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Structural Identification (St-Id) Concept for Performance Prediction of Long-Span Bridges

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Abstract

Long-span cable-supported bridges are the lifeline structures for the transportation network in a country/state. An effective solution of this type of bridges is therefore indispensable not only to better understand structural response of them but also to conduct an efficient maintenance and management strategy for these bridges. In this study, structural identification (St-Id) is implemented to estimate the performance of the Bosphorus Bridge. In addition, certain efforts from finite element modeling (FEM) to utilization for performance prediction are given based on each step of St-Id. St-Id concept is divided into two main parts: experimental and numerical investigations. Due to the high cost and time limitation for testing of long-span bridges, the most effective solution to the experimental research is SHM system (SHMs). For this purpose, the SHMs of the Bosphorus Bridge is considered, finite element modeling provides an extended solution from analysis to model updating of the bridges. Considering structural performance of the bridge under extreme wind load and multi-point earthquake motion is estimated. The results from the current study indicate that St-Id concept is a robust approach for overall structural condition assessment and performance prediction of long-span cable-supported bridges.

Keywords: structural identification (St-Id), long-span bridges, structural health monitoring (SHM), finite element model (FEM), FEM calibration, multi-point earthquake analysis (Mp-sup)

1. Introduction

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Long-span bridges, such as cable-stayed and suspension bridges having considerably different structural system compared with other structures are one of the main components in the transportation network in a city/state. Therefore, the governments make sizeable investment

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both for their construction and maintenance costs as wells as rehabilitation and retrofit projects. Considering such crucial functions of them and various investments for improving their structural performance, it is clear that comprehensive investigations on long-span bridges are necessary before and after its construction since they fall outside the scope of general bridge codes.

Over the last decades, the engineers and researchers have focused on both experimental and analytical studies taking the complexity and non-linear characteristics of long-span cable-supported bridges into consideration. For analytical studies, these structures are modeled numerically by finite element model (FEM). With utilizing FEM method, modal analysis, buckling analysis and earthquake-induced analysis of complex structures are readily carried out. Although this sophisticated analytical modeling is a powerful tool for simulating three dimensional local and global behavior of long-span bridges, it does not reflect the real structural behavior owing to uncertainty in idealization and assumption, such as in material model and analysis method. Therefore, only FE model is not enough for fully understanding the response and behavior of this type of large-scale structures.

Experimental field studies of long-span cable-supported bridges give reliable consequences for the current performance of them. Therefore, this effort is relatively significant to compare the outcomes from FEM analysis with those obtained from experimental field studies; however, this analysis could not be possible many times, especially for long-span cable-supported bridges. Additionally, data analysis and management are necessary for interpretation of collected experimental data. For this objective, structural health monitoring (SHM) is proposed as a complementary experimental technique, including structural condition evaluation, model development and calibrating, and real-time monitoring. With the major leaps in sensing and information technology, utilizing SHM to properly assess new designed and existing structures is growing interest worldwide though a standard approach for SHM has not been available yet.

In an effort to deal with the incompatibility between measured and simulated response of long-span cable-supported bridges and make an overall condition assessment of these bridges, structural identification (St-Id) concept presents an integrated approach. Structural identification is the process of developing calibrated/updated analytical model (mathematical or geometric) of structures from experiments and observations for reliable performance evaluation, simulation and decision-making. Structural identification (St-Id) and system identification (Sys-Id) are two concepts that are closely related to each other. Therefore, St-Id is a result of translation and application of system identification to mechanical and civil structural system [1]. This concept was first applied to engineering mechanics [2] and to civil-structural engineering [3]. Although many efforts are made to implement St-Id to structural engineering field, applications of this concept have not been wide-spread in civil engineering practice yet [4]. Depending upon developments in sensing and information technology, St-Id concept becomes more popular for confidential performance assessment and simulation of structures [5]. For different aspect of the St-Id concept, a number of studies were found in literature. The key point in these studies is that structural health monitoring (SHM) is utilized for experimental step of St-Id.

The most comprehensive study for St-Id was carried out by the ASCE SEI Committee on Structural Identification of Constructed Systems [1]. In addition to detailed knowledge for this process given in this study, a set of case studies are presented to illustrate the application of St-Id to building and bridge structures. Six chapters are introduced to properly comprehend St-Id concept. The scope of these sections is related to modeling, experimentation, data processing, comparison of model and experiment and decision-making. As schematically shown in **Figure 1**, St-Id consists of six steps: (i) Visualization and conceptualization (ii) Priori modeling (iii) Experimentation (iv) Data analysis (v) Calibration (vi) Utilization.

