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THE EFFECTS OF MULTI-SUPPORT EARTHQUAKE EXCITATION ON SEISMIC PERFORMANCE OF THE BOSPHORUS BRIDGE

S. Bas [1, 2], N. M. Apaydin [3] and E. Harmandar[4]

[1] *Res. Assist., Department of Civil Engineering, Bartin University, 74100 Bartin, Turkey, sbas@bartin.edu.tr*
[2] *PhD Cand., Graduate School of Science, Engineering and Technology, Istanbul Technical University, 34469 Istanbul, Turkey, selcukbas@itu.edu.tr*
[3] *Assoc. Prof. Dr. and Head of Structure Department, General Directorate of Turkish State Highways, 06100, Ankara, Turkey, napaydin@kgm.gov.tr*
[4] *Dr., Department of Civil Engineering, Osman Gazi University, 26480 Eskisehir, Turkey, ebru.harmandar@gmail.com*

Abstract

In this study, it is aimed at better understanding the response of the Bosphorus Bridge to earthquake excitation by considering the specifically produced strong ground motions for the bridge. The Bosphorus Bridge, one of the first long-span bridge in Turkey, is located on the Bosphorus Straits and has a vital function of connecting the two continents, the Asian and the European. Since opened to traffic in 1973, the bridge has been subjected to various extreme events, such as wind, truck, marathon and earthquake loads. Due to high importance of earthquake, the bridge needs to be investigated under the realistic earthquake to take required measures to no interruption in its operation. For this purpose, the multi-support earthquake analysis (MSA) of the bridge is performed and the results from the analysis are compared with those from the previous study of the uniform-support analysis and the retrofit project. Based on the project drawings, 3-D advanced finite element-FE model of the bridge is established. The developed FE model is then verified in terms of modal characteristics with the previous studies in literature. Considering the geometric coordinates of the bridge's supports, site-specific strong ground motions including the Mw=7.5 scenario earthquakes on the main Marmara Fault are produced. With the help of these efforts, the non-linear time-history analysis is conducted for multi-support excitation. The outcomes from the analysis is compared and the effects of multi-support earthquake excitation on the structural behavior of the bridge are identified. Based on the results from the MSA of the bridge, the tensile force of the main and side span cables noticeably increased under the MSA compared to the uniform support and retrofit project. These results directly affected the axial force of the main cable at the tower top saddle; however, balancing effect of the deck at the expansion joint level led to the decrease in the shear force at the tower top saddle. As to the sectional actions at the tower base section, the compressive axial force, shear force and bending moment were relatively increased and such increase is related to the increase in the main and side span cables. This study demonstrated that the previously obtained results for the critical components of the bridge cannot satisfy compared to the MSA. Therefore, the MSA should be considered to make reliable seismic analysis and to conduct reliable structural rehabilitation for long-span bridges. Another important result of the study is that general procedure and rules for the multi-support earthquake analysis and site-specific ground motion have to be included in the codes.

Keywords: suspension bridge; multi-support earthquake excitation; site-specific ground motion, seismic performance

1. Introduction

Long-span bridges are special structures compared to other structures. They are not only a component of transportation system of country/state but also are kept in mind as the symbol of their located region. Hence, many transportation departments pay special attention to this type of bridges to continue their service without any interruption. Of many costs of long-span bridge, such as maintenance, management i.e., rehabilitation cost for structural safety constitutes of the major part of allocated budget. Due to higher complexity and vulnerability of long-span bridges to unpredictable extreme events than other type of structures, such as seismic, strong wind and marathon etc., better understanding the structural behavior of them under these events become inevitable for reliable structural rehabilitation. For detecting changes in structural response of bridges, Structural Health Monitoring-SHM system provides a cutting-edge technology being recently implemented in most long-span bridges. In addition, a center for SHM system has also been included at the beginning of the newly designed long-span bridge in order to reduce needs for structural rehabilitation.

Along with the aforementioned loading events, seismic load and seismic behavior are first considered from the bridge authority/bridge owner owing to the destructive response of earthquakes. In literature; therefore, a number of various studies were conducted to identify earthquake behavior of cable-supported bridges. Ambient vibration test was carried out to obtain natural frequency and associated mode shapes of structural components of the Golden Gate Bridge. A good relationship between experimental and numerical results was obtained [1, 2]. The effects of travelling seismic load on vertical behavior of the Golden Gate Bridge of San Francisco was also investigated in time and frequency domains. Internal forces and displacements values were determined for the critical section of the bridge, and the results obtained from time domain were compared with those from frequency domain [3]. Similar study was performed for lateral response of the Golden Gate Bridge. The study indicated that uniform ground motion could not be considered and that a number of vibration modes have to be required to reliably identify the response of the bridge [4]. Site-specific ground motions were utilized for stochastic earthquake analysis of a cable-stayed bridge. From the analysis, the supports of the bridge were relatively affected under spatially varying earthquake motions [5, 6]. Recently conducted studies [7-11] were also focused on the investigation of the effects of multi-support earthquake excitation on existing long-span bridges.

