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Wind Analysis of the Bosphorus Suspension Bridge: Numerical and Experimental Investigation

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ABSTRACT: Long-span suspension bridges are subjected to various loading events in their life-cycle. Along with operational loads, they have experiences on extreme loads, such as earthquake, wind, marathon etc. Of all these extreme events, wind is the most critical one, which in turn design considerations of the structural components of long-span bridges are adopted according to wind load. Based on these considerations, wind-induced behavior of the Bosphorus Bridge is presented in this study. For this aim, the extreme wind events that happened in April 18 2012 is considered and the data obtained from the Structural Health Monitoring system-SHMs of the bridge during the event are utilized for experimental analysis. Conducting certain data processing methods to make the SHM data more identifiable on the basis on modal characteristics of the bridge, the response of the bridge to the strong wind event are determined. For numerical investigation on wind behavior of the bridge, 3-D full-scale shell finite element model (FE) of the bridge is established and the sophisticated FE model is verified with the SHM data from the extreme wind event. The results from the data analysis exhibited that the bridge relatively excited in lateral direction; however, no damage is predicted under the strong wind. For the certain critical issue of fatigue prediction not only in the local system but also in global system, stress controlling on the component of the bridge, stress-strain observation, local buckling investigation and optimum sensor location prediction, numerical dynamic wind analysis of the bridge should be performed simulating the recorded strong wind to time-history dynamic wind load.

1 INTRODUCTION

Due to the increasing in the population and the critical location of Istanbul, the need for transportation infrastructures such as long-span crossing bridges over the Bosphorus Straits and railway/ motorway tube-tunnel under the Bosphorus River have relatively increased. As depicted in Figure 1, three long-span bridges are currently in service in Istanbul, one of which is newly-completed hybrid bridge, the Yavuz Sutlan Selim Bridge. Moreover, the other bridge, the Osman Gazi Bridge as shown in Figure 1d, is also located on the Izmit Bay relatively close to Istanbul. The Bosphorus Bridge is one of the life-line infrastructures of the transportation networks of Istanbul. As indicated in Figure 1a, the Bosphorus Bridge is located on the Bosphorus River that are naturally surrounded with two continents of Asia and Europe. Until the construction of the 2nd crossing bridge named Fatih Sultan Mehmet Bridge (Figure 1b), the bridge carried entirely all Istanbul's traffic loads between two continents. After the passage of the heavy truck traffic are limited on the bridge and are diverted to the 2nd Bridge, the bridge is only permitted to passage of the car traffic. With the newly-completed 3rd Bosphorus Bridge, Yavuz Sultan Selim Bridge (Figure 1c), three long-span bridges serve as vital links between Europe and Asia continents.