In addition to theoretical aspects, St-Id is widely utilized from estimating structural condition evaluation, rehabilitation to SHM system improvement and optimization of scaled and existing/new constructed long-span bridges under different loading and environmental conditions. A St-Id study on a newly constructed arch bridge in China was conducted in order to make FE model updating of the bridge through certain data-driven methods [6]. They demonstrated that the updated numerical model could be reliably adopted for the detailed structural analysis of arch bridges. Similar study was made in [7]. They proposed a method of frequency response function parameter identification for full-scale bridge using field-testing data. The developed approach to the model updating/calibration of the bridge is indicated to be confidently considered for FE model calibration of full-scale bridges. For various objectives of structural identification, many studies were carried out from the numerical model calibration to SHM system modification/improvement in [8–13]. In these studies, either all or certain steps of St-Id concept are aimed to be identified especially for long-span cable-supported bridges.

The Bosphorus Bridge as shown in **Figure 2** also called the 1st Bosphorus Bridge is one of the three long-span bridges in Turkey, which provides a connection between two continents of



Figure 1. Layout for structural identification (St-Id).



the Asian and the European. When opened to traffic in 1973, the bridge was classified as the 4th longest suspension bridge in the world according to its main span. The bridge serves as vital link on the Motorway-1 (O1) connecting the city center of Istanbul. Significant part of heavy traffic of Istanbul has been carried from the bridge along with the Fatih Sultan Mehmet Bridge named the 2nd Bosphorus Bridge located on the northern side of the Bosphorus Bridge.

Taking the efficiency of St-Id into account, this approach is utilized for the Bosphorus Suspension Bridge and the results are presented in this study. Each step of the concept is handled to be conducted for the bridge. Along with establishing the numerical model of the bridge to obtain its analytical modal frequencies, the experimental study is conducted using SHM data collected during the extreme wind event. Based on the discrepancy between FEM and experimental results, model verification/calibration is performed. The calibrated model is then used for utilization of multi-point earthquake analysis of the bridge. The outcomes from this study illustrated that St-Id concept is a robust methods to properly predict the structural performance of the Bosphorus Bridge.

2. Finite element modeling and modal analysis

As in many disciplines, the application of a detailed accurate finite element model in bridge engineering field has been relatively significant to properly assess structural performance of bridges. The major leaps in computation technology enable to make advanced FE modeling and analysis. Due to the complexity of long-span cable-supported bridges, these structures are modeled based on certain assumptions: (a) simplified spine-beam model, (b) multiscale (hybrid) FE model. The spine-beam model that enables to reduce degree-of-freedom (DOF) of bridge structures presents the results from the global behavior of bridges. Using the spine-beam model, modal analysis can be readily conducted to obtain the effective mode frequencies and associated mode shapes. In addition, preliminary FE model that is developed based on as-built project drawings can also be validated using this modeling technique. Therefore, the spine-beam modeling technique helps to check the considered equivalent sectional properties of structural components. On the other hand, multi-scale modeling becomes very significant upon making analysis for local structural component. This modeling technique also provides that different element types, beam, solid, shell, and truss, are used together to establish 3D full-scale bridge FE model. Accordingly, both modeling techniques are utilized for different goals, and generally, they have been used together for structural analysis of bridge structures.

The modal analysis of structures is a powerful tool for earthquake excitation analysis of structures. Through this analysis, the response of structures to dynamic input can be estimated and certain outcomes related to dynamic inputs can be explained [17]. For large-scale bridge structures with different large size of structural component, such as main deck, tower etc., the mode shapes may show which component dominates the dynamic response of long-span bridges [14–16].

The bridge's structural components of the tower, the main deck, the portal beams, and approach span are modeled as equivalent frame element corresponding their mechanical



Figure 3. Sectional properties of the Bosphorus Bridge [17].

and sectional properties. The details of the structural components of the bridge are given in **Figure 3**. For elaborate sectional properties, all points of the components are precisely determined depending on the project drawings, and thus much more realistic dimensions of them are adopted. Based on these project specifications and general properties of the Bosphorus Bridge, FE model of the bridge is developed utilizing the spine-beam modeling approach as shown in **Figure 4**.