Fig. 1 – General view from the Bosphorus Bridge

After from the destructive earthquakes in last two 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 [12] for the most critical long-span bridges in Turkey, the Bosphorus Bridge as shown in Fig. 1 and the Fatih Sultan Mehmet Bridges. Besides, researchers in bridge engineering carried out important studies for these bridges. The first informative and prominent studies were made on system identification of the bridges based on the experimental results [13-17]. Ambient vibration test was performed to extract the vibration properties of the Bosphorus Bridge using monitoring data [13, 14]. They resulted in the studies with a closure agreement between experimental outcomes and those from numerical analysis. A much more comprehensive study on full-scale dynamic testing of the Fatih Sultan Mehmet Bridge was conducted to identify experimental and theoretical dynamic characteristics of the bridge. Utilizing data recorded from the reference accelerometer installed on the critical points at the deck and the towers of the bridge, lateral, vertical, torsional and longitudinal mode shapes and associated frequencies were extracted [15]. In other studies [16, 17], dynamic properties of the Fatih Sultan Mehmet Bridge and earthquake-induced behavior of the bridge were also investigated. Recently new studies were also conducted for these bridges [18-23]. In order to determine natural vibration characteristics of the Bosphorus Bridge and to verify experimental results with those from the other studies in literature, ambient vibration survey was utilized and finite element model-FE of the bridge was established [18]. Relatively detailed investigation was performed for the 2nd Bosphorus Bridge. Along with experimental testing results, earthquake behavior of the bridge was also investigated considering uniform-support excitation [19]. The needs for considering the multi-support earthquake excitation analysis were also stated for these bridges in [20]. In that study, dampers replaced to the tower-deck points close to rocker bearings was recommended so as to reduce longitudinal translation of the deck. Based on this study, the multi-point earthquake analysis was conducted for the Fatih Sultan Mehmet Bridge [22]. This study yielded to relatively important results for reliable rehabilitation of the bridge. In this study, another significant consideration was to generate site-specific earthquake ground motion for the bridge taking local site properties of the bridge's supports.

Based on the studies, a detailed investigation on structural performance of the Bosphorus Bridge under multi-support earthquake excitations has not been made till now. In this study, the effects of spatially varying earthquake motion on the Bosphorus Suspension Bridge are determined. For this objective, the results from the multi-support analysis (MSA) are compared with those from the uniform-support analysis [20] and retrofit project [12]. Developing 3-D advanced FE model of the bridge, non-linear geometric time-history analysis including P-Δ effects is performed for the MSA. Specifically produced seismic motions considering the geographic coordinates of the bridge supports of anchorage, approaching span and tower at each continent are used in the analysis. The study showed that the MSA should be considered to make reliable seismic analysis and to conduct reliable structural rehabilitation for long-span bridges. Another important result of the study is that general procedure and rules for the multi-support analysis and site-specific ground motion have to be included in the codes.

2. Description of the Bosphorus Bridge

The Bosphorus Bridge is the longest suspension bridge opened to service in 1973. The bridge serves as vital link for the Motorway-1 (O-1) connecting the city center of Istanbul. Apart from the main span, the bridge has two approaching spans supported at the base instead of hangers. The main span, Ortakoy and Beylerbeyi side span

