Dynamic Analysis of a Suspension Bridge Using CFRP Composite Material

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ABSTRACT

Fiber reinforced polymer (FRP) is a class of advanced composite materials used in civil engineering because of their advantages when these materials are compared to traditional ones. These advantages are light weight, high stiffness-to-weight and strength-to-weight ratios, damping capabilities, and high resistance to environmental degradation. This paper presents a numerical study on the dynamic analysis of a suspension bridge subjected to earthquake ground motion using carbon fiber reinforced polymer (CFRP) materials. Bosporus Suspension Bridge is selected for application. The cross-sectional areas of CFRP elements are determined by the principle of either equivalent-stiffness or equivalent-strength methods. The YPT330 component of Yarımca station records of 1999 Kocaeli Earthquake is chosen as a ground motion. The calculated displacement and internal forces occurring in the towers and deck are examined. It is seen from the analyses results that, CFRP material are more effective than steel material for suspension bridges.

INTRODUCTION

At present, the use of suspension bridges has increased. They are built for either crossing the long spans (>550 m) or giving to rise to the usage of domains under the bridge. Suspension bridges consist of elements such as tower, cables, deck and hangers which are usually made of traditional steel. There is no doubt that steel is today the most common materials preferred in the construction of the long span bridge. The traditional steel materials were unable to respond the need with the developing technology because of its self-weight, low corrosion resistance, fatigue performance and high replacement and maintenance cost. Hence, this bring forward a new material, the name of fiber reinforced polymer (FRP), used in bridge application.

FRP is a class of advanced composite materials used in civil engineering application as the construction of the first all composite bridge. The use of FRP composite materials, which are used for deck, beams, cables and superstructures, are gaining popularity for bridges in worldwide. There are various FRP composite materials used in constructions of bridge. One of these CFRP composite materials is accepted as a perfect material to build large-span structures due to low weight, high strength, corrosion resistance and low maintenance cost. In the present time, CFRP composite materials are commonly preferred long span bridges due to their beneficial properties. Thus, the dynamic behavior of this kind of structures under the earthquake must be accurately determined.

In the literature, some papers exist about the dynamic analysis of the bridges using FRP composite materials. Khalifa et al. [1] described the analysis and design methodology of a FRP cable-stayed footbridge, and studied the behaviors of the bridge under the static and dynamic loads. Hodhod and Khalifa [2] investigated the dynamic characteristics and the seismic response of a glass FRP cable-stayed footbridge and compared to a conventional steel-concrete cable-stayed footbridge. Meiarashi et al. [3] designed of two same dimensional specification highway suspension bridges made of conventional steel and advanced all-composite CFRP, and analyzed their life-cycle cost. They also investigated both static and dynamic analyses and presented the results briefly. It was concluded that the composite bridge becomes more life-cycle cost-effective than the conventional steel bridge, due to the drastic cost reduction of the composite product. The dynamic responses of three FRP composite bridges were presented by Aluri et al [4]. Zhang and Ying [5] investigated the dynamic behavior, aerostatic and aerodynamic stability of suspension and cable-stayed bridges using CFRP cables. They also discussed the feasibility of using CFRP cables in suspension and cable-stayed bridges on the wind resistance. Wang and Wu [6] studied about the integrated high-performance thousand-meter scale cable-stayed bridge with hybrid FRP cables. In the study, the suitability of hybrid basalt and carbon FRP cables instead of steel cables was investigated. Cavdar et al [7] carried out stochastic finite element analysis of long-span bridges with CFRP cables under earthquake ground motion. A comparative study on static and dynamic responses of FRP composite and steel suspension bridges presented by Adanur et al [8]. Kuyumcu and Ates [9] observed the behavior of cable-stayed bridge under spatially varying earthquake ground motion by taking into account soil-structure interaction effect.

The purpose of this work is to assess dynamic behaviour of a suspension bridge subjected to earthquake ground motion using CFRP materials in lieu of steel materials. Both equivalent-stiffness and equivalent-strength methods are used to determine the cross-sectional areas of CFRP elements such as tower, deck, cable and hangers.