Since the bridge was made of structural steel, modal damping ratio of $\xi = 0.02$ is also considered to calculate the proportional structural damping for the bridge. The first 50 natural frequencies and associated mode shapes are obtained and the first five modes and associated frequencies are shown in Figure 5. From the analysis, the main deck of the bridge is obtained to be effective for lateral and vertical response of the bridge to a dynamic input. Particularly, modal participating total mass ratio for transverse direction of the main deck is determined as 60% at the end of the first five modes directly pertinent to the main deck mode shapes. Compared to modal participating total mass ratio of 96% at the end of the fifty modes, this value indicated the efficiency of the main deck mode shapes on the dynamic response of the bridge. Similar single mode shapes are also determined for the tower after the main deck mode shapes. All these single mode shapes of the main deck and the tower are seen in the first ten mode shapes. The other mode shapes are obtained as the combination of these single mode shapes. Based on these consequences, the main deck and the tower dynamic response are estimated to dominate the dynamic behavior of the Bosphorus Bridge. The obtained analytical modal frequencies are also compared with those from the experimental results so as to verify/calibrate FEM of the bridge.



Figure 4. 3-D full-scale FE model of the Bosphorus Bridge.

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Figure 5. The first five mode frequencies and corresponding shapes of the Bosphorus Bridge.

3. Structural health monitoring system (SHM)

In general, the components of a SHM system are; (i) Sensory systems (ii) Data acquisition and transmission systems (iii) Data processing and control system (iv) Data management systems (v) Structural evaluation system [18]. Design of SHM systems is based on clearly describing the monitoring objectives. Therefore, working SHM designer together with bridge designer is inevitable to identify the objectives very well. Considering the objectives, monitoring requirements should be properly identified [19]. The requirements can be considered as below;

- The parameters to be monitored (wind, displacement, temperature)
- The design value and measurement range of the parameters
- The spatial and temporal properties of the parameters
- The accuracy requirements
- The environmental condition of the monitoring
- The duration of the monitoring

Following identification of the monitoring parameters, the next step is to determine the number of sensors based on the monitoring objectives. In order to compensate for the requirements of the monitoring, it is important to select which types of sensor are used. For this purpose, technical specifications of the sensors including measurement range, sampling rate, sensitivity, resolution, linearity, stability, accuracy, repeatability, frequency responses should be identified clearly.

With the daily traffic capacity of 195 thousands vehicles, the Bosphorus Bridge serves as its significant function without no traffic interruption in the transportation network of Istanbul. Due to the seismicity and location of Istanbul, the bridge has been subjected to many critical loading events from earthquake, wind, heavy traffic to marathon. Therefore, it is a crucial issue to track the structural response of the Bosphorus Bridge under these type of excitations. The bridge was decided to be donated with SHM system due to the unpredicted failure of hanger rope in 2004. With the total number of 258 channels and 168 sensors varying from accelerometers, tilt meters, force transducers, strain gauges, laser displacement, GPS, thermocouples to weather stations, a permanent structural health monitoring system (SHM) is developed considering the bridge's own characteristics and critical points to be monitored [20].

The quantity and location of the sensors are determined after certain temporal installation tests on its SHM system. In **Table 1**, the number and type of sensors installed on the bridge are listed with their preferences. Moreover, general sensor arrangement of the SHM system of the bridge is presented in **Figure 6**.

Туре	Preferences	Quantity	
Accelerometers	Measuring range of +/- 2 g	19	
Tiltmeters	Measuring range (°): ±14.50	15	
Force transducer	Measuring range (mm): ±1.50 mm	12	
Strain gauges	Resistance tolerance (%): ±0.30	70	
Laser displacements	Measuring range (mm): 200–2000	8	
GPS	Precision (mm): 0.2	5	
Thermocouples	Accuracy (%): ±0.10	33	
Weather station	Wind speed range (mph): 0–130	6	
Total		168	

Table 1. Sensor types and quantity of the SHM system of the bridge [20].

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Figure 6. General layout for the sensors of the SHM system of the bridge.

4. Structural identification (St-Id)

4.1. Description of extreme wind event

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 that the bridge experienced such a high wind. According to measurement of Turkish Meteorology Service, the peak 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 precaution-ary measure. The change of wind speed with time is shown in **Figure 7**. This variation is also obtained by weather stations installed on the bridge. As seen from **Figure 7**, the mean wind speed before the storm was around 20 km/h. However, it suddenly increased to 100–120 km/h in 10 minutes [21]. This variation is also verified with meteorology data as shown in **Figure 7**. In addition, the excitation of the strong wind load is also corrected with the other weather station data recorded from different critical points of the bridge. As seen from **Figure 8**, the lateral wind direction is verified with the polar charts through SHM data at the deck mid-span, and the bridge was determined to be greatly induced in N-S direction during the critical wind event.