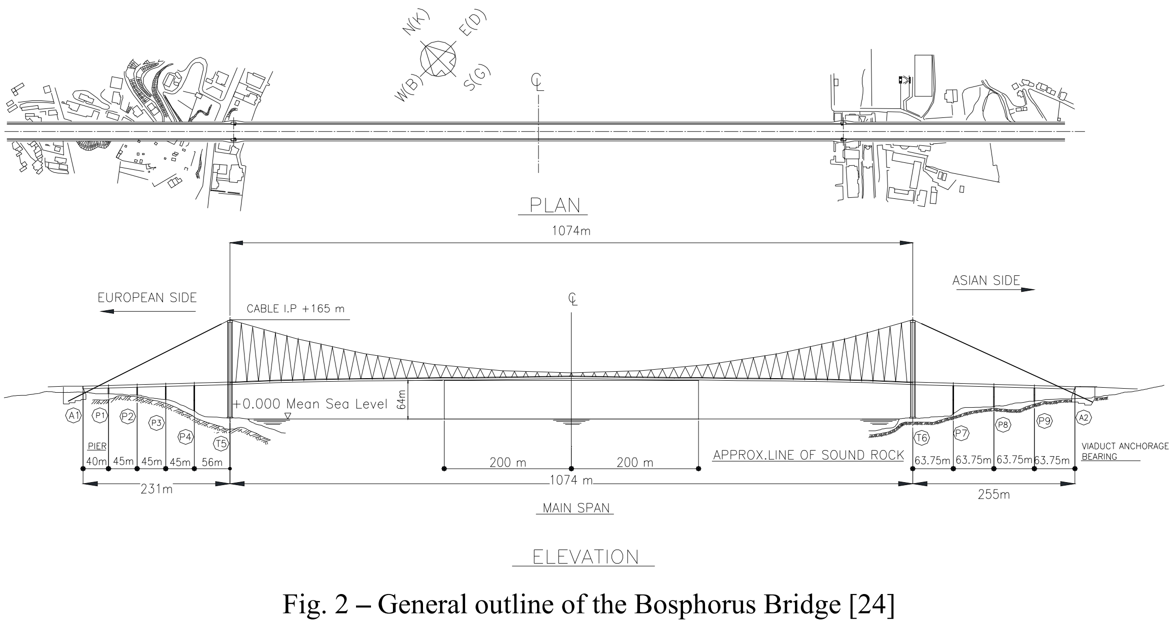

Fig. 2 – General outline of the Bosphorus Bridge [24]

have a length of 1074 m, 231 m and 255 m, respectively. The height of the tower with tapered box section is 165 m and the width of the steel box deck designed to carry six lanes traffic loading is 33.4 m. Plan and elevation of the Bosphorus Bridge is given in Fig. 2. The bridge has also camber of approximately 8.0 meter at the deck mid-span. Approach viaducts consist of continuous steel box beams restrained from the steel circular box columns and cross steel girder I-beams.

3. Finite Element Modeling of the Bridge

The detailed 3-D finite element model of the bridge is developed based on the assumptions of equivalent frame elements using the sectional properties of the components of the bridge. For this aim, elaborate cross-sectional properties of the main deck, the towers, the portal beams, continuous box beams are adopted depending the full-scale section including longitudinal and transverse bracing plates. Considering the sectional parameters of moment of inertia, shear area, torsional constant, plastic modulus etc. these components are modeled as equivalent frame element. Cable element is utilized for the main cable, the back-stay cable and the hanger elements. Sag effect is also considered for these elements. Asphalt and concrete surface are also modeled with shell elements. Deck-tower and approach viaducts-tower connections are provided by link elements with no mass. Since the main deck of the bridge can move limitedly in longitudinal direction through the rocker bearings, gap elements are used for reliable simulation. These details and FE model of the bridge are shown in Fig. 3. The SAP2000 software [25] was used for all efforts to establish FE model of the bridge.

