuous single cell box girder. 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 members are constant as 8cm. Fig. 2 Steel reinforcement details for each structural element.

The bridge model was constructed considering dimensions given in Figs. 1 and 2 (Fig. 3). To determine the material characteristics of concrete, the cylindrical and cubic samples were taken during cast in place and experimental studies were conducted at laboratory. Fig. 4 shows some view from the samples and compression tests. The stress-strain diagrams are given in Fig. 5. The failure loads, related compression strengths and material properties considered in the analyses are summarized in Tables 1-3.

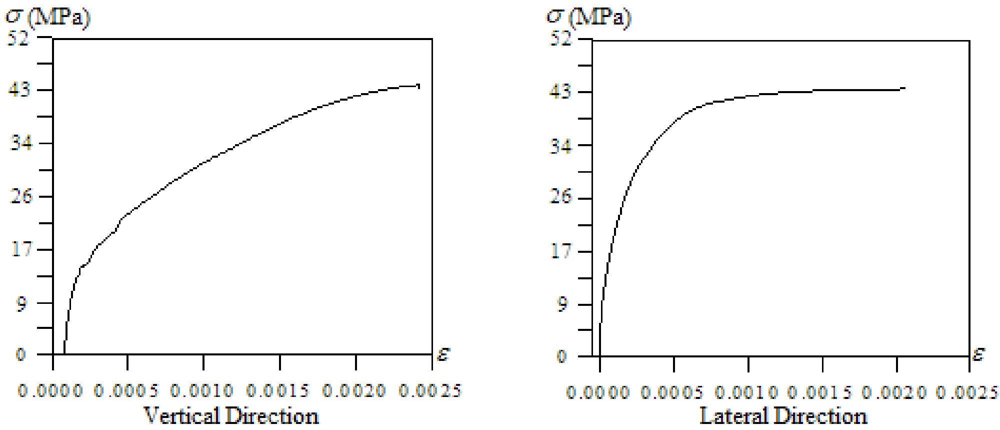


Fig. 5 The stress-strain diagrams attained from the sample compression tests

Table 1 Some properties of cubic samples attained from the uniaxial compression tests

Sample	Area (cm^2)	Volume (cm^3)	Age (Days)	Load (kgf)	Strength (f_{cubic})	
					(kgf/cm^2)	(MPa)
1	225	3375	7	62000	276	27.6
2	225	3375	7	71000	316	31.6
3	225	3375	28	74000	329	32.9
4	225	3375	28	88000	391	39.1

Table 2 Some properties of cylindrical samples attained from the uniaxial compression tests

Sample	Height (cm)	Diameter (cm)	H/D	Age (Days)	Load (N)	Strength (f_{cyl}) (MPa)	Elasticity Module (MPa)
1	30	15	2	28	460720	26.07	28500
2	30	15	2	28	606330	34.31	30000
3	30	15	2	28	614140	34.76	30000

Table 3 Material properties considered in the finite element analyses

Elements	Material Properties		
	Elasticity Module (N/m^2)	Poisson Ratio (-)	Density (kg/m^3)
Deck	2.85E10	0.2	2500
Columns	3.00E10	0.2	2500
Foundation	3.00E10	0.2	2500

3. Experimental measurements

Ambient vibration tests are conducted on bridge model to determine the damages and

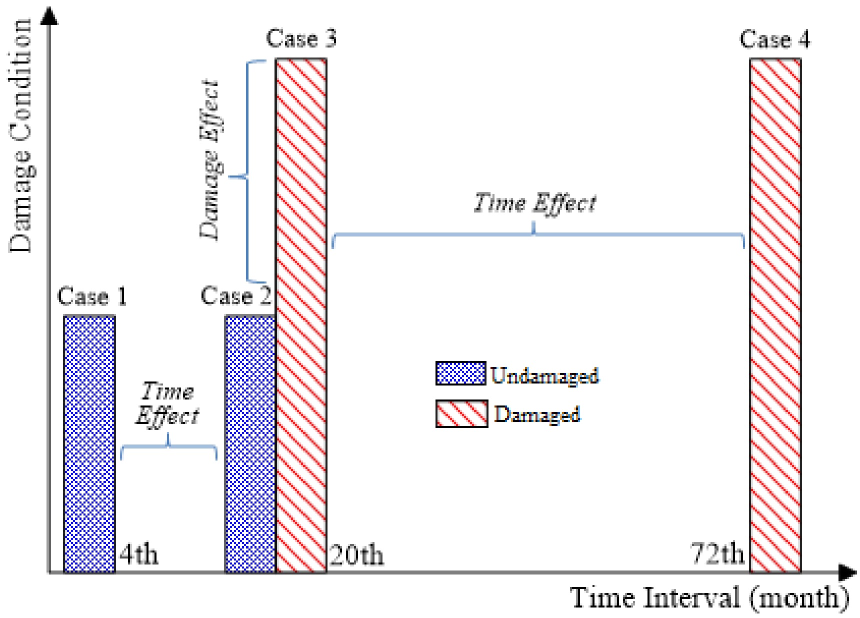


Fig. 6 The differences between the analyses case

environmental condition effects with time in dynamic characteristics such as natural frequencies, mode shapes and damping ratios. The experimental measurements performed for this purpose are grouped as follows:

• Case 1: Ambient vibration tests for undamaged condition on June 2009

• Case 2: Ambient vibration tests for undamaged condition on October 2010 to determine the environmental condition effect with time

• Case 3: Ambient vibration tests for damaged condition on October 2010 to determine the damage effect

• Case 4: Ambient vibration tests for damaged condition (no additional damage other than the ones performed on October 2010) on February 2015 to determine the environmental condition effect with time

The differences between 4 (four) analyses cases is indicated graphically in Fig. 6.

To extract the dynamic characteristics more accurately, selection of measurement equipment is very important. Because, accelerometer type, frequency span and test time, which are used for scaled bridge models, must not be used for highway bridges.

Ambient vibration tests are conducted on the bridge model between June 2009 and February 2015 for different scenarios to extract the natural frequencies, mode shapes and damping ratios under undamaged and damage conditions.

In the ambient vibration tests, B&K 3560 data acquisition system, B&K 4507 and B&K 8340 type uni-axial, B&K 4506 type three-axial accelerometers are 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 software is used (OMA 2006).

The dynamic characteristics of the model bridge are extracted by Enhanced Frequency Domain Decomposition (EFDD) and Stochastic Subspace Identification (SSI) methods.

