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Stochastic Seismic Analysis of a Cable-Stayed Bridge Using CFRP Cables

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ABSTRACT

Fiber reinforced polymer (FRP) composites have found increasingly wide applications in civil engineering due to their high strength-to-weight ratio and high corrosion resistance for last two decades. This paper presents a numerical study on the stochastic seismic analysis of a cable-stayed bridge subjected to earthquake ground motion using carbon fiber reinforced polymer (CFRP) cables. Jindo Bridge is chosen and schemed using CFRP cables. The cross-sectional areas of CFRP cables are determined by the principle of either equivalent cable stiffness or equivalent cable strength. The analysis of the selected bridge is conducted and the results obtained for CFRP cables are compared with steel counterpart. The results indicate that response values obtained for CFRP cables correspond well with those of the steel cables.

INTRODUCTION

The stay cables have significant influence on structural appearance and performance of cable-stayed bridges. Presently, the stay cable is commonly made of conventional high strength steel wires. Resulting in significant sagging effect due to its self-weight, the steel cable is relatively heavy on the structural performance; therefore reducing its effective stiffness and making it behave softer under service load. In addition, corrosion and fatigue are two major problems for the conventional steel cable in cable-stayed bridges with high traffic volume or the bridges located in corrosion environment, which cause the premature breakage of the wires inside the cable. Moreover, the cost of replacement and maintenance of the stay cables is generally high [1].

Fiber reinforced polymer (FRP) is a class of advanced composite materials used in civil engineering since the construction of the first all composite bridge Miyun, China, in 1982. The use of FRP composite materials are gaining popularity for bridge application worldwide and they have been used for deck, beams, cables and superstructures of suspension bridge, footbridge and highway bridges. There are various FRP composite materials used in bridge application. One of these CFRP composite materials is accepted as a perfect material to build large-span structures like cable-stayed bridge due to low weight, high strength, corrosion resistance and low maintenance cost. Nowadays, CFRP composite materials are commonly preferred in cable-stayed bridges thanks to their beneficial properties. Thus, the dynamic behavior of this kind of structures under the earthquake must be determined accurately.

In the literature, there are some papers about the dynamic analysis of the FRP cable-supported bridges. Khalifa et al. [2] described the analysis and design of a FRP cable-stayed footbridge, and studied the behaviors of the bridge under the static and dynamic loads. Hodhod and Khalifa [3] 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. [4] 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. Zhang and Ying [1] 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 [5] studied about the integrated high-performance thousand-metre scale cable-stayed bridge with hybrid FRP cables. In this current study, the suitability of hybrid basalt and carbon FRP cables instead of steel cables was investigated. Kuyumcu and Ates [6] observed that behavior of cable-stayed bridge under spatially varying earthquake ground motion by taking into account soil-structure interaction effect. As seen in literature, there is not sufficient research about the dynamic analysis of the FRP cable-stayed bridges.

The aim of this study is to compare the stochastic seismic analysis of a cable stayed bridge subjected to earthquake ground motion using CFRP cables in lieu of steel cables. Except for the sectional properties of the cables, other design parameters of the Jindo Bridges were considered the same. Both principle of equivalent cable stiffness and equivalent cable strength are used to determine the cross-sectional areas of CFRP cables.

FORMULATION

There are two basic methods to account for the dynamic motions namely deterministic which is a time-domain approach and stochastic that is a frequency-domain approach. An acceleration-time history of ground motion recorded at one point is used as seismic input in the deterministic method. In the stochastic method, however, recorded ground motions appropriate to the site are characterized as statistically. Since the ground motion caused by seismic disturbance is random, the best way to characterize the random excitation statistically is to employ a power density function and autocorrelation function. Once, the power spectral density function or the autocorrelation function of the seismic input is known, the cross power spectral density function can be determined easily.

In this study, only the final expression for the cross power spectral density function will be given. Detailed expressions for this function are explained elsewhere [7]. If a single ground acceleration record is used for the input, cross power spectral density function, $S_{ij}(\omega)$, can be determined by using the equation of motion of the system as [8].

$$S_{ij}(\omega) = S_{in}(\omega)\sum_{r=1}^{N}\sum_{s=1}^{N}\psi_{ir}\psi_{js}H_{ir}(\omega)H_{js}^{*}(\omega) \tag{1}$$

where ω is the frequency, $H(\omega)$ is the frequency response function, $S_{in}(\omega)$ is the power spectral density function of the ground motion, N is the number of modes which are considered to contribute to the response, ψ_{jr} is the contribution of the rth mode to $U_j(t)$ displacement and * denotes the complex conjugate [8].