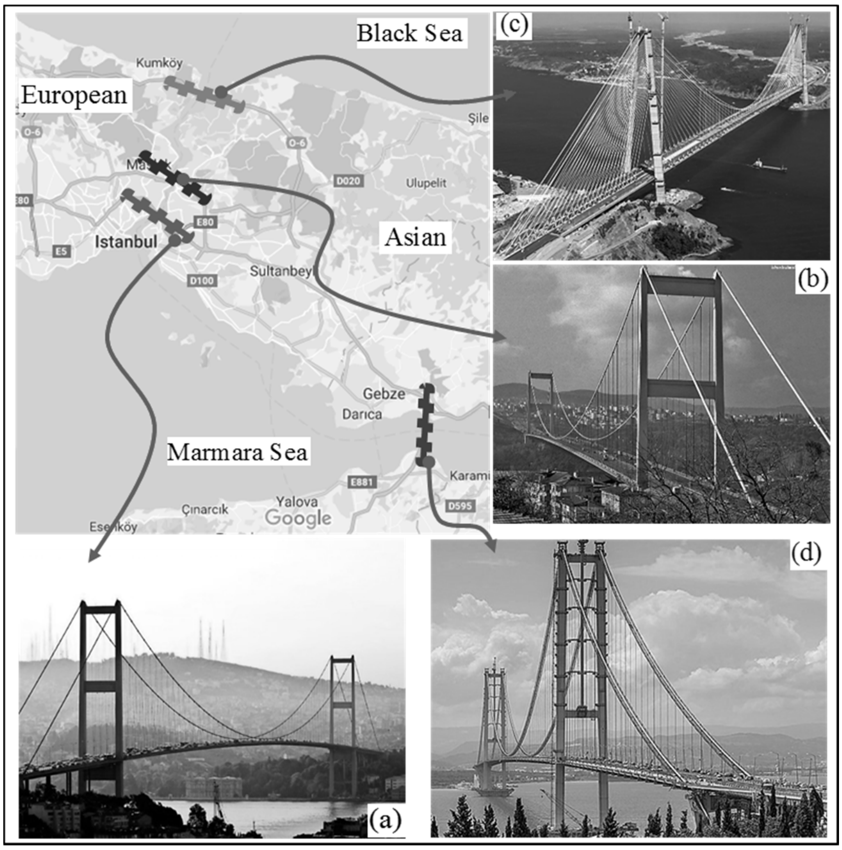

Figure 1. Long-span cable-supported bridges in Turkey: (a) the 1st Bosphorus Bridge (b) Fatih Sultan Mehmet Bridge (c) Yavuz Sultan Selim Bridge (d) Osman Gazi Bridge

The first attempts to experimentally investigate ambient and traffic-induced response of the Bosphorus Bridge were made by Tezcan et al. (1975) and Petrovski et al. (1974) for three days before and after the bridge was opened to traffic. Using temporal SHMs, limited number of studies on vibration characteristics of the bridge under ambient and traffic effects were conducted by Brownjohn et al. (1989) and Erdik et al. (1988). They compared the results from experimental data analysis with those from FE model of the bridge. Based on the calibration of FE model with experimental results, they indicated that the developed FE model could be considered for further investigation of the bridge. Using a sensory system with 28 channels, Beyen et al. (1994) also carried out ambient vibration study-AVS to determine the dynamic characteristics of the bridge and to compare the obtained results with the previous results in literature. New studies on the monitoring and advanced analysis of the Bosphorus Bridge were performed by Bas et al. (2016a, 2016b, 2015a and 2015b), Apaydin (2010) and Apaydin et al. (2015), Erdik et al. (2007) and Kosar (2002).

This study aims at experimentally identify the response of the Bosphorus Bridge to the extreme wind events and at developing 3-D full-scale shell FE model of the bridge by verifying the bridge's modal parameters with those obtained from the SHM data recorded during this event. For future performance and behavior of the bridge under strong wind events, numerical dynamic wind analysis is concluded to be carried out.

2 GENERAL PROPERTIES OF THE BOSPHORUS BRIDGE

The Bosphorus Bridge also called the 1st Bridge is a modern gravity-anchored steel suspension bridge due to aerodynamic stiffening deck, box towers and portal beams. The suspender elements of the hangers were designed with an inclined form instead of a vertical form. Within the scope of recently conducted elaborate retrofit projects, the hanger cables are replaced to vertical form.