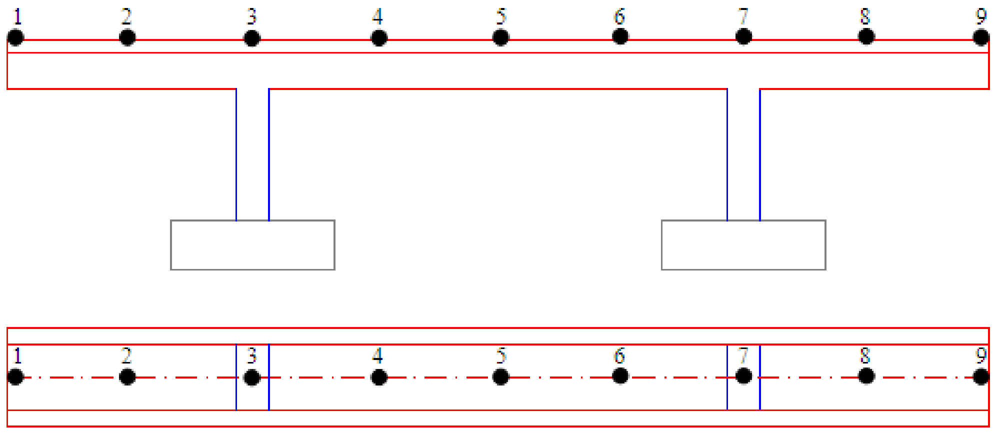


Fig. 7 Accelerometers locations on the bridge deck

Table 4 Measurement tests setups and accelerometers locations

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

3.1 Case 1: Ambient vibration tests for undamaged condition on June 2009

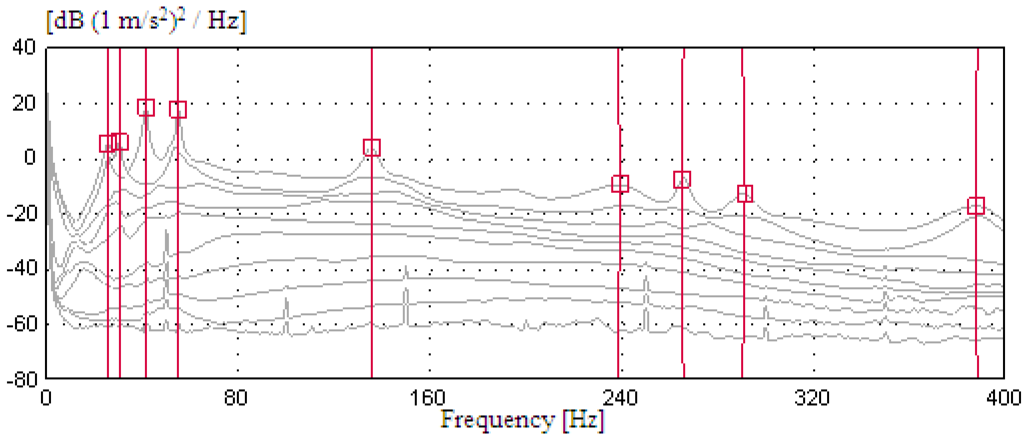
In the first measurements on June 2009 (Case 1), six ambient vibration tests are performed on the bridge deck. Nine special points are selected considering initial finite element analyses to obtain the mode shapes more accurately. B&K 4507 type uni-axial and B&K 4506 type three-axial accelerometers are used for measurements. These accelerometers have 1000mV/g sensitivity and 0.1-6000Hz frequency span. During the tests, the frequency span selected is 0-400Hz. Measurements occurred during five/fifteen-minute intervals, and impact hammer (B&K 8210 type impact hammer with 0.225 mV/N sensitivity, 22.2k (5000) N range full scale, 44.4k (10k) N maximum force, 22.2k (5000) N maximum compression and 0.5kHz frequency range) effects provided excitations. Experimental measurements are performed on the bridge model after poured concrete (outside the laboratory building) aged for 5 months with 20MPa compression strength under the influence of 65% humidity, averagely. The minimum and maximum temperature in Trabzon, Turkey is -15^{o}C and +35^{o}C, respectively.

Fig. 8 Some views from measurements on June 2009

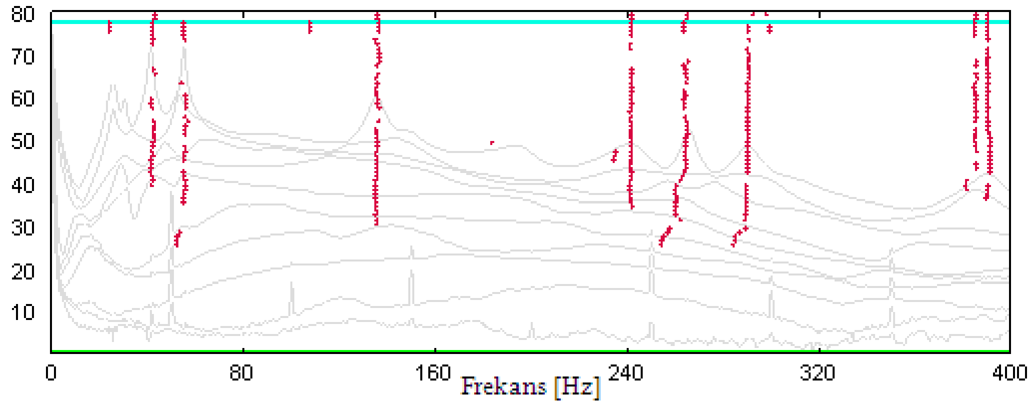
The detail information about the ambient vibration test of the bridge performed on June 2009 can be found in the literature (Altunışık *et al*. 2013). In this paper, the results are used as references parameters to display the damage and environmental condition effects on the dynamic characteristics such as natural frequencies, mode shapes and damping ratios with time. So, only one measurement results are given in this paper.

Accelerometers locations on the bridge deck are shown in Fig. 7. Table 4 summarizes details of six groups of measurements. Since the intended number of measurements was larger than the number of channels and sensors available, measurements are performed in three steps in the fourth and fifth test setups. The signals obtained from the each step are incorporated using a reference accelerometer. 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 experimental mode shapes obtained from all tests are compared with each other, it is seen that eight mode shapes are extracted from the combination of six measurements. Vertical and transverse mode shapes are determined more accurately from first and second tests, respectively. Longitudinal mode shapes were determined more accurately from third and fifth tests. Also, 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 OMA



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 on June 2009 (Case 1)

software by EFDD and SSI methods are given in Tables 5 and 6. The basic formulation of these methods can be available from the literature (Ewins 1984; Juang 1994; Brincker *et al.* 2000; Peeters 2000; Bendat and Piersol 2004; Yu and Ren 2005).

3.2 Case 2: Ambient vibration tests for undamaged condition on October 2010 to determine the environmental condition effect with time

In the second measurements on October 2010 (Case 2), ambient vibration tests are performed on the bridge deck for undamaged condition to determine the environmental condition effect with time on the dynamic characteristics. Fourteen special points are selected to obtain the mode shapes more accurately. B&K 8340 type uni-axial accelerometers are used for measurements at the vertical and transverse directions. These accelerometers have 1000mV/g sensitivity and 0.1-6000Hz frequency span. During the tests, the frequency span selected is 0-100Hz. Measurements occurred during ten minute intervals, and impact hammer effects provided excitations.