FORMULATION

The cross-sectional areas of CFRP elements can be determined by the principle of either equivalent-stiffness or equivalent-strength, which is described as follows [10]:

Equivalent-strength:

$$[\sigma]_{CFRP} A_{CFRP} = [\sigma]_{steel} A_{steel} \tag{1}$$

Equivalent-stiffness:

$$E_{CFRP} A_{CFRP} = E_{steel} A_{steel} \tag{2}$$

Where $[\sigma]_{CFRP}$, $[\sigma]_{steel}$ are the allowable tensile stress of CFRP and steel respectively, E_{CFRP}, E_{steel} are the elastic modulus of CFRP and steel respectively, A_{CFRP}, A_{steel} are the cross-sectional areas of CFRP and steel elements respectively.

The material properties of the steel and CFRP, were obtained from the literature [3-11], are given in Table 1. According to the material properties shown in Table 1, the cross-sectional areas of CFRP elements can be determined as follows:

Table 1 Material properties of the element

Elements	Parameter	CFRP	Steel
Deck	The allowable tensile stress (MPa)	102	137.3
	Modulus of elasticity (kN/m^2)	64000000	205000000
Tower	The allowable tensile stress (MPa)	147	137.3
	Modulus of elasticity (kN/m^2)	122000000	205000000
Cable	The allowable tensile stress (MPa)	980	980
	Modulus of elasticity (kN/m^2)	160000000	193000000
Hanger	The allowable tensile stress (MPa)	980	980
	Modulus of elasticity (kN/m^2)	160000000	162000000

Equivalent-strength:

$$A_{CFRP} = A_{steel} \tag{3}$$

Equivalent-stiffness:

$$A_{CFRP} = 1.25 A_{steel} \tag{4}$$

APPLICATION

The Bosporus suspension bridge (Figure 1) connecting the Europe and Asia Continents in Istanbul, Turkey is a 1560 m long with a main span of 1074 m and side spans of 231m and 255m on the European and the Asian sides respectively, without any side spans supported by cables. Construction of the bridge started in 1973 and completed in 1983. The decks of the side spans at the bridge are supported on the ground by piers. The bridge has flexible steel towers of 165m high, inclined hangers and a steel box-deck. The horizontal distance between the cables is 28 m and the roadway is 21 m wide, accommodating three lanes each way. The roadway at the mid-span of the bridge is approximately 64 m above the sea level.

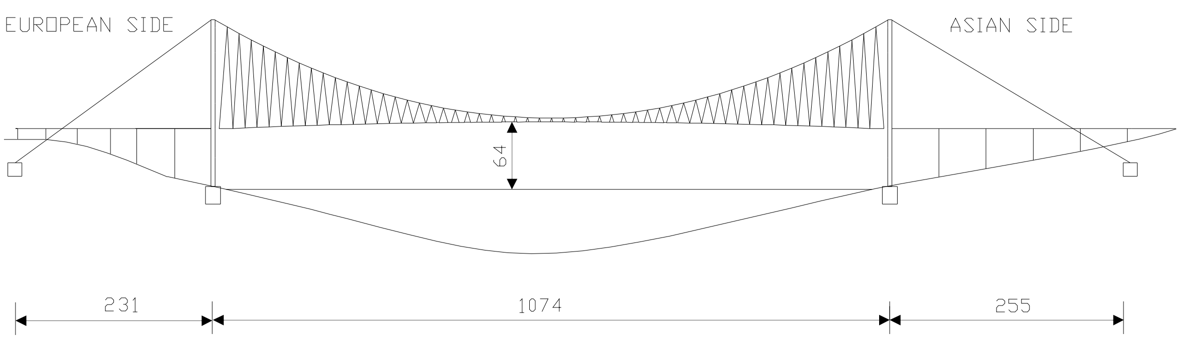

Figure 1 Bosporus Suspension Bridge and its schematic representation (dimensions as m)

Three dimensional finite element model of the bridge is created by SAP2000 [14] software using both steel and CFRP composite materials. To investigate the dynamic analysis of the Bosporus Bridge subjected to earthquake ground motion using CFRP materials, 3D finite element model (Figure 2) is considered, in which the deck, towers and cables are represented by 241 beam elements, and the hangers are represented by 236 truss elements in the model. The selected finite element model of the bridge is represented by 1372 degrees of freedom. The materials and section properties of the elements used in the finite element model are given in Table2.