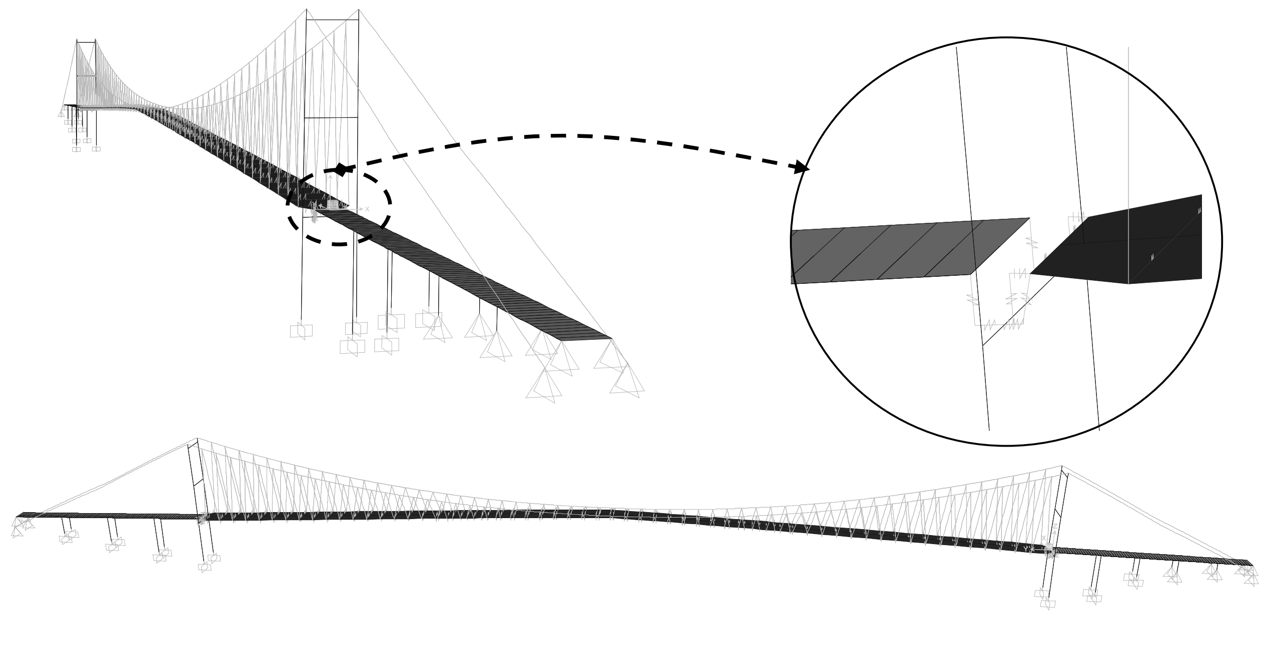

Fig. 3 – 3-D FE Model of the Bosphorus Bridge

4. Modal Analysis of the Bridge

In order to verify the developed FE model of the bridge, modal analysis is performed, and the results from the analysis are compared with the previous studies including experimental and theoretical results. In Fig. 4, mode shapes and corresponding frequencies are depicted. In addition, comparative results are given in Table 1. As shown in the table, a closure agreement is obtained when compared to the studies in literature.