4.2. System identification of the bridge

Before the identification, data processing on the acceleration data is implemented. Firstly, base-line correction is performed to get rid of offset value. The next step is to remove linear trends from the data using de-trend technique. Besides, the mean value (DC) of the data



Figure 7. Identification of strong wind: meteorology data and SHM data.



Figure 8. Identification of wind direction from the deck mid-span SHM data.

is subtracted. In order to remove the unwanted noise component, a standard fourth order Butterworth band-pass filter with the first corner frequency of 0.05 Hz and the second corner frequency of 5.0 Hz is performed [21]. For all these works, MATLAB computing program developed by the Math Works [22] is utilized. 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 for the bridge in literature.

In order to determine the effects 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 9**: "Before", "During" and "After". The data analysis shows that meaningful results are not

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Figure 9. Three ranges on SHM data: "Before", "During" and "After".

obtained for "Before" range since the data is relatively distorted with traffic noise. Therefore, "After" range is considered for the comparison with "During" range. The obtained SHM data from the accelerometers mounted at the specific points of the bridge are utilized for structural identification of the bridge. The locations of the accelerometers are indicated with the considered directions in **Figure 10**. In this figure, the FFT analyses of the all accelerometers are also given for "During" range to determine modal characteristics of the bridge. This effort is repeated again for "After" range and the outcomes from frequency-domain analysis are summarized in **Table 2**.

As mentioned previously, the results from "After" range can be considered as natural vibration characteristics of the bridge. In addition to the other studies in literature, "After" range provides an opportunity to make calibration of the developed FE model. Therefore, the comparison of the outcomes from "After" with those from the developed FE model is made as given in **Table 3**.

According to % change in **Table 3**, the maximum error % in terms of frequency is obtained for Mode-2 with approximately 12%. For the other modes, the error is in the range of 0–3.0%.



Figure 10. The FFT analysis of the extreme wind data for "During" range.

Mode-2 is identified only from "During" range instead of "After" range considered for ambient vibration. Therefore, such high error in Mode-2 is dependent on that the mode is not be identified from "After" range. Generally, the error range for the first five mode shapes of the bridge is allowable level. These conclusions reveal that the considerations utilized in FE mod-

Mode number	Mode shape	Frequency/period [Hz]/[s]					
		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	$1 \mathrm{st} \mathrm{V}_{\mathrm{asym}}$	8.065	0.124	7.853	0.127	2.698	-2.362
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

Table 2. FFT analysis results for "During" and "After" ranges.

	Mode shape	FE model and experimental					
Mode number		FEM		Experimental		Change (%)	
		Period [s]	Freq. [Hz]	Period [s]	Freq. [Hz]	Period [s]	Freq. [Hz]
Mode-1	1st L _{sym}	12.984	0.077	12.766	0.078	1.707	-1.679
Mode-2	$1 \mathrm{st} \mathrm{V}_{\mathrm{asym}}$	7.217	0.139	8.065	0.124	-10.505	11.738
Mode-3	$1 { m st V}_{ m sym}$	6.453	0.155	6.250	0.160	3.251	-3.149
Mode-4	1st L _{asym}	4.926	0.203	4.967	0.201	-0.819	0.825
Mode-5	2nd V _{sym}	4.561	0.219	4.525	0.221	0.809	-0.803

Table 3. Comparison of FEM with those from experimental results.

eling of the Bosphorus Bridge are estimated well and are properly implemented. Accordingly, the developed FE model can be reliably utilized for advanced analysis of the bridge.

5. Utilization, decision-making and performance prediction

After the destructive earthquakes in last 2 decades in Turkey, Izmit (1999) and Duzce (1999) earthquakes, the public awareness of structural earthquake safety and performance of the existing structures in Turkey has increased progressively. General Directorate of Turkish State Highways (KGM) conducted a number of rehabilitation projects (JBSI) [23] for the most critical long-span bridges in Turkey, such as the Bosphorus Bridge. The related studies for the Bosphorus in literature were basically focused on the uniform support earthquake analysis (U-sup) of the bridge. Therefore, the multi-point earthquake analysis (Mp-sup) is required to better understand the seismic behavior of the Bosphorus Bridge. Considering these recommendations, this chapter aims at determining the effects of spatially varying earthquake motion on the Bosphorus Bridge using the calibrated FEM of the bridge in the previous section.