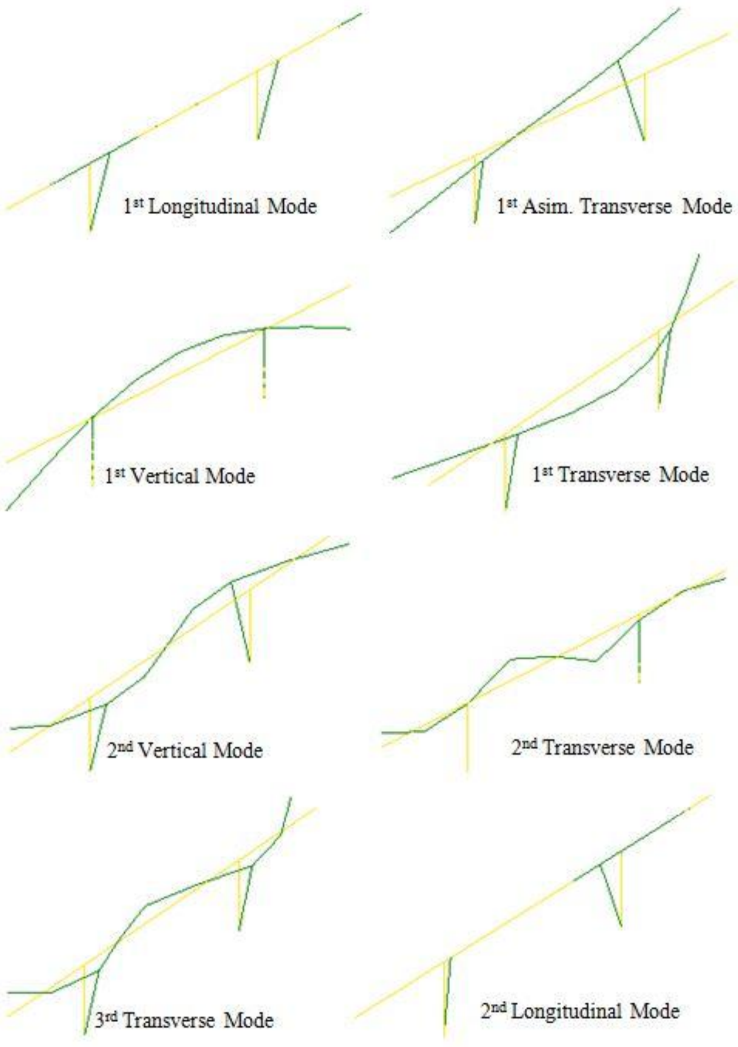


Fig. 10 The first eight mode shapes obtained from the experimental measurements conducted on June 2009 (Case 1) by using EFDD and SSI methods

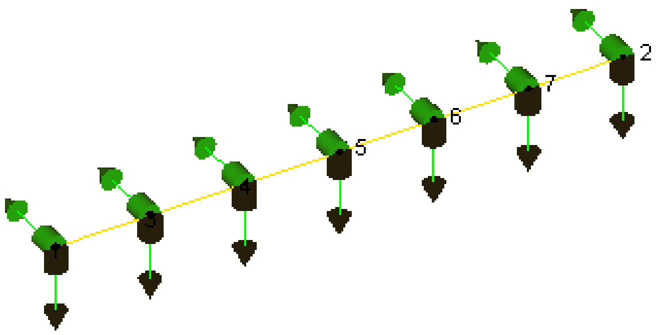


Fig. 11 Accelerometers locations on the bridge deck

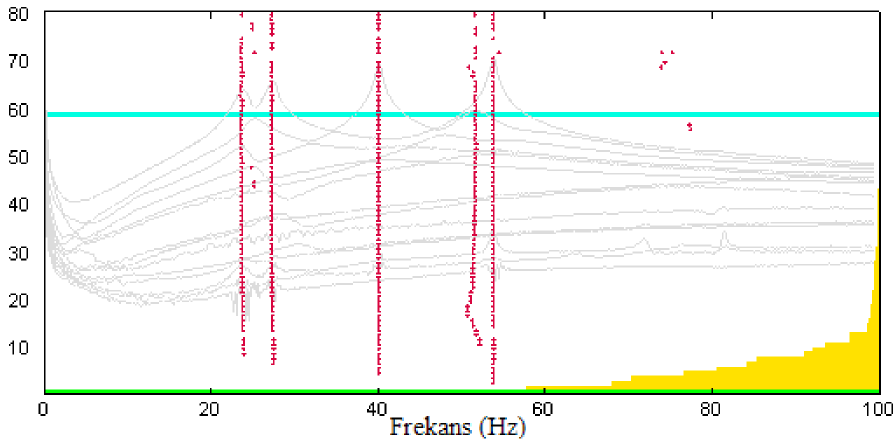
Table 5 Natural frequencies and damping ratios attained from experimental measurements conducted on June 2009 (Case 1) using EFDD method

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

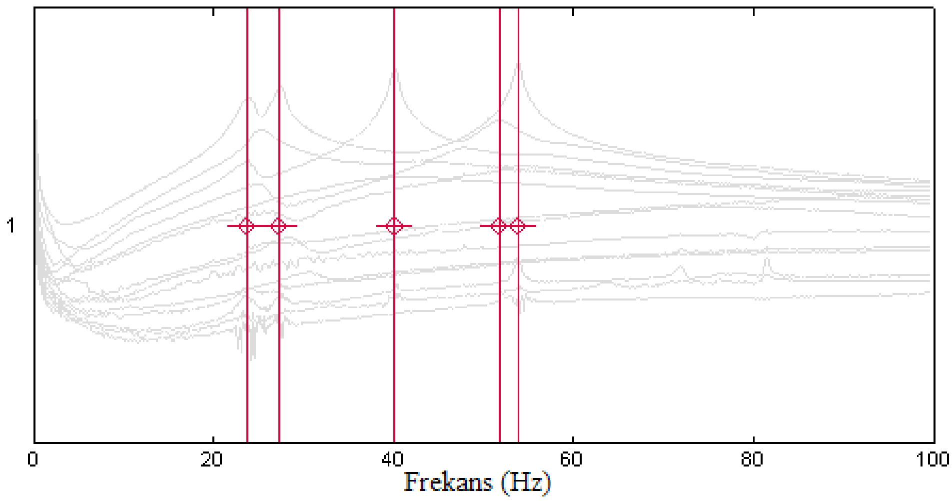
Table 6 Natural frequencies and damping ratios attained from experimental measurements conducted on June 2009 (Case 1) using SSI method

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

Fig. 12 Some views from measurements on October 2010



a) Stabilization diagram



b) Selected-linked modes across data sets

Fig. 13 Stabilization diagram of estimated state space models and selected-linked modes across data sets attained from the measurement test on October 2010 (Case 2)

Table 7 Natural frequencies and damping ratios attained from experimental measurements conducted on October 2010 (Case 2) using SSI method

Modes	Frequency (Hz)	Damping Ratio (%)
1	23.637	2.386
2	27.238	1.954
3	40.086	0.766
4	51.655	3.640
5	53.809	0.582

Table 8 Comparison of natural frequencies and damping ratios obtained from Case 1 and Case 2

Modes	Frequency (Hz)			Damping Ratio (%)		
	June 2009	October 2010	Max. Dif. %	June 2009	October 2010	Max. Dif. %
1	26.00	23.637	*10.00*	2.600	2.386	*8.97*
2	30.50	27.238	*11.98*	2.800	1.954	*43.30*
3	41.50	40.086	*3.53*	1.520	0.766	*98.43*
4	55.00	51.655	*6.48*	1.715	3.640	*112.24*

Accelerometers locations on the bridge deck are shown in Fig. 11. Some pictures from the measurements are shown in Fig. 12.

Stabilization diagram of estimated state space model and selected-linked modes across data sets are shown in Fig. 13. When the experimentally identified mode shapes are examined, it is seen that there is a good agreement and the mode shapes are obtained similar to June 2009 (Case 1) (Fig. 10). Natural frequencies and damping ratios obtained from the Case 2 using SSI method is are in Table 7.