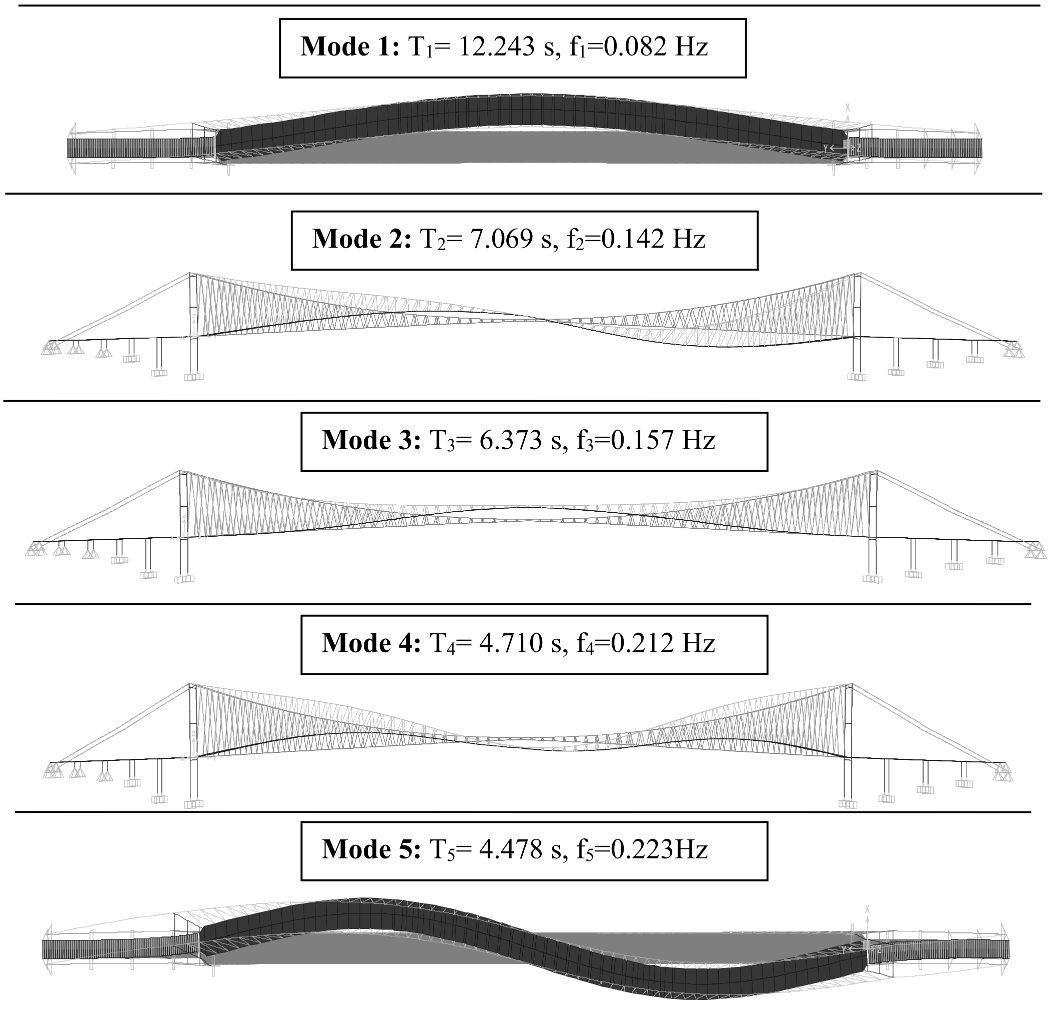

Fig. 4 – Mode shapes and corresponding frequencies

Table 1 – Comparative results for the modal analysis

Mode Number	Mode Shape	Frequency (cyc/s)				
		[13]	[14]	[18]	[20]	Current study
Mode-1	1st L_{sym}	0.072	0.073	0.069	0.074	0.082
Mode-2	1st V_{asym}	0.144	0.126	0.125	0.120	0.142
Mode-3	1st V_{sym}	0.202	0.165	0.190	0.158	0.157
Mode-4	2nd V_{sym}	0.225	0.180	0.223	0.210	0.212
Mode-5	1st L_{asym}	0.323	0.218	0.273	0.262	0.223

L_{sym}: Lateral symmetric; L_{asym}: Lateral asymmetric; V_{sym}: Vertical symmetric; V_{asym}: Vertical asymmetric

5. Simulation of Site-Specific Earthquake Motions

Considering the geographic properties of the bridge as shown in Fig. 5 and the Mw=7.5 scenario earthquakes on the main Marmara Fault, site-specific earthquake motions are produced utilizing the stochastic modeling technique (FINSIM-FINite fault SIMulation program) [26, 27]. After from the simulation of the records, they are refined with principal data processes of baseline correction and detrendending. In Fig. 6, displacement time-histories are given for four support points. Owing to less enough width of the deck, four ground motions were generated instead of eight ground motions as depicted in Fig. 5. Thus, total number of four multi-supports were taken into consideration in the MSA.