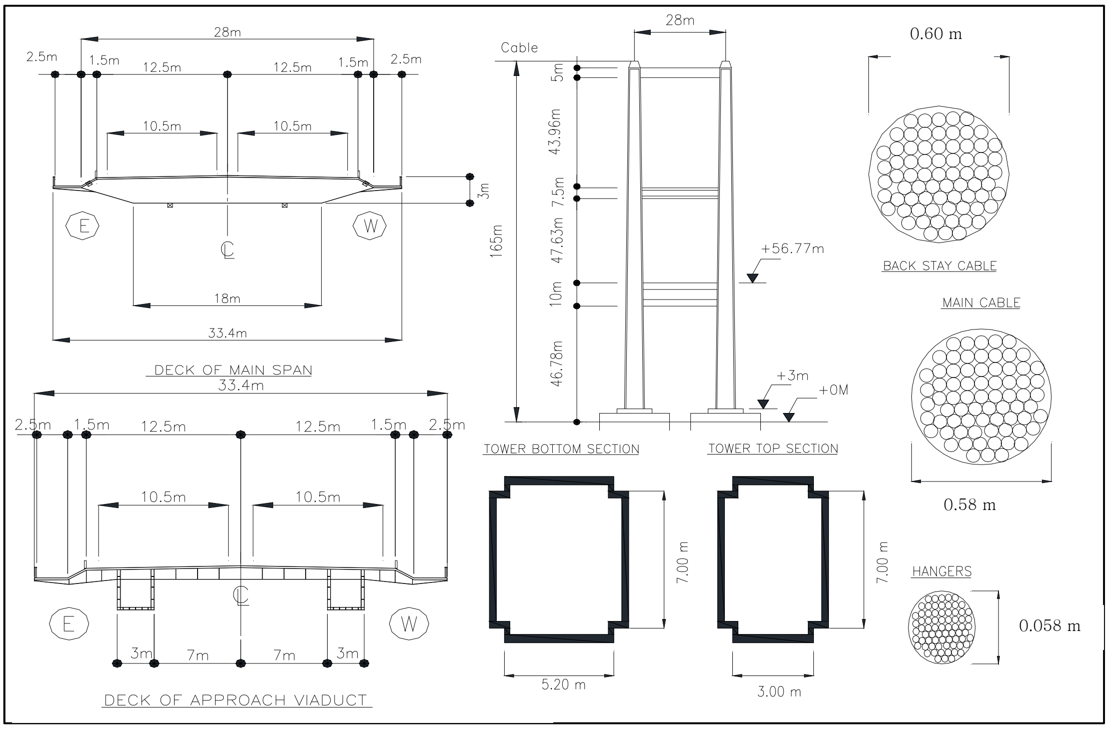

Figure 2. General specifications of the bridge KGM (1973)

As depicted in Figure 2, the width and height of the deck is 33.40 m and 3.00 m, respectively. The tower with the height of 165 m from the sea level has a tapered section decreasing from bottom section to top-saddle section. The approach spans of the bridge are supported at the base instead of hanger suspenders. Due the fact that the bridge is symmetric according to mid-span, diameter of the main and back-stay cables are approximately same. The hanger elements have a diameter that is 1/10 times of the main and back-stay cables.

3 STRUCTURAL HEALTH MONITORING-SHM SYSTEM OF BRIDGE

The Bosphorus Bridge has experienced various excitation events; however, has still continued its function without any damage or adverse effect on the structural components of the bridge. Heavy traffic condition of Istanbul reaching daily 3.5 billion vehicles in traffic and the location of the bridge over the Bosphorus River lead to the need for monitoring the response of the bridge to extreme loading events, such as earthquake, marathon and strong wind.

Table 1. Sensor types and corresponding quantity of SHM system of the bridge

Type	Quantity
Accelerometers	19
Tiltmeters	15
Force Transducer	12
Force Transducer	12
Strain Gauges	70
Laser Displacements	8
GPS	5
Thermocouples	33
Weather Station	6
Total	168

After the critical wind events in 2004, a permanent SHM system with the ability of tracking the behavior of the bridge in real-time was decided to be installed on the bridge. The installed SHMs has 168 sensors which are accelerometer, tiltmeters, force transducer (LVDT), strain gage, whether station, laser displacement, thermocouple and GPS. Sensor type and corresponding quantity are given in Table 1.

4 WIND-INDUCED BEHAVIOR OF THE BRIDGE

Strong winds are not very frequent in Istanbul due to its location. However, during the daytime on April 18 2012, a strong storm occurred in Istanbul. It was the first time, the bridge experienced such high wind. According to measurement of Turkish Meteorology Service, the maximum wind-speed reached to 122 km/h. Although ultimate design wind speed of the bridge is 162 km/h, the bridge was closed to the traffic for a period of time as a precautionary measure. The change of wind speed with time is shown in Figure 3. This variation is also obtained by weather stations installed on the bridge. As seen from Figure 3a, the average wind speed before the storm was around 20 km/h. However, it suddenly increased to 100-120 km/h in 10 minutes. This variation is also verified with meteorology data as shown in Figure 3b. In order to determine the effect of the strong wind on dynamic characteristics and operational performance of the bridge, all SHM data are divided into three ranges as shown in Figure 4: *Before, During* and *After*. The data analysis showed that meaningful results are not obtained for *Before* range since the data is relatively distorted with traffic noise. Therefore, *After* range is considered for the comparison with *During* range. For more refined results from FFT (Fast Fourier Transform), data averaging technique including windowing and overlapping is also implemented. Window length is determined considering the minimum frequency range of the modal values obtained from the previous experimental study in literature. The obtained SHM data from the accelerometers mounted at the specific points of the bridge are utilized for system identification of the bridge. The locations of the accelerometers are indicated with the considered directions in Figure 5. In this figure, the FFT analyses of the all accelerometers are also given to determine modal characteristics of the bridge. The outcomes from the frequency-domain analysis are summarized in Table 2.