To determine the environmental condition effect with time, the first four natural frequencies obtained from Case 1 and Case 2 compared with each other in Table 8. It is seen from the Table 8 that the first four natural frequencies are obtained between 26.00Hz and 55.00Hz for Case 1, 23.637Hz and 51.655Hz for Case 2. The first four damping ratios are obtained between 1.520% and 2.800% for Case 1, 0.766% and 3.640% for Case 2. There is not a suitable distribution for damping ratios obtained from both methods. Maximum differences between Case 1 and Case 2 obtained as 11.98% and 112.24% for natural frequencies and damping ratios, respectively. It is observed that dynamic characteristics such as natural frequencies and damping ratios changed considerably under environmental effects with time. More information about the finite element modelling, experimental measurements and finite element model updating of the bridge can be found in Türker's doctorate thesis (Türker, 2011)

3.3 Case 3: Ambient vibration tests for damaged condition on October 2010 to determine the damage effect

In the third measurements on October 2010 (Case 3), ambient vibration tests are performed on the bridge deck for damaged condition to determine the damage effect on the dynamic characteristics. For this purpose, two damage conditions (location and approximate size are

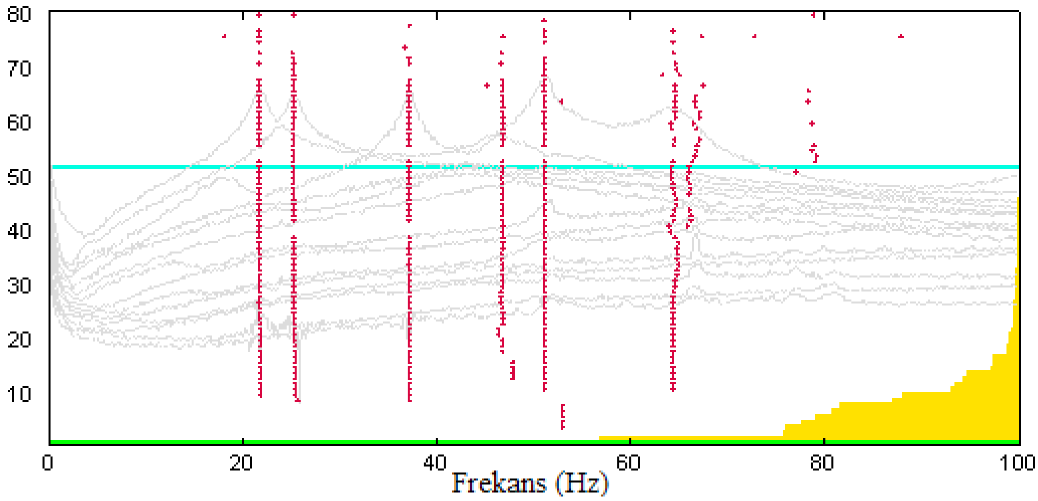
a) Sectional reduction at the top point of one column

b) Cracks along to the lateral direction on bridge deck

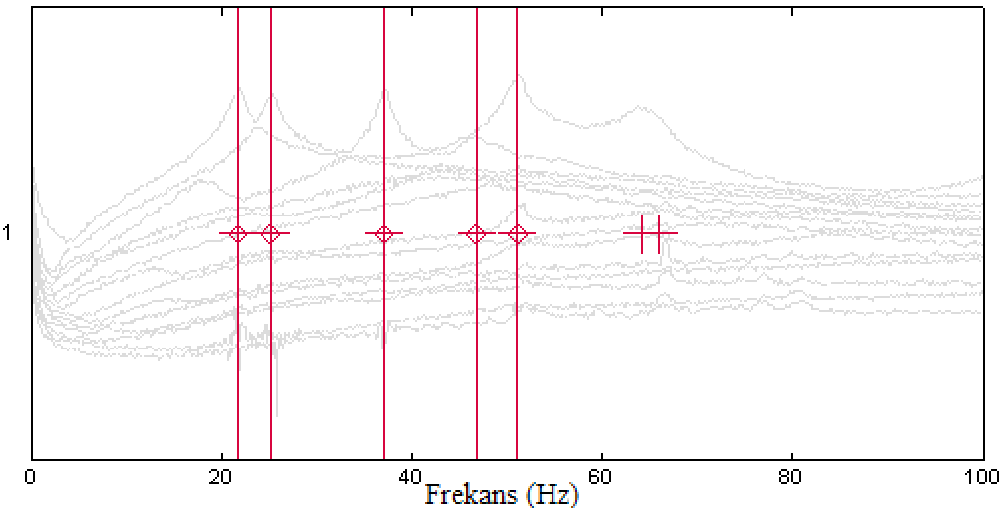
Fig. 14 Some views from two damage conditions considered in Case 3

known) are constituted on the bridge. In the first damage condition, sectional reduction is taken into account at the top point of one column by using breaker drill. In the second damage condition, it is assumed that the box girder bridge deck cracked along to the lateral direction at the contact point of damaged column and bridge deck. Measurement properties such as accelerometer type, locations, number, frequency span, time are considered similar to Case 2. Some pictures from the measurements are shown in Fig. 14.

Stabilization diagram of estimated state space model and selected-linked modes across data sets are shown in Fig. 15. Natural frequencies and damping ratios obtained from the Case 3 using SSI method is are in Table 9. The mode shapes obtained from Case 3 is given in Fig. 16. It is seen that first and second modes are obtained as symmetrical and asymmetrical transverse modes, respectively. Third and fourth modes are attained as vertical modes. Fifth mode is obtained as transverse mode. When the Fig. 10 (Case 1 and Case 2) and Fig. 16 (Case 3) compared with each other, it can be easily seen that there is not any agreement between mode shapes. The occurrence arrangements changed after damage and cracks. Also, the movements of the selected special mod points are not symmetrical and harmonic due to damage and cracks constituted at the one column and one section of the box girder deck.



a) Stabilization diagram



b) Selected-linked modes across data sets

Fig. 15 Stabilization diagram of estimated state space models and selected-linked modes across data sets attained from the measurement test on October 2010 (Case 3)

Table 9 Natural frequencies and damping ratios attained from experimental measurements conducted on October 2010 (Case 3) using SSI method

Modes	Frequency (Hz)	Damping Ratio (%)
1	21.716	2.363
2	25.181	2.232
3	37.127	0.967
4	46.830	4.353
5	51.091	1.071

Table 10 Comparison of natural frequencies and damping ratios obtained from Case 2 and Case 3

Modes	Frequency (Hz)				Damping Ratio (%)			
	June 2009	October 2010 Undamaged	October 2010 Damaged	Max. Dif. %	June 2009	October 2010 Undamaged	October 2010 Damaged	Max. Dif. %
1	26.00	23.637	21.716	*8.85*	2.600	2.386	2.363	*0.97*
2	30.50	27.238	25.181	*8.17*	2.800	1.954	2.232	*14.23*
3	41.50	40.086	37.127	*7.97*	1.520	0.766	0.967	*26.24*
4	55.00	51.655	46.830	*10.30*	1.715	3.640	4.353	*19.59*