In order to simulate site-specific ground motions, the geographic coordinates of the bridge's support points have firstly to be determined. As indicated in **Figure 11**, the support coordinates of the bridge are obtained depending on the general coordinates of the bridge. **Figure 11** also presents the general considerations of the multi-point earthquake analysis of the bridge. Taking the scenario earthquake of Mw = 7.4 predicted to occur with the probability of 70% in next 30 years in Istanbul and these coordinates of the bridge into consideration, the stochastic modeling technique proposed in [24] is used to generate spatially varying site-specific earthquake ground motions.

The simulation process is performed and the acceleration ground motion time-histories (ATH) are generated for the Bosphorus Bridge. Although the process yields to the ATHs, the displacement ground motion time histories (DTH) need to be obtained for the multi-point earthquake analysis. Therefore, the DTHs are presented in **Figure 12** instead of the ATHs. As shown in **Figure 12**, the triple-direction (two horizontals and one vertical) ground motions are generated for the each considered multi-point, A, B, C and D. Total number of twelve ground motions are defined for the analysis.



Figure 11. Geographic coordinates and multi-support earthquake analysis considerations.



Figure 12. Simulated spatially varying site-specific multi-point earthquake records.

In **Figure 13**, the variation of the tensile strength of the main and the back stay cables is presented. The tensile strength value of the main cable increases as 74% and 78% under the Mp-sup compared to the U-sup and JBSI retrofit project, respectively. The different percentage change reveals that JBSI retrofit project is highly conservative in terms of sectional forces. Similar percentage change is obtained for the back-stay cable as shown in

Figure 13. All these results demonstrate the importance of the behavior of the deck. As to the main cable, the axial force of the main cable at the tower top-saddle also increases relatively. This increase is mostly related to the displacement of the deck and high increase in the tensile strength of the main and the back-stay cables. The results exhibit again the efficiency of the deck.

Another important point of the bridge is the base-section of the tower columns, which is first considered for the retrofit investigation for long-span bridges. The maximum value of the sectional forces including the axial force, the shear force and the bending moment is given in **Figure 13**. Due to noticeably high increase in the tensile axial force of the main and the



Figure 13. Comparison sectional force of the critical elements/points of the bridge.

back-stay cables, the axial force of the tower directly increased as 56% and 60% according to the U-sup and JBSI retrofit project, respectively. Although the shear force of the main cable at the tower top-saddle decreases, the shear force of the tower at the base considerably increases since the deck forces the tower at the level of the expansion joints (tower-deck connections) leading to high additional shear force. Therefore, the bending moment of the tower at the base increases highly as similar percentage increase to that of the shear force as shown in **Figure 13**.

6. Conclusion

In this study, St-Id concept is identified with implementation of the real suspension bridge, the Bosphorus Bridge. Each step of the concept from visualization to utilization is aimed to carry out for the bridge considering the strong wind event SHM data. The FEM calibration of the bridge is also made according to the outcomes from the experimental data analysis. Reliably established and calibrated FEM of the bridge is then adopted for the last step of St-Id approach, utilization/interpretation/decision-making. For this purpose, the multi-point earth-quake analysis (Mp-sup) of the bridge is conducted. Based on the consequences of the study, the following important points are concluded;

- Under the extreme wind loading, the first modal frequency (lateral symmetric) of the bridge decreased in the range of 12%. The change was only obtained in the deck modes of the bridge. The tower modes are not affected from the strong wind. 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.
- The comparison between FEM and experimental results proved that the developed model could be reliably adopted for advanced structural analysis and performance prediction of the bridge.
- Under multi-point seismic excitation, the most critical components are determined as the main deck and tower base-section. The high increase in sectional force of the main and side-span cables is identified to be pertinent to the response of the main deck.
- In spite of no movement in the lateral direction at the expansion joints according to project specifications of the bridge, lateral movement is obtained from the Mp-sup analysis at these points. Hence, shear key elements are proposed to be considered to provide the restricted lateral movement at the expansion joints.

Based on the consequences obtained from this study, St-Id approach is shown to be a robust technique for overall assessment of long-span bridges. Apart from the implementation of the all steps of St-Id, each step also gives important results, which means that the concept can be divided into certain groups according to the aim of the study. Therefore, St-Id approach is recommended to be considered for performance prediction and structural condition evaluation of long-span cable-supported bridges.

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