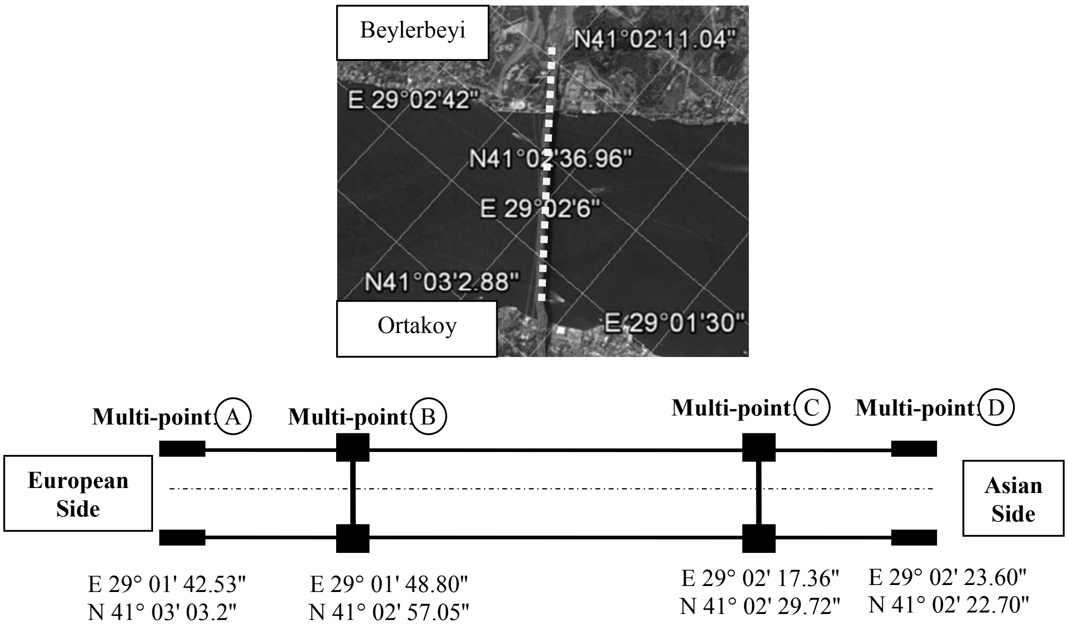

Fig. 5 – Geographic coordinates of the bridge

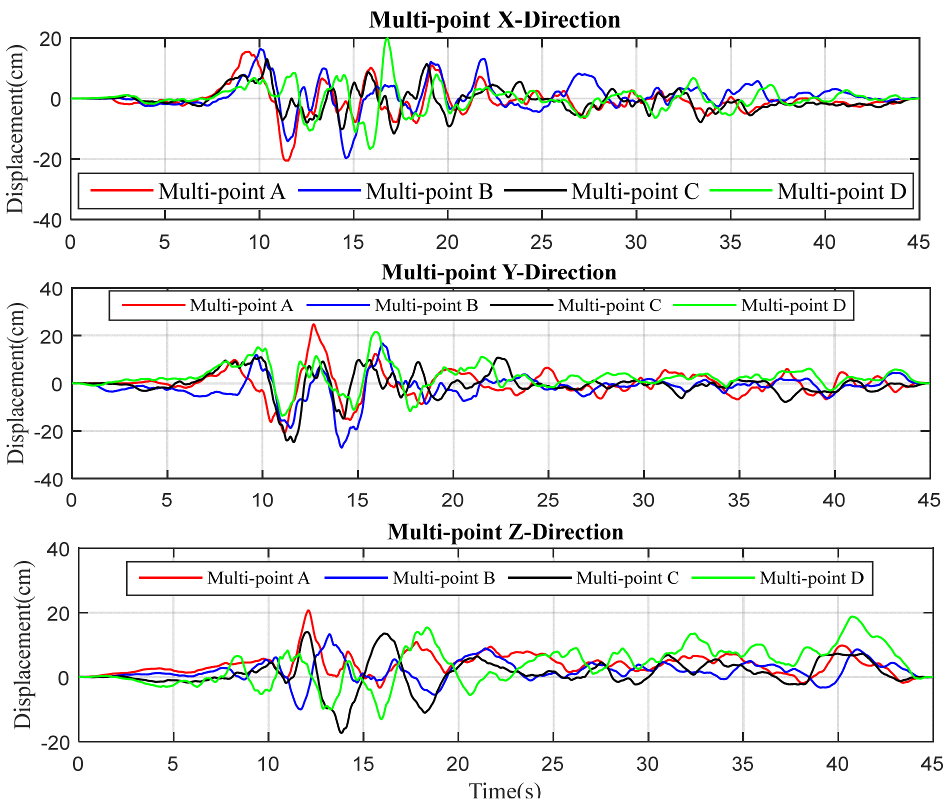

Fig. 6 – Site-specific earthquake records for the multi-support analysis

6. Multi-Support Earthquake Analysis (MSA)

The multi-support earthquake analysis of the Bosphorus Bridge is performed considering schematic representation given in Fig. 7. Multi-supports are defined as A, B, C and D corresponding to two anchorage supports and two tower supports. This analysis is achieved by support displacement controlled by the displacement time-history of each support. Total number of 12 earthquake time-histories are adopted for the non-linear geometric time-history analysis. This produce developed in [22] for the Fatih Sultan Mehmet Bridge is utilized in this study for the Bosphorus Bridge.