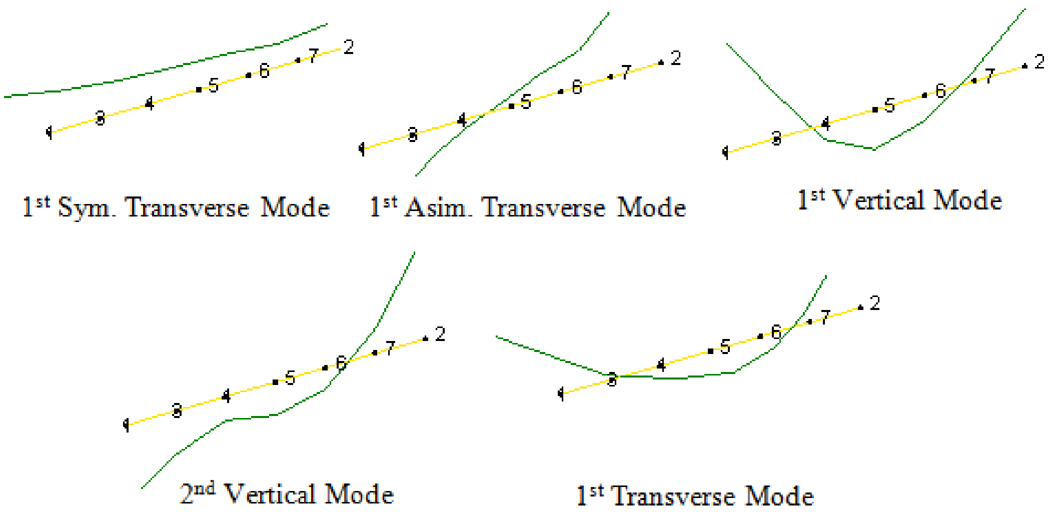
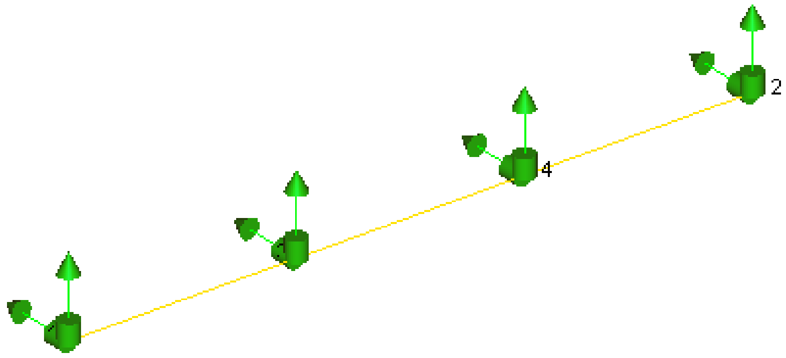


Fig. 16 The first five mode shapes obtained from the experimental measurements conducted on October 2010 (Case 3) by using SSI method

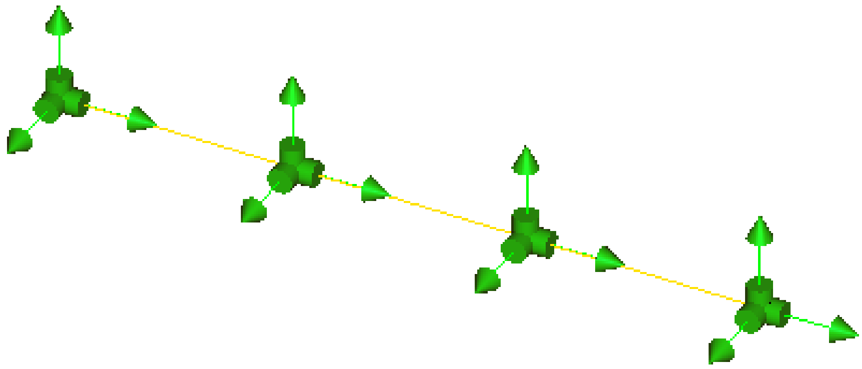
To determine the damage and cracks effects, the first four natural frequencies obtained from Case 2 and Case 3 compared with each other in Table 10. It is seen from the Table 10 that the first four natural frequencies are obtained between 23.637Hz and 51.655Hz for Case 2, 21.716Hz and 46.830Hz for Case 3. The first four damping ratios are obtained between 0.766% and 3.640% for Case 2, 0.967% and 4.353% for Case 3. There is not a suitable distribution for damping ratios obtained from both methods. The natural frequencies are reduced after damages and cracks. Maximum differences between Case 2 and Case 3 obtained as 10.30% and 26.24% for natural frequencies and damping ratios, respectively. It is observed that dynamic characteristics such as natural frequencies and damping ratios changed considerably after damages and cracks. More information can be found in Türker's doctorate thesis (Türker 2011).

3.4 Case 4: Ambient vibration tests for damaged condition on February 2015 to determine the environmental condition effect with time

In the fourth measurements on February 2015 (Case 4), ambient vibration tests are performed on the bridge deck for damaged condition to determine the environmental condition effect with

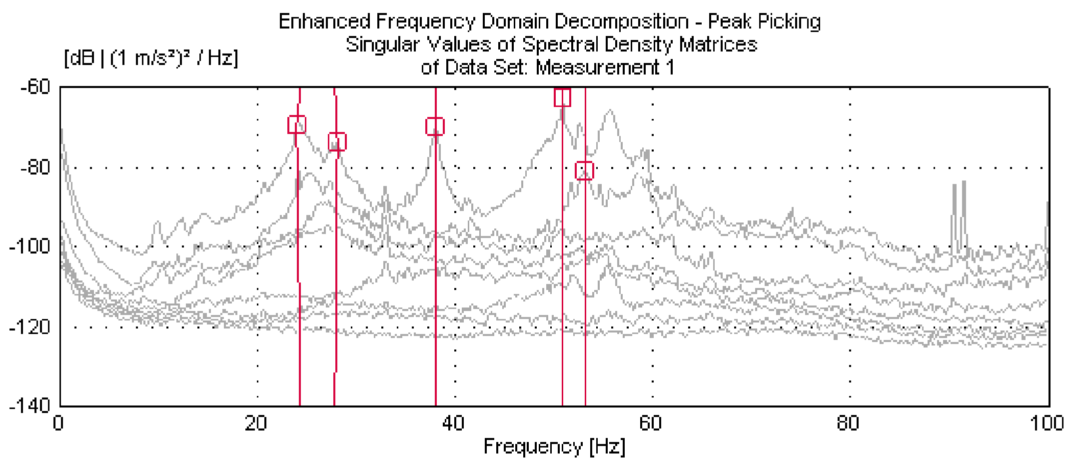


a) Accelerometer location for first measurement



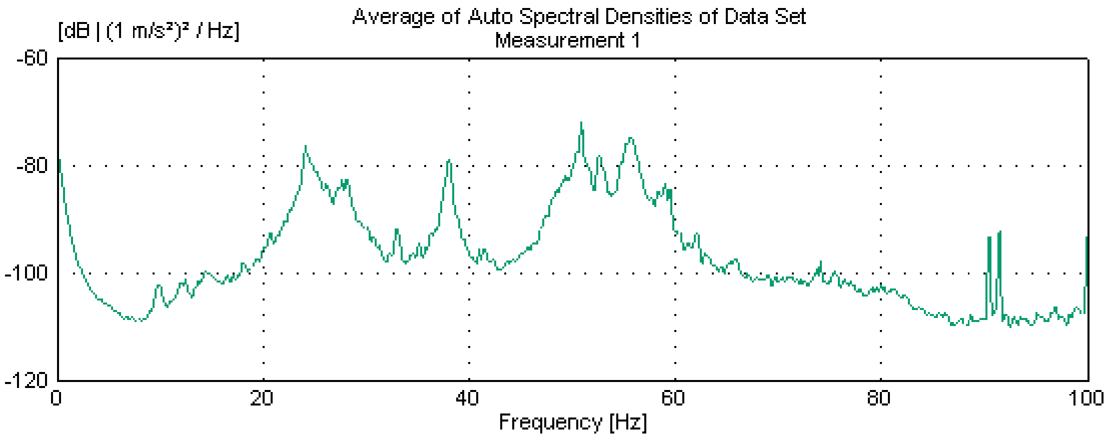
b) Accelerometer location for second measurement