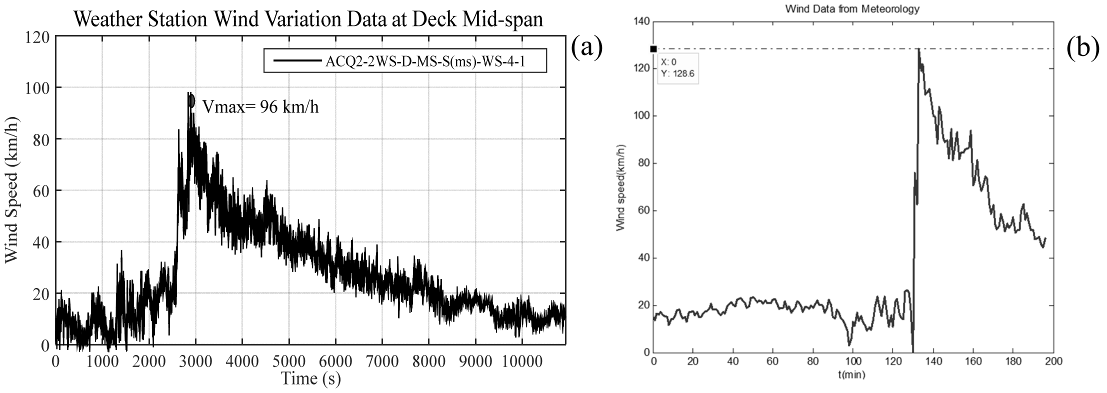

Figure 3. Variation of the extreme wind: (a) SHM data (b) Meteorology data

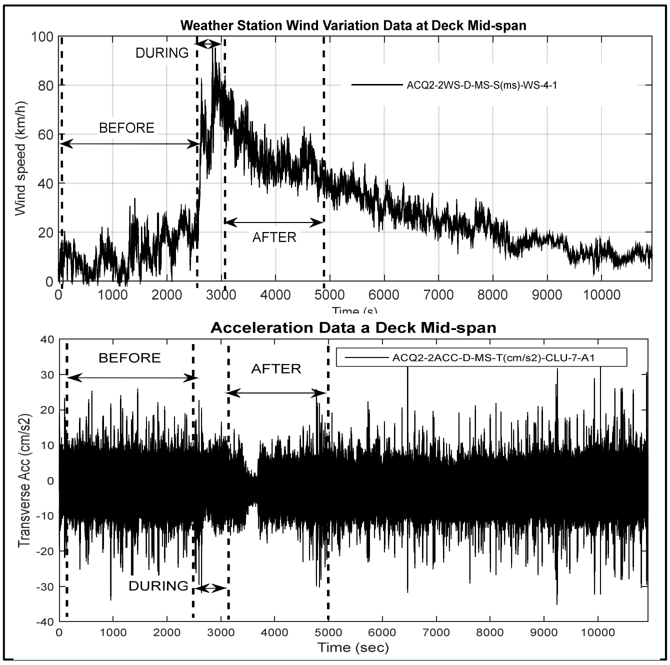

Figure 4. Seperated wind data into three ranges

Table 2. Wind-induced vibration properties of the bridge

Mode Number	Mode Shape	Frequency/Period [Hz]/[s]					
		Transvers Direction					
		During		After		Change (%)	
		Period [s]	Freq. [Hz]	Period [s]	Freq. [Hz]	Period [s]	Freq. [Hz]
Mode-1	1st L_{sym}	14.706	0.068	12.766	0.078	15.196	-13.191
Mode-2	1st V_{asym}	8.065	0.124	8.065	0.124	0.000	0.000
Mode-3	1st V_{sym}	6.096	0.164	6.250	0.160	-2.469	2.531
Mode-4	1st L_{asym}	4.854	0.206	4.967	0.201	-2.265	2.318
Mode-5	2nd V_{sym}	4.561	0.219	4.525	0.221	0.798	-0.792

Lsym: Lateral symmetric; Lasym: Lateral asymmetric;Vsym:Vertical symmetric; Vasym:Vertical asymmetric