Statistics related to the structural behaviour for a stationary process can be determined by using the zeroth, the first and the second spectral moments of the output process [7]. Spectral moments, which can be expressed in terms of power spectral density function and frequency, may be calculated as follows

$$\lambda_{m,ij} = 2\int_{0}^{\infty}\omega^{m}S_{ij}(\omega)d\omega \quad ; \quad m = 0,1,2 \tag{2}$$

where $m = 0,1,2$ is the zeroth, the first and the second spectral moments, respectively. These parameters will then be used while obtaining the mean of maximum value, variance and frequency of occurrence [9].

The expected maximum value is considered to be the most important parameter in the stochastic analysis of structures affected by seismic loads. In the stochastic analysis the expected maximum value (μ) is the mean value of all maximum values. The expected maximum value, which depends on the peak factor and the root-mean-square response, can be expressed as

$$\mu = p\sqrt{\lambda_0} \tag{3}$$

Standard deviation of μ is expressed as

$$\sigma = q\sqrt{\lambda_0} \tag{4}$$

where λ_0 is the zeroth spectral moment defined by Eq. (2), p and q are the peak factors, which are the functions of the duration of the motion and the mean-zero crossing rate, respectively [8].

$$p = \sqrt{(2\ln\upsilon_e T)} + \frac{0.5772}{\sqrt{(2\ln\upsilon_e T)}} \quad (5)$$

$$q = \frac{1.2}{\sqrt{(2\ln\upsilon_e T)}} - \frac{5.4}{13 + (2\ln\upsilon_e T)^{3.2}} \quad (6)$$

where v_e is the equvalent mean-zero crossing rate

$$\upsilon_e = (1.9\xi^{0.15} - 0.73)\upsilon \quad (7)$$

in which T is the duration of the motion, ξ is the modal damping ratio and υ is frequency of occurrence. Frequency of occurrence is described as the average number of times that the line ($y(t) = 0$) is crossed by the response in a unit of time. For Gaussian process of zero average, the average number of times in the zero level crossed by the process in a unit of time is expressed as

$$\upsilon = \frac{1}{\pi}\sqrt{\frac{\lambda_2}{\lambda_0}} \quad (8)$$

Because the zero level is crossed two times for each cycle, frequency of occurrence for the response process will be equal to $\upsilon / 2$ as

$$f_0 = \frac{\upsilon}{2} = \frac{1}{2\pi}\sqrt{\frac{\lambda_2}{\lambda_0}} \quad (9)$$

where λ_2 is the second spectral moment defined by Eq. (2).

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

$$[\sigma]_{CFRP} A_{CFRP} = [\sigma]_{steel} A_{steel} \quad (10)$$

Equivalent cable stiffness:

$$E_{CFRP} A_{CFRP} = E_{steel} A_{steel} \quad (11)$$

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 cables respectively.

APPLICATION

Jindo Bridge, which was built in Jeollanam-do, South Korea, connects the mainland to Jindo Island is chosen as application. This bridge was opened on 18 October 1984 and having a total span of 484 m with a main span of 344 m and two side spans of 70 m. The bridge consist of two A shaped towers. The bridge cables was arranged in a fan configuration and merged at the top of the A-frame towers. The diameters of the cables are 56 mm, 67 mm, 76mm and 87 mm. Each carries 24 cables and the towers are 69 m height above the piers where they are supported.

To investigate the stochastic seismic analysis of the Jindo Bridge subjected to earthquake ground motion using CFRP cables, two-dimensional finite element model is considered (Figure 1). As the deck, towers are represented by 139 beam elements, the cables are represented by 30 truss elements in the model. The materials and section properties of the elements used in the finite element model are given in Table1.