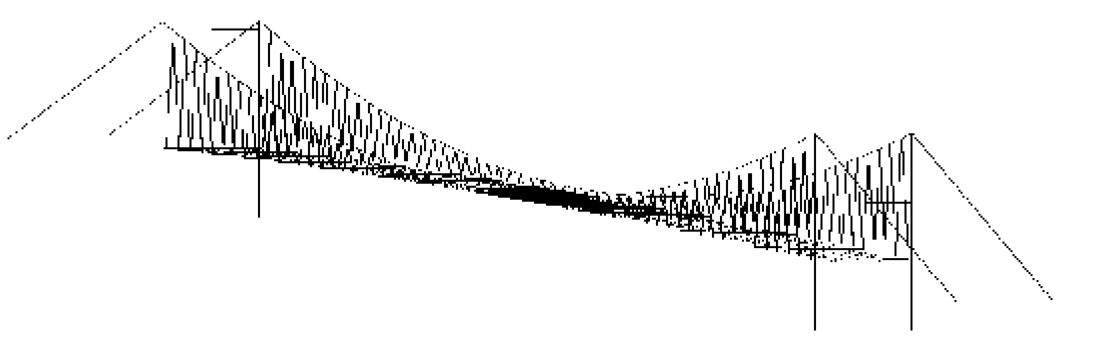

Figure 2 3D finite element model of Bosporus Suspension Bridge

Table 2 Material and section properties of the element of Bosporus Bridge

Elements	Area *(m^2)*	Modulus of elasticity *(kN/m^2)*	Torsional constant *(m^4)*	Moment of inertia (I_{33}) *(m^4)*	Moment of inertia (I_{22}) *(m^4)*
Deck	0.851	205000000	3.35	1.238	63.61
Tower	0.68	205000000	4.481	4.9	2.2
Main Cable	0.205	193000000	-	-	-
Side Cable	0.219	193000000	-	-	-
Hanger	0.0021	162000000	-	-	-

In the dynamic analysis, time history method is used. Yarımca Petrochemistry Institution acceleration records of 1999 Kocaeli Earthquake are utilized as ground motion (Figure 3) [12].

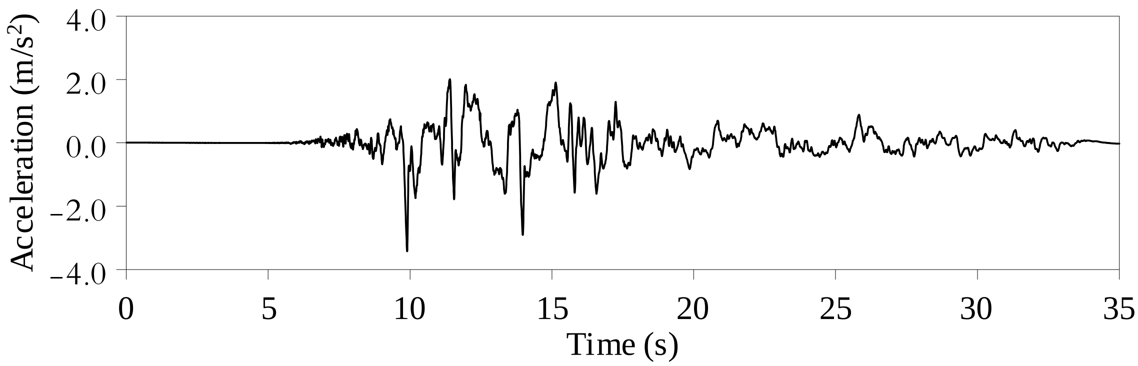

Figure 3 The time-history of ground motion acceleration of 1999 Kocaeli earthquake

In this paper, three different finite element analyses are carried out to compare the dynamic behavior of Bosporus Suspension Bridge. To this end, CFRP and steel materials are used separately, in which the cross sectional area of the CFRP elements are determined by the principle of either equivalent-stiffness or equivalent-strength methods. Damping coefficients of the FRP composite structures are higher than those of typical steel structures [13]. In the analysis, a damping ratio of %2 is considered for the steel bridge model, while a %5 damping ratio is used for the CFRP composite bridge model. Also, geometrical non-linearity is taken into consideration in the analyses. The eigenvalue is solved for the steel and CFRP composite bridge models, eigensolutions are obtained for the first 20 mode shapes of the considered bridge models and their frequencies extracted. Table 3 summarizes the frequencies and periods of the selected modes for either steel cables or CFRP cables.