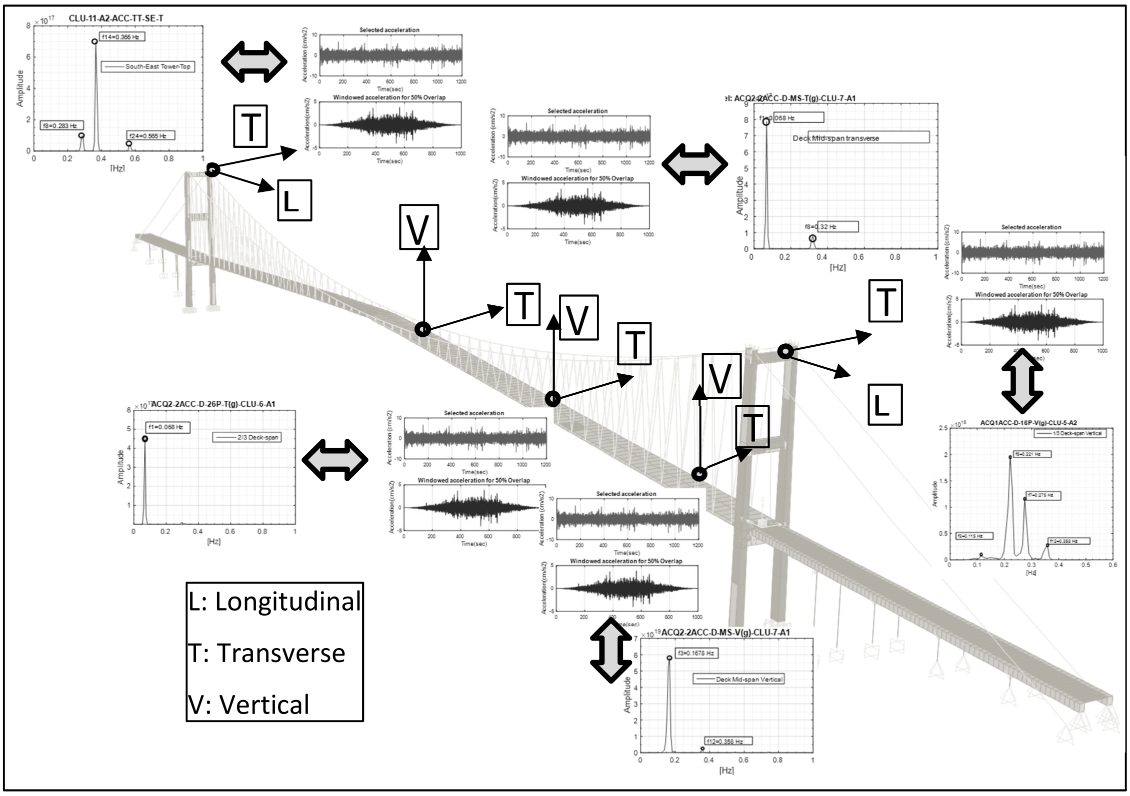

Figure 5. Structural identifcation of the Bosphorus Bridge under the wind event

5 NUMERICAL FE MODEL OF THE BRIDGE

All structural components of the bridge were made of steel thin plate. Internal diaphragms were also used to provide additional stiffness for these components. Based on its project drawings, the bridge was modeled using shell element. Besides, link element was considered for deck-tower and side span-tower connections. Considering cable sag effect, cable element features were assigned to the main cable, backstay cable and hangers. The cross girder I beams with tapered

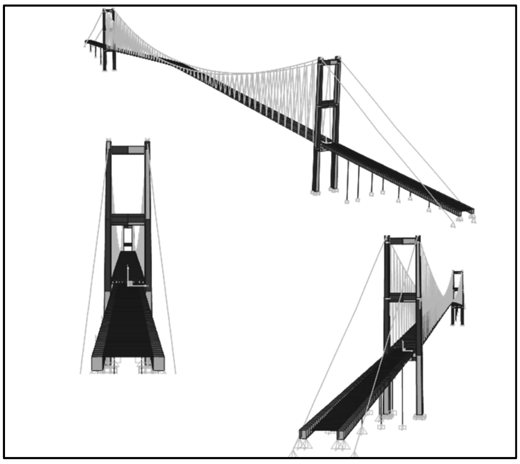

Figure 6. 3-D full-scale shell FE model of the bridge

section and the circular box columns of the approach viaducts were modeled as frame element. The established FE model is shown in Figure 6. In this model, 4121 points, 263 frame elements, 387 cable elements and 3996 shell elements were used. For all efforts, SAP2000 (2016) software was utilized. As expected, the first effective mode shape frequency is in transvers direction. In Figure 7, the first 5 modes are shown. These results are then compared with those from *After* range data. As given in Table 3, closure agreement between the established 3-D full-scale shell FE model and those experimental data is obtained.