Fig. 17 Accelerometers locations on bridge deck for first and second test setups of Case 4

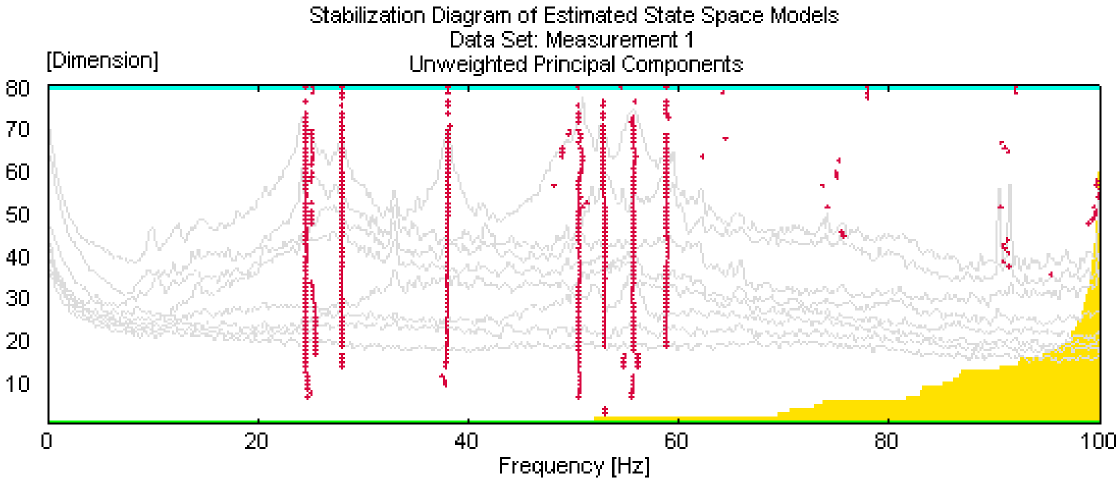


a) SVSDM of data set

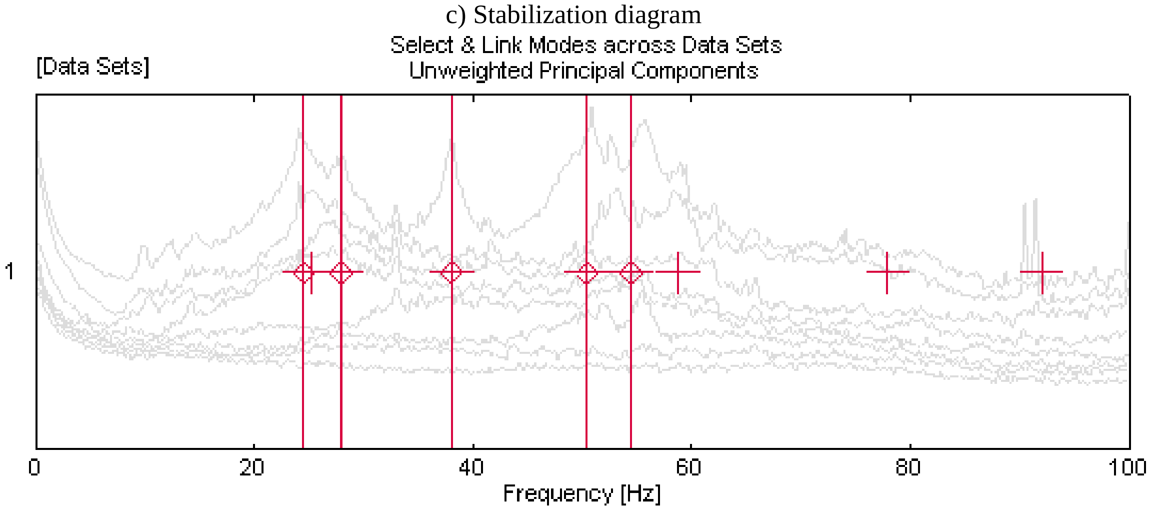
Fig. 18 SVSDM of data set, average of auto spectral densities of data set, stabilization diagram of estimated state space model and selected-linked modes across data sets attained from the first measurements using EFDD and SSI methods on February 2015 (Case 4)