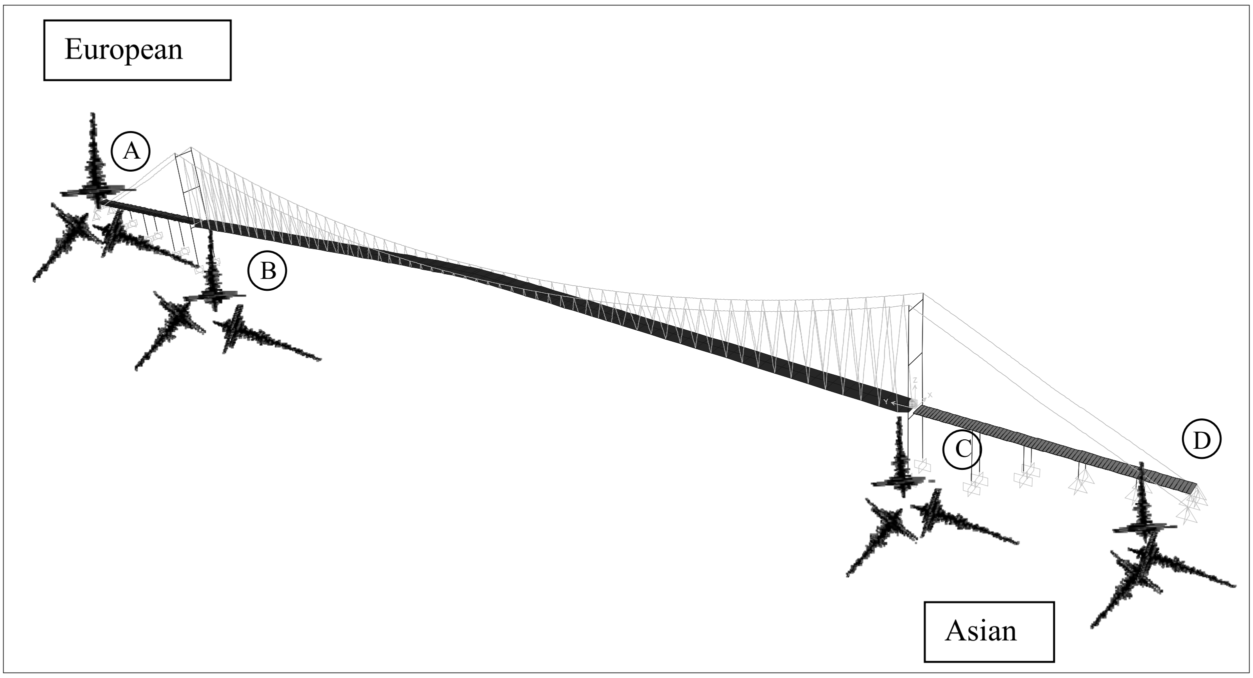

Fig. 7 – The multi-support earthquake analysis procedure of the Bosphorus Bridge

7. Results and Conclusion

The results from the MSA are given in Table 2 for the critical elements. Besides, the results of the uniform-support analysis conducted in [20] and retrofit project [12] are presented in this table to compare them with the MSA. As given in Table 2, the tensile force of the main and the side span cables increased highly according to the both previous studies of the uniform-support analysis and retrofit project. Also, the percentage increase in these studies is almost same. Similar outcomes were obtained for the side-span cable as 72% and %75 compared to the uniform support analysis and retrofit project, respectively. Such high increase in the main and side span cables led to relatively increase in the axial force of the main cable at the tower top saddle. Despite of the increase in axial force, the shear force at the tower top saddle decreased due to balancing effect of the deck on the tower at the deck level. These results denoted the dominated effect of the deck on the structural behavior of long-span suspension bridge. When it comes to the tower base section, the high axial compressive force change of 61% is directly pertinent to relatively increase in the tensile axial force of the main and side span cables. The increase in the shear force at the tower base section results from balancing effect of the deck at the deck level on the tower base. Depending on the increase in the shear force, the bending moment at this section increased as 30 % similar to that of the shear force. From these results, the deck is proved to be the most effective component under the MSA. The tower also has also critical structural member of the bridge since the modal properties of the bridge can be changed by the tower modes. The outcomes from this study denoted that the tower leg from the base to the deck level should be strengthened by increasing the sectional capacity of the section. For this aim, additional stiffener elements can be placed into inner surface of the box tower section.

Table 2– The results from the multi-support earthquake analysis

Structural elements	Multi-support earthquake analysis (Max.)	Uniform-support earthquake analysis (Max.)	Retrofit project	Change (%)	Change (%)
	Current study	[20]	[12]	Current study&[20]	Current study&[12]
Tensile Force of Main Cable (kN)	238556	137000	133674	74	78
Tensile Force of Side Span Cable (kN)	249939	145000	142687	72	75
Axial Force of Main Cable at Tower Top Saddle (kN)	189037	117100	111100	61	70
Shear Force of Main Cable at Tower Top Saddle (kN)	3022	3591	4513	-16	-33
Base Section of Tower Column Axial Force (kN)	204796	131448	127578	56	61
Base Section of Tower Column Shear Force (kN)	5840	4920	4049	19	44
Base Section of Tower Column Bending Moment (kN.m)	194132	168653	149604	13	30

The outcomes in the present study indicated the importance of the multi-support earthquake analysis, especially for large-scale structures, and that the MSA should be taken into account to conduct reliable structural rehabilitation. Also, this study results in a remarkable conclusion that general procedure and requirements for performing the multi-support earthquake analysis and generating site-specific ground motion need to be determined and to be included in the codes.

8. References

[1] Abdel-Ghaffar AM, Scanlon RH (1985): Ambient vibration studies of Golden Gate Bridge: I. Suspended structure. *Journal of Engineering Mechanics ASCE*, **111**, 463–82.

[2] Abdel-Ghaffar AM, Scanlan RH (1985): Ambient vibration studies of Golden Gate Bridge: II. Pier-tower structure. *Journal of Engineering Mechanics ASCE*, **111**, 483–99.

[3] Abdel-Ghaffar AM, Rubin LI (1984): Response of suspension bridges to travelling earthquake excitations: Part I. Vertical response. *Soil Dynamics and Earthquake Engineering*, **3**, 62–72.

[4] Abdel-Ghaffar AM, Stringfellow RG (1984): Response of suspension bridges to travelling earthquake excitations: Part II. Lateral response. *Soil Dynamics and Earthquake Engineering*, **3**, 73–81.

[5] Dumanoglu AA, Soyluk KA (2003): Stochastic analysis of long span structures subjected to spatially varying ground motions including the site-response effect. *Engineering Structures*, **25**, 1301–10.