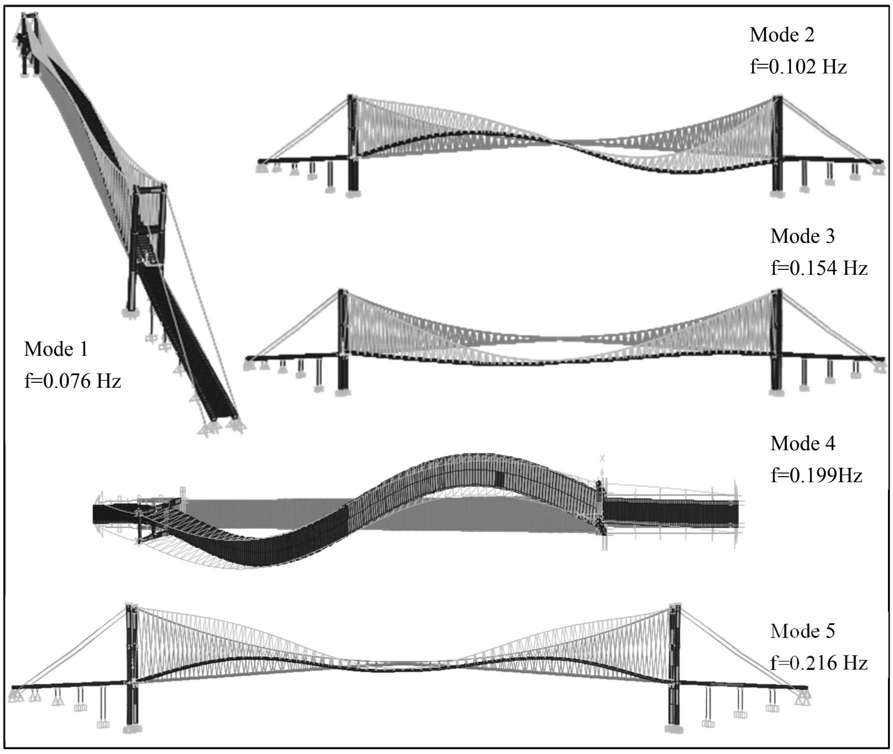

Figure 7. Modal analysis of the bridge

Table 3. Comparison of numerical and experimental dynamic characteristics of the bridge

Mode Number	Mode Shape	Frequency/Period [Hz]/[s] 3-D Shell FE Model (S-FEM)					
		S-FEM		After		Change (%)	
		Period [s]	Freq. [Hz]	Period [s]	Freq. [Hz]	Period [s]	Freq. [Hz]
Mode-1	1st L_{sym}	13.090	0.076	12.766	0.078	2.538	-2.979
Mode-2	1st V_{asym}	7.220	0.139	8.065	0.124	-10.472	12.097
Mode-3	1st V_{sym}	6.481	0.154	6.250	0.160	3.696	-3.750
Mode-4	1st L_{asym}	5.020	0.199	4.967	0.201	1.069	-1.159
Mode-5	2nd V_{sym}	4.620	0.216	4.525	0.221	2.102	-2.262

6 CONCLUSION

The current study presents the experimental behavior of the Bosphorus Bridge under the extreme wind event occurred in April 18 2012 and advanced 3-D full-scale shell FE modelling considerations of the bridge. The FE model is updated with the *After* range data corresponding to natural vibration and relatively good agreement is obtained between the outcomes from FE model and those from the After range. For the *During* range simulation of the updated sophisticated FE mode, dynamic wind analysis should be performed considering the experimentally varying wind speed as shown in Figure 3 recorded during the extreme wind event. Accordingly, certain performance predictions pertinent to fatigue prediction not only in the local system but also in global system, stress controlling on the component of the bridge, stress-strain observation, local buckling investigation and optimum sensor configuration are made through the dynamic wind analysis. As to the experimental consequences of the bridge, the first modal frequency (lateral symmetric) of the bridge decreased in the range of 13% under the extreme wind loading. Only change in the deck modes of the bridge is obtained. This is pertinent to high rigidity of tower box section in transverse direction. After the extreme wind excitation, the natural frequencies of the bridge are also obtained, meaning that no damage is estimated under the strong wind. High modal periods during the wind indicated that damping of the bridge increased.

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