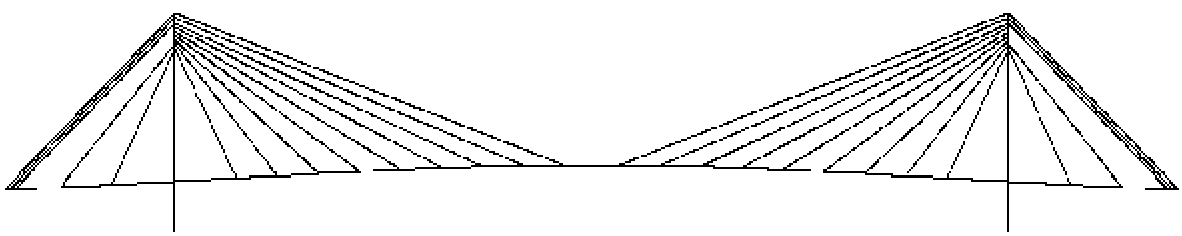


Figure 1 2D finite element model of the Jindo Bridge

Table 1 Material and section properties of the element of Jindo Bridge

Elements	Section Areas *(m^2)*	Modulus of Elasticity *(kN/m^2)*	Density *(kN/m^3)*
Deck	0.827	205000000	151.17
	0.416	205000000	152.64
	0.464	205000000	154.02
	0.464	205000000	152.64
Tower	0.658	205000000	86.33
	0.608	205000000	86.33
	0.541	205000000	86.33
	0.473	205000000	86.33

	0.647	205000000	86.33
Cable	0.02010	154000000	81.72
	0.00556	153600000	81.72
	0.00428	156100000	81.72
	0.00756	147600000	81.72
	0.01004	142400000	81.72
Pier	35.600	21000000	25,00

East-west component of 13 March 1992 Erzincan, Turkey earthquake (Figure 2) [11] is chosen as ground motion to obtain stochastic seismic analysis of Jindo Bridge.

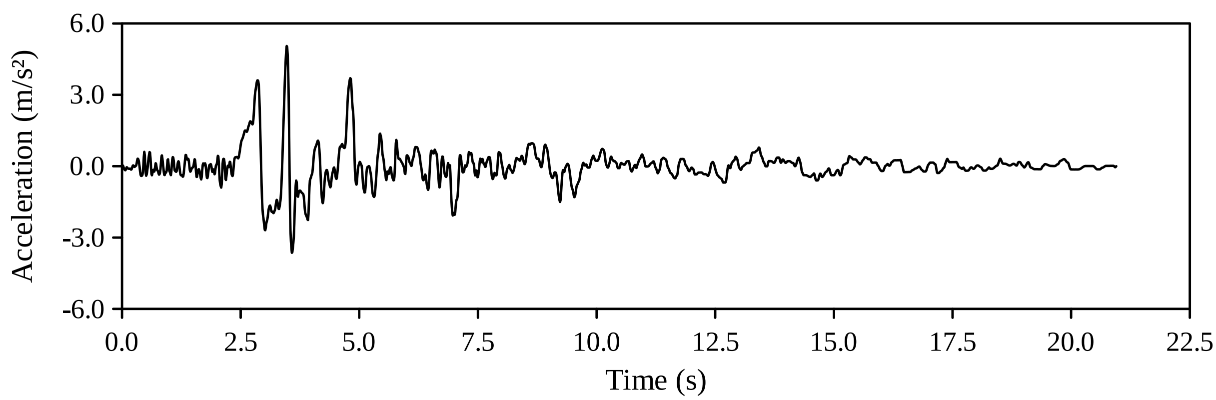


Figure 2 East-west component of 13 March 1992 Erzincan earthquake

The nonlinearity of the cable is taken into account with equivalent modulus of elasticity, which includes the normal modulus of elasticity, the effect of sag and tension load. The equivalent modulus of elasticity is calculated as follows

$$E_i = \frac{E}{1+\left(\gamma_c^2 l^2 E/12\sigma^3\right)} \qquad (12)$$

where, E is the modulus of elasticity of the straight cable, l is the horizontal length of the cable, γ is specific weight of the cable and σ is the tensile stress in the cable [12].

Damping ratio of %2 is considered for the bridge models through the stochastic seismic analysis. The modal analysis is solved for both steel cables and CFRP cables to determine the frequency and mode shapes of the all bridge models. The first fifteen mode shapes and their frequencies obtained in the modal analysis are extracted. Table 2 summarizes the frequencies and periods of the selected modes for either steel cables or CFRP cables.