b) Average of auto spectral densities of data set

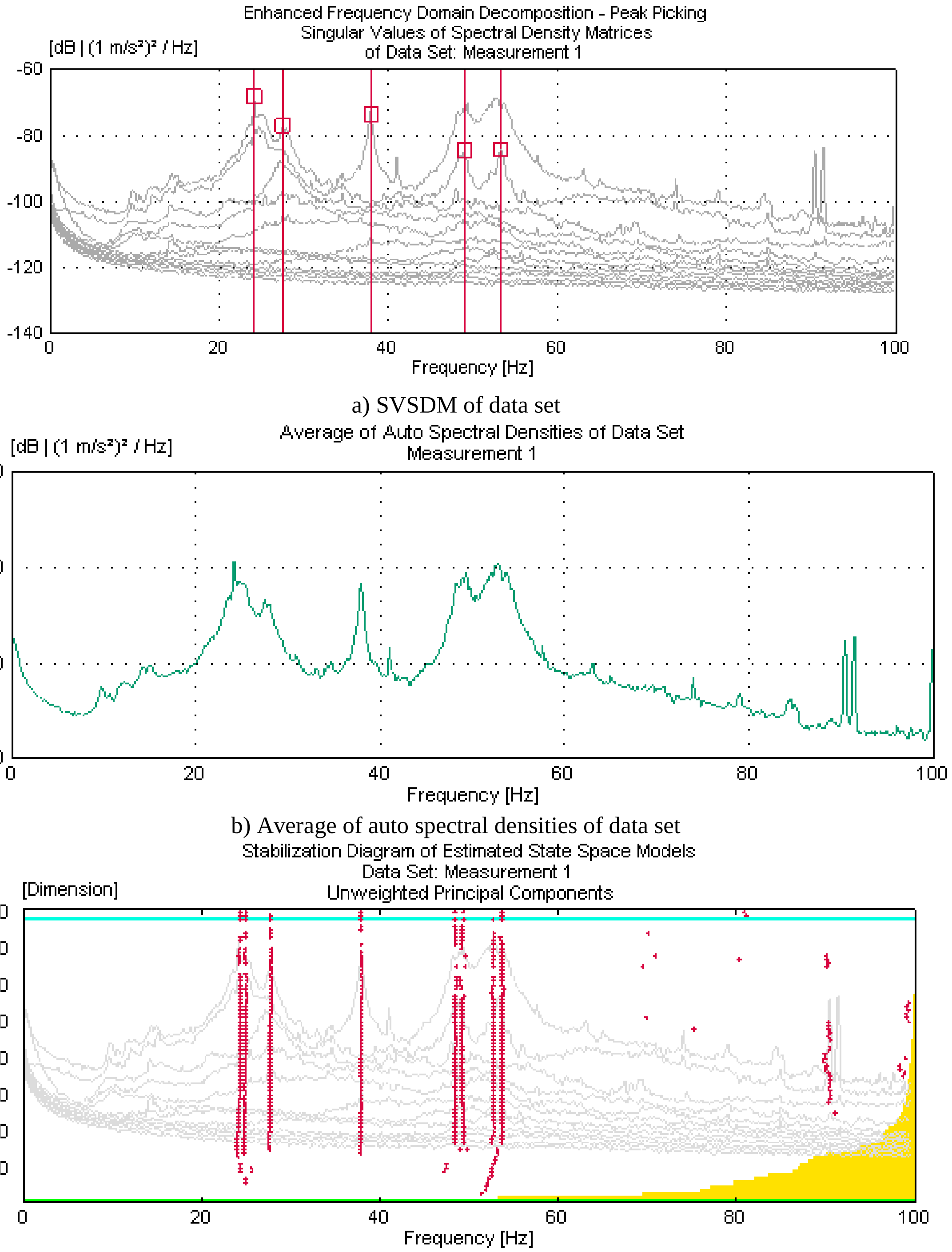


c) Stabilization diagram



d) Selected-linked modes across data sets

Fig. 18 Continued

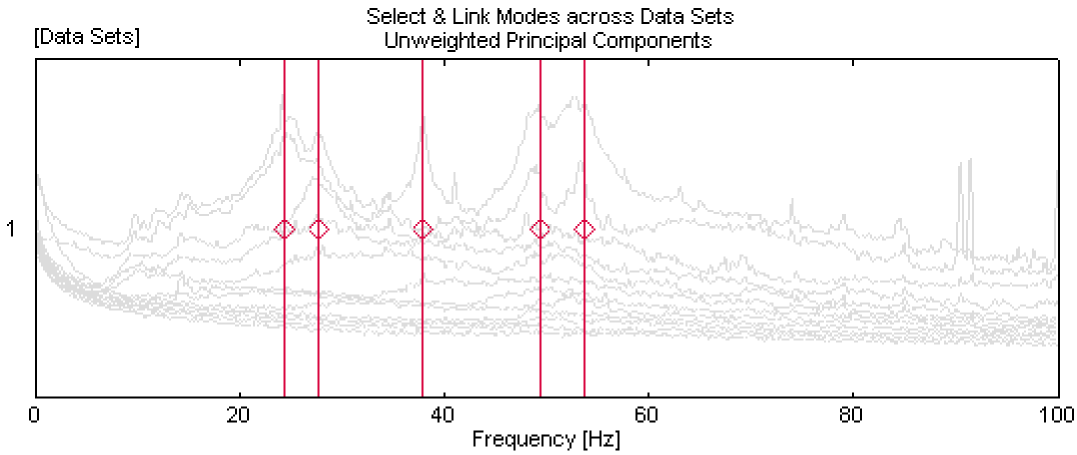


a) SVSDM of data set

b) Average of auto spectral densities of data set

c) Stabilization diagram

Fig. 19 SVSDM of data set, average of auto spectral densities of data set, stabilization diagram of estimated state space model and selected-linked modes across data sets attained from the second measurements using EFDD and SSI methods on February 2015 (Case 4)



d) Selected-linked modes across data sets
Fig. 19 Continued

Table 11 Natural frequencies attained from Case 4 using EFDD and SSI methods

Modes	Experimental measurements conducted on February 2015			
	First Measurements		Second Measurements	
	EFDD (Hz)	*SSI (Hz)*	*EFDD (Hz)*	*SSI (Hz)*
1	24.40	24.53	24.14	24.37
2	27.87	27.99	27.60	27.76
3	38.04	38.09	37.93	37.90
4	50.88	50.42	48.94	49.37
5	53.15	54.49	53.38	53.73

Table 12 Damping ratios attained from Case 4 using EFDD and SSI methods

Modes	Experimental measurements conducted on February 2015			
	First Measurements		Second Measurements	
	EFDD (%)	*SSI (%)*	*EFDD (%)*	*SSI (%)*
1	3.1460	2.346	0.3360	2.8420
2	1.8100	1.8000	1.1580	1.6170
3	0.6753	0.5589	0.4436	0.7314
4	0.8680	1.2540	0.4316	1.1520
5	0.3347	1.4830	0.5029	0.8658

time on the dynamic characteristics. No additional damage other than the ones created previously on October 2010. Two different measurement test setups are constituted to obtain the both transverse and longitudinal modes. In the first measurements, the bridge deck is divided into three groups and eight accelerometers are located on the four special points at the vertical and transverse directions (Fig. 17a). In the second measurements, the bridge deck is divided into three groups and

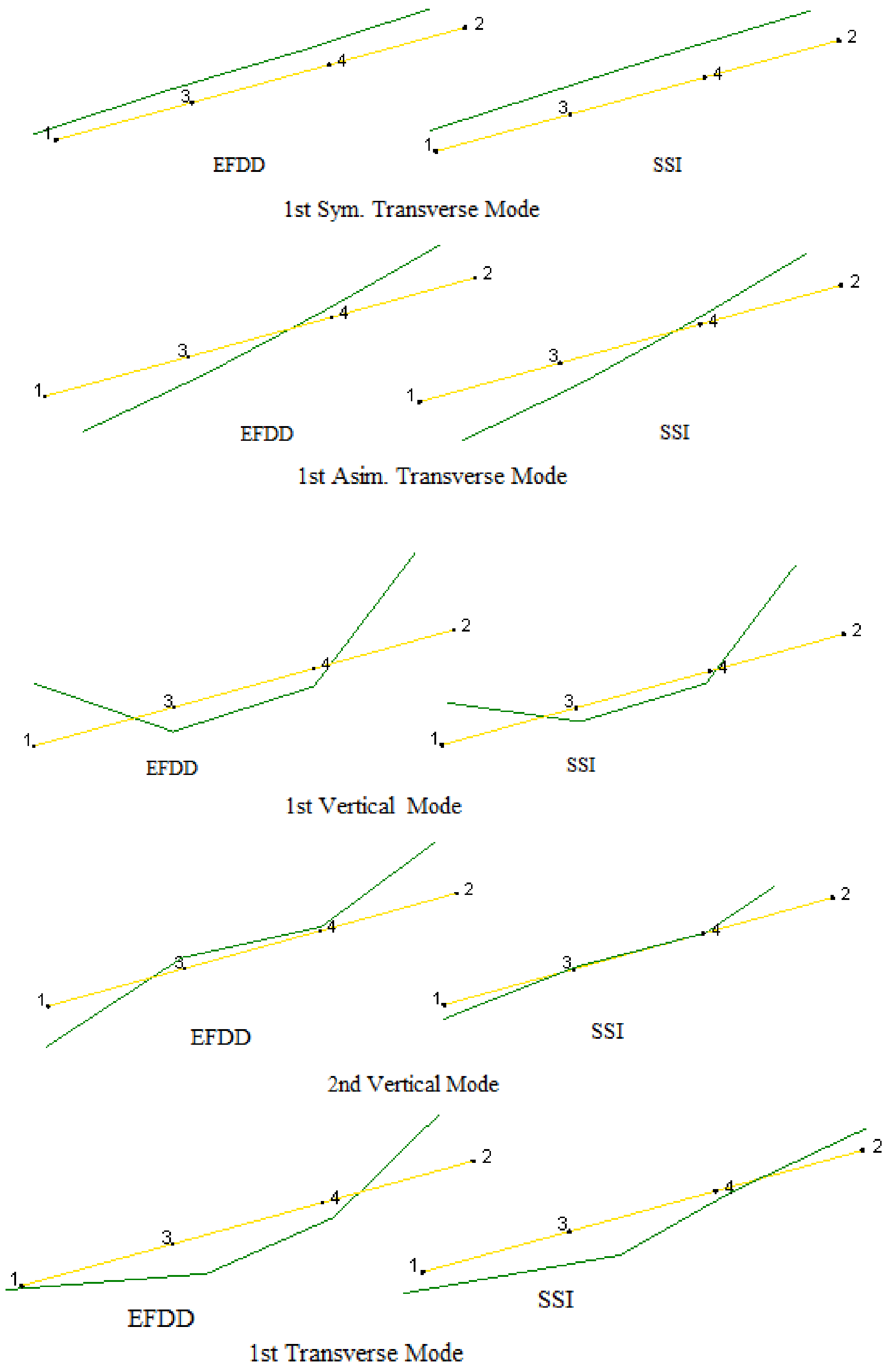


Fig. 20 The first five mode shapes obtained from the experimental measurements conducted on February 2015 (Case 4) by using EFDD and SSI methods