[6] Dumanoglu AA, Severn RT (1990): Stochastic response of suspension bridges to earthquake forces. *Earthquake Engineering and Structural Dynamics*, **19**, 133–52.

[7] Zhao B, Wang Y, Chen Z, Shi Y, Jiang Y, Wang Y (2015): Research on the random seismic response analysis for multi- and large-span structures to multi-support excitations. *Earthquake Engineering and Engineering Vibration*, **14**(3), 527–38.

[8] Karmakar D, Ray-Chaudhuri S, Shinozuka M (2012): Seismic response evaluation of retrofitted Vincent Thomas Bridge under spatially variable ground motions. *Soil Dynamics and Earthquake Engineering*, **42**, 119–27.

[9] Soyluk K, Sicacik EA (2012): Soil–structure interaction analysis of cable-stayed bridges for spatially varying ground motion components. *Soil Dynamics and Earthquake Engineering,* **5**, 80–90.

[10] Alexander NA (2008): Multi-support excitation of single span bridges, using real seismic ground motion recorded at the SMART-1 array. *Computers and Structures*, **86**(1–2), 88–103.

[11] Wang J, Carr AJ, Cooke N, Moss PJ (2009): The response of a 344 m long bridge to non-uniform earthquake ground motions. *Engineering Structures*, **31**(11), 2554–67.

[12] Japanese Bridge and Structure Institute—JBSI (2004): Seismic reinforcement of large scale bridges in Istanbul. *Project reports and basic design documents for the project prepared for the General Directorate of State Highways*, Turkey.

[13] Erdik M, Uckan E (1989): Ambient vibration survey of the Bogazici Suspension Bridge. Istanbul-Turkey. *Technical Report No: 89-5*, Department of Earthquake Engineering Kandilli Observatory and Earthquake Research Institute, Bogazici University, Turkey.

[14] Brownjohn JMW, Dumanoglu AA, Severn RT, Blakeborough A (1989): Ambient vibration survey of the Bosporus Suspension Bridge. *Earthquake Engineering and Structural Dynamics*, **18**, 263–283.

[15] Brownjohn JMW, Severn RT, Dumanoglu AA (1992): Full-scale dynamic testing of the 2nd Bosporus Suspension Bridge. *The 10th World Conference on Earthquake Engineering*, Madrid, Spain.

[16] Brownjohn JMW, Dumanoglu AA, Severn RT (1992): Ambient vibration survey of the Fatih Sultan Mehmet (Second Bosporus) Suspension Bridge. *Earthquake Engineering and Structural Dynamics*, **90**, 710–24.

[17] Dumanoglu AA, Brownjohn JMW (1992): Seismic analysis of the Fatih Sultan Mehmet (the Second Bosphorus) Suspension Bridge. *Earthquake Engineering and Structural Dynamics*, **5**, 881– 906.

[18] Kosar U (2003): System identification of Bogazici Suspension Bridge. *M.Sc. Thesis*, Department of Earthquake Engineering, Bogazici University, Istanbul, Turkey.

[19] Apaydın NM (2002): Seismic analysis of Fatih Sultan Mehmet Suspension Bridge. *Dissertation*, Bogazici University, Turkey.

[20] Apaydın N (2010): Earthquake performance assessment and retrofit investigations of two suspension bridges in Istanbul. *Soil Dynamics and Earthquake Engineering*, **30**, 702–10.

[21] Erdik M, Apaydin N (2005): *Earthquake response of suspension bridges*. Vibration Problems, ICOVP, Volume 111 of the series Springer Proceedings in Physics

[22] Apaydin NM, Bas S, Harmandar E (2016): Response of the Fatih Sultan Mehmet Suspension Bridge under spatially varying multi-point earthquake excitations. *Soil Dynamics and Earthquake Engineering*, **84**, 44-54.

[23] Bas S (2008): Dynamic Analysis and Seismic Performance Assessment of the two Approach Viaduct of the Bosphorush Bridge. *MSc. Thesis*, Department of Structural Earthquake Engineering, Istanbul Technical University, Istanbul, Turkey.

[24] Freeman, Fox and Partners Consulting Engineers (1968): Bosporus Bridge towers, suspended structures, cables, anchorage drawings, Westminster, London.

[25] SAP2000v18.0.1 (2015): Integrated structural finite element analysis and design of structures. *Computers and Structures Inc*., Berkeley, CA, USA.

[26] Beresnev IA, Atkinson GM (1998): FINSIM–a FORTRAN program for simulating stochastic acceleration time histories from finite faults. *Seismological Research Letters*, **69**, 27–32.

[27] Harmandar E (2009): Spatial variation of strong ground motion, *Dissertation*, Bogazici University, Istanbul.