Table 3 Effects of CFRP materials on structural frequencies and period

Mod Number	Steel Bridge		CFRP-1		CFRP-2	
	F (Hz)	*P (s)*	*F (Hz)*	*P (s)*	*F (Hz)*	*P (s)*
1	0.11269	8.874161	0.19454	5.140332	0.18981	5.268460
2	0.15226	6.567736	0.20899	4.784947	0.28336	3.529050
3	0.20334	4.917938	0.25253	3.960001	0.33195	3.012537
4	0.25156	3.975197	0.26532	3.768988	0.34599	2.890297
5	0.26123	3.828101	0.26946	3.711159	0.35854	2.789088
6	0.27450	3.642976	0.30777	3.249225	0.36150	2.766238
7	0.27806	3.596288	0.31594	3.165125	0.42711	2.341319
8	0.28133	3.554578	0.38808	2.576814	0.46866	2.133753
9	0.29923	3.341856	0.40556	2.465743	0.49588	2.016606
10	0.34267	2.918248	0.45302	2.207396	0.52764	1.895214
11	0.34823	2.871637	0.45881	2.179565	0.60150	1.662520
12	0.39339	2.542008	0.51952	1.924848	0.60587	1.650530
13	0.40036	2.497751	0.51964	1.924417	0.60683	1.647895
14	0.42400	2.358480	0.54793	1.825065	0.64154	1.558750
15	0.44639	2.240219	0.55478	1.802525	0.72784	1.373931
16	0.46059	2.171123	0.63904	1.564838	0.73327	1.363757
17	0.46246	2.162366	0.65082	1.536527	0.80185	1.247111
18	0.47200	2.118659	0.67550	1.480392	0.84186	1.187852

19	0.51172	1.954205	0.71520	1.398213	0.85338	1.171808
20	0.55993	1.785952	0.72752	1.374526	0.95973	1.041956
F: Frequency ;P:Period; CFRP-1:Equivalent-strength;CFRP-2: Equivalent-stiffness						

Although the different mode sequences, in general, the steel and CFRP bridge models have similar mode shapes. As seen in Table 3, as CFRP materials are used, the frequencies obtained from CFRP-1 and CFRP-2 bridge models are greater than the frequencies of steel bridge model. The frequencies which are obtained in the case of equivalent stiffness are bigger compared to the other bridge models. Because of lower self-weight of the CFRP composite bridges relative to steel bridge, the frequencies of the CFRP bridges are bigger than the frequencies of steel bridge.

Figure 4 shows the mean of vertical displacements and bending moments along the bridge deck calculated for both steel bridge and CFRP bridge. The maximum displacements at the middle of the bridge deck for the steel, CFRP-1 and CFRP-2 bridge models occurred as 0.1994 m, 0.06156 m and 0.09329 m, respectively. The maximum bending moments for the steel, CFRP-1 and CFRP-2 bridge models obtained as 4266 kNm, 918 kNm and 2375 kNm, respentively. As seen in Figure 4, when CFRP materials are used, the displacement and bending moments along the bridge span are decreased.

Figure 5 illustrates the mean of displacement and bending moment values height of the bridge tower. The maximum displacements at the top of the bridge tower for the steel, CFRP-1 and CFRP-2 bridge models are 0.011479 m, 0.003291 m and 0.003664 m, respectively. The maximum bending moments for the steel, CFRP-1 and CFRP-2 bridge models obtained as 238 kNm, 36 kNm and 52 kNm, respectively. As seen in figure, displacement and bending moment values for the steel bridge models are bigger than the values obtained CFRP bridge models.