Table 13 Comparison of natural frequencies and damping ratios obtained from Case 3 and Case 4

Modes	Frequency (Hz)			Damping Ratio (%)		
	October 2010	February 2015	Max. Dif. %	October 2010	February 2015	Max. Dif. %
1	21.716	24.400	*12.36*	2.3630	3.1460	*33.14*
2	25.181	27.870	*10.68*	2.2320	1.8100	*23.31*
3	37.127	38.040	*2.46*	0.9670	0.6753	*43.19*
4	46.830	50.880	*8.65*	4.3530	0.8680	*401.5*

twelve accelerometers are located on the four special points at the vertical, transverse and longitudinal directions (Fig. 17b). Measurement properties such as accelerometer type, frequency span, time, line number are considered similar to Case 2 and Case 3.

Singular values of spectral density matrices, average of auto spectral densities of data set, stabilization diagram of estimated state space model and selected-linked modes across data sets obtained from EFDD and SSI methods for first and second measurements are shown in Figures 18 and 19.

Natural frequencies and damping ratios obtained from the Case 4 using EFDD and SSI methods are given in Tables 11 and 12. The mode shapes obtained from Case 4 is given in Fig. 20. It is seen that first and second modes are obtained as symmetrical and asymmetrical transverse modes, respectively. Third and fourth modes are attained as vertical modes. Fifth mode is obtained as transverse mode.

When the Fig. 16 (Case 3) and Figure 20 (Case 4) compared with each other, a good agreement is found between mode shapes. The movements of the selected special mod points are not symmetrical and harmonic due to damage and cracks constituted at the one column and one section of the box girder deck.

To determine the environmental condition effect with time, the first four natural frequencies obtained from Case 3 and Case 4 compared with each other in Table 13. It is seen from the Table 13 that the first four natural frequencies are obtained between 21.716Hz and 46.830Hz for Case 3, 24.400Hz and 50.880Hz for Case 4. The first four damping ratios are obtained between 2.363% and 4.353% for Case 3, 3.146% and 0.868% for Case 4. There is not a suitable distribution for damping ratios obtained from both methods. Maximum differences between Case 3 and Case 4 obtained as 12.36% and 401.50% for natural frequencies and damping ratios, respectively. It is observed that dynamic characteristics such as natural frequencies and damping ratios changed considerably under environmental effects with time.

4. Conclusions

This paper describes the evaluation of structural behavior for box girder scaled bridge model under undamaged and damaged conditions considering environmental condition effect with time between June 2009 and February 2015 using ambient vibration tests. Four experimental measurement cases are considered between 2009 and 2015. The first measurement case is conducted on June 2009 under undamaged conditions. The second and third measurement cases are performed on October 2010 under undamaged and damaged conditions to emerge the damage and environmental condition effect with time, respectively. The fourth measurement tests are carried out on February 2015 to display the time effect on dynamic characteristics. The following observations can be made from the study

Case 1: Ambient vibration tests for undamaged condition on June 2009

• 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.

• 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.

Case 2: Ambient vibration tests for undamaged condition on October 2010 to determine the environmental condition effect with time

• When the experimentally identified mode shapes are examined, it is seen that there is a good agreement and the mode shapes are obtained similar to June 2009 (Case 1).

• The first four natural frequencies are obtained between 26.00Hz and 55.00Hz for Case 1, 23.637Hz and 51.655Hz for Case 2.

• The first four damping ratios are obtained between 1.520% and 2.800% for Case 1, 0.766% and 3.640% for Case 2.

• There is not a suitable distribution for damping ratios obtained from both methods.

• Maximum differences between Case 1 and Case 2 obtained as 11.98% and 112.24% for natural frequencies and damping ratios, respectively.

• It is observed that dynamic characteristics such as natural frequencies and damping ratios changed considerably under environmental effects with time.

Case 3: Ambient vibration tests for damaged condition on October 2010 to determine the damage effect

• There is not any agreement between mode shapes. The occurrence arrangements changed after damage and cracks. Also, the movements of the selected special mod points are not symmetrical and harmonic due to damage and cracks constituted at the one column and one section of the box girder deck.

• The first four natural frequencies are obtained between 23.637Hz and 51.655Hz for Case 2, 21.716Hz and 46.830Hz for Case 3.

• The first four damping ratios are obtained between 0.766% and 3.640% for Case 2, 0.967% and 4.353% for Case 3.

• There is not a suitable distribution for damping ratios obtained from both methods.

• The natural frequencies are reduced after damages and cracks.

• There is an increasing trend with the damage in damping ratios.

• Maximum differences between Case 2 and Case 3 obtained as 10.30% and 26.24% for natural frequencies and damping ratios, respectively.

• It is observed that dynamic characteristics such as natural frequencies and damping ratios changed considerably after damages and cracks.

Case 4: Ambient vibration tests for damaged condition on February 2015 to determine the environmental condition effect with time

• The first and second modes are obtained as symmetrical and asymmetrical transverse modes, respectively. Third and fourth modes are attained as vertical modes. Fifth mode is obtained as transverse mode.

• A good agreement is found between mode shapes. The movements of the selected special mod points are not symmetrical and harmonic due to damage and cracks constituted at the one column and one section of the box girder deck.

• The first four natural frequencies are obtained between 21.716Hz and 46.830Hz for Case 3, 24.400Hz and 50.880Hz for Case 4.

• The first four damping ratios are obtained between 2.363% and 4.353% for Case 3, 3.146% and 0.868% for Case 4.

• There is not a suitable distribution for damping ratios obtained from both methods.

• Maximum differences between Case 3 and Case 4 obtained as 12.36% and 401.50% for natural frequencies and damping ratios, respectively.

• It is observed that dynamic characteristics such as natural frequencies and damping ratios changed considerably under environmental effects with time.

❖ It can be easily seen from the study that damages and environmental conditions affect the structural behavior of concrete bridges, substantially.
❖ Time dependent environmental conditions such as temperature, humidity and ageing are as important as cracks and damages.
❖ These changes may be emerged/determined under fatigue conditions in field on current highway bridge using ambient vibration tests.
❖ For the next studies, the study about the fire effect on the dynamic characteristics of bridge model considering different fire time (10s, 20s, ……2h) is planned.
❖ The results should be validated with finite element results.
❖ The updated model should be used to assessment for sustainability and resiliency.

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