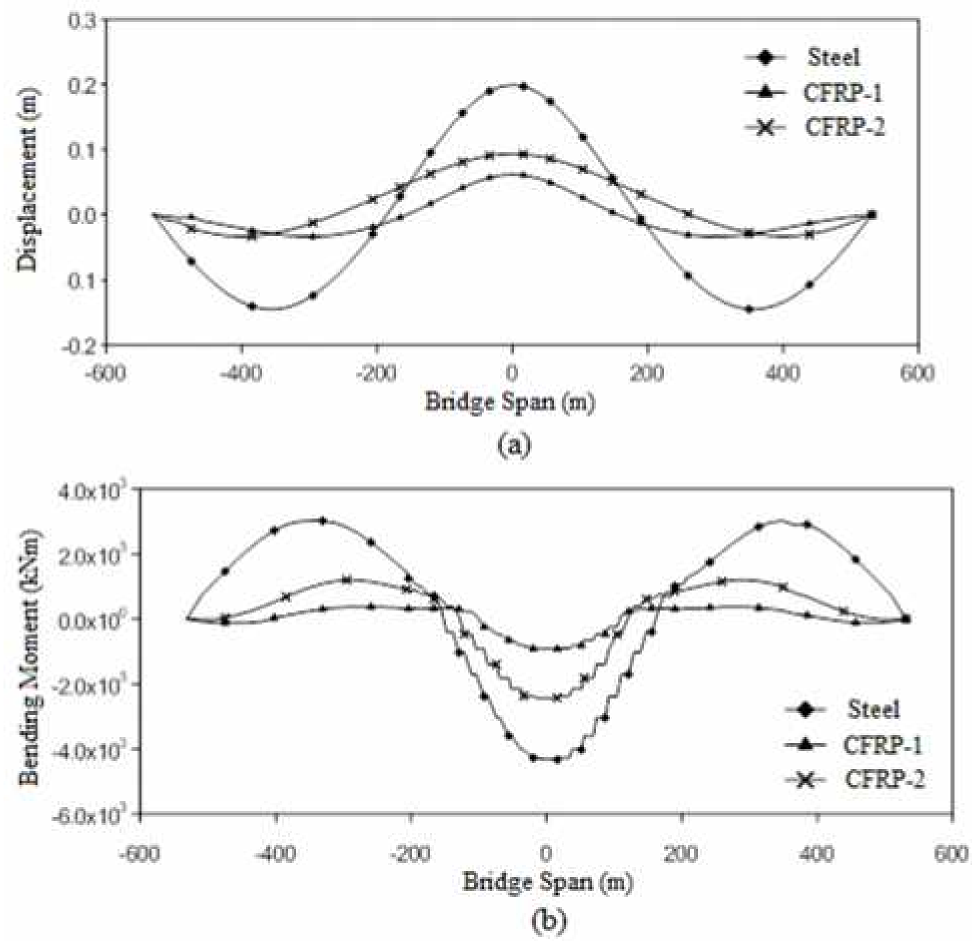

Figure 4 Mean of (a) vertical displacements and (b) bending moments of the deck

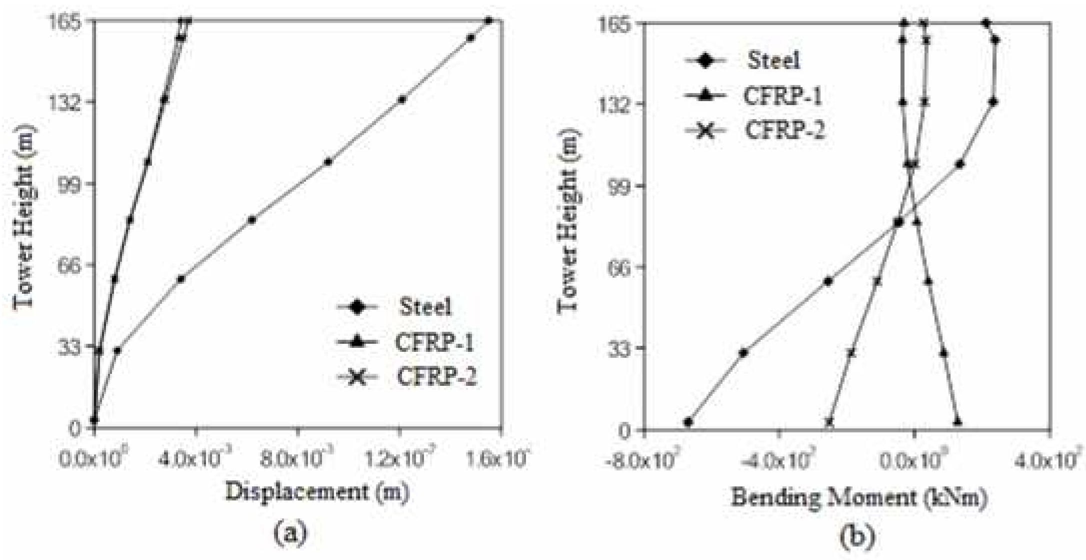

Figure 5 Variation (a) horizontal displacements and (b) bending moments of the tower

The variation of the axial forces and shear forces obtained from steel and CFRP bridges for the bridge tower are given in Figure 6. The maximum axial force and shear forces acquired as 1645 kN and 11.44 kN for steel bridge model. On the other hand, the minumum axial and shear force values occurred for CFRP-1 bridge model as 285 kN and 0.7358 kN, respectively, in which cross-sectional area of the bridge elements are determined by the principle equivalent strength method.

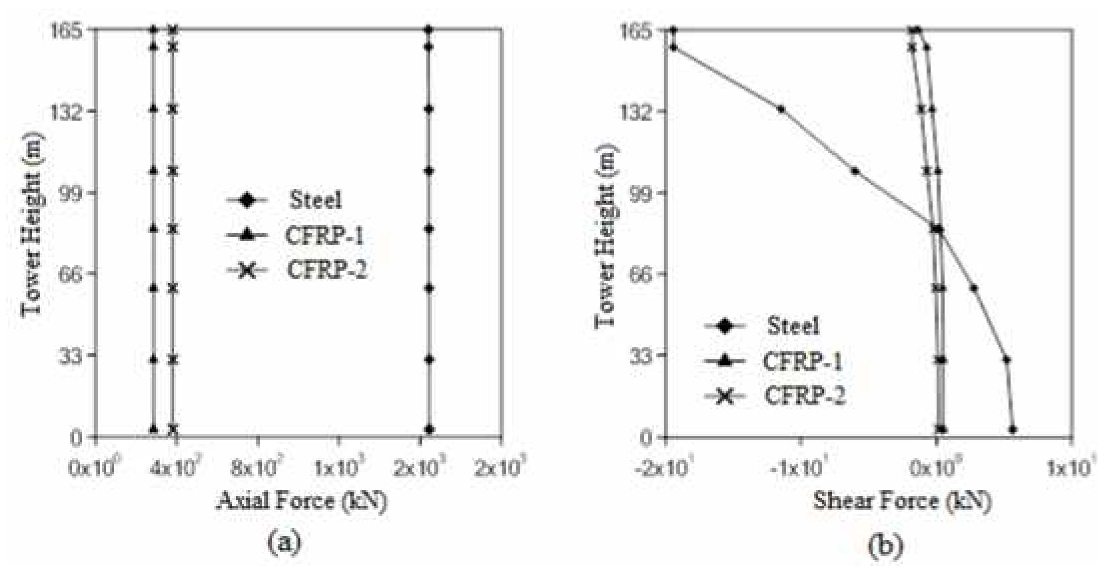

Figure 6 Variation (a) axial forces and (b) shear forces along the bridge tower

CONCLUSION

In this paper, dynamic analysis of Bosporus Suspension Bridge subjected to earthquake ground motion using either steel and CFRP composite materials are investigated. The cross-section areas of the elements like tower, deck, cable and hangers, are determined using either equivalent-stiffness or equivalent-strength methods. While orthotropic material type is taken into account for the CFRP bridge model, the isotropic material properties are adopted for the steel bridge model. The displacement and internal forces obtained for CFRP composite bridges are compared those of steel bridge. It is concluded from this study that the using of CFRP material is feasible for suspension bridges, and determination of the cross-sectional areas of CFRP bridge elements by the equivalent-strength is more favourable.

Based on the results of this study, it can be said that CFRP element might use application of suspension bridges thanks to beneficial properties and various advantages such as high strength, high rigidity, low weight, high corrosion resistance, low maintenance cost and aesthetic appearance when compared to steel.

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