Table 2 Effects of cable types on structural frequencies and period for Jindo Bridge

Mod Number	Steel Bridge		CFRP-1		CFRP-2	
	F (Hz)	*P (s)*	*F (Hz)*	*P (s)*	*F (Hz)*	*P (s)*
1	0.447	2.238	0.468	2.138	0.455	2.196
2	0.647	1.546	0.668	1.496	0.657	1.522
3	0.954	1.049	0.981	1.020	0.966	1.035
4	1.276	0.784	1.302	0.768	1.290	0.775
5	1.602	0.624	1.631	0.613	1.618	0.618
6	1.839	0.544	1.865	0.536	1.855	0.539
7	1.978	0.506	2.022	0.495	2.017	0.496
8	2.045	0.489	2.089	0.479	2.082	0.480
9	2.387	0.419	2.419	0.413	2.411	0.415
10	2.731	0.366	2.768	0.361	2.755	0.363
11	2.793	0.358	2.846	0.351	2.830	0.353
12	2.961	0.338	2.997	0.334	2.992	0.334
13	3.674	0.272	3.720	0.269	3.716	0.269
14	4.466	0.224	4.530	0.221	4.526	0.221
15	4.584	0.218	5.287	0.189	5.275	0.190
F: Frequency ;P:Period; CFRP-1:Equivalent cable strength; CFRP-2: Equivalent cable						

Because of lower self-weight of the CFRP cables, the frequencies obtained from CFRP-1 and CFRP-2 Bridge models are greater than the frequencies of steel cable bridge. The frequencies which is attained in the case of equivalent cable strength and equivalent cable stiffness are closest each other according to case of steel cables. Besides both steel and CFRP cable bridges have generally similar mode shape.

Figure 3 shows the mean of maximum vertical displacements and bending moments along the bridge deck calcalated for both steel and CFRP cable bridges. The maximum displacement and bending moment occurred at the middle of the bridge deck for steel and CFRP bridges. It is seen from the Figure 3 that values obtained from using either steel or CFRP cables is closed to each other.

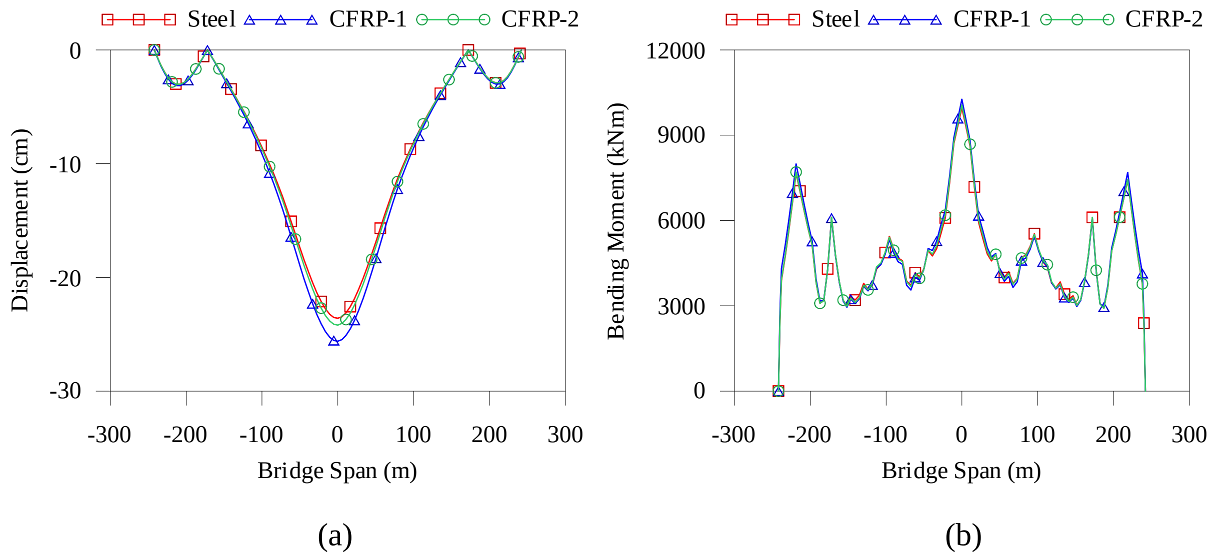


Figure 3 Mean of maximum (a) vertical displacements and (b) bending moments of the deck

Changing of axial forces and shear forces obtained from steel and CFRP cable bridges at the deck are given in Figure 4. The maximum axial forces and shear forces occurred as 2017 kN and 1380 kN for CFRP-1. It can be seen from the figure that there are small differences between the values of the axial forces and shear forces obtained in the steel and CFRP cable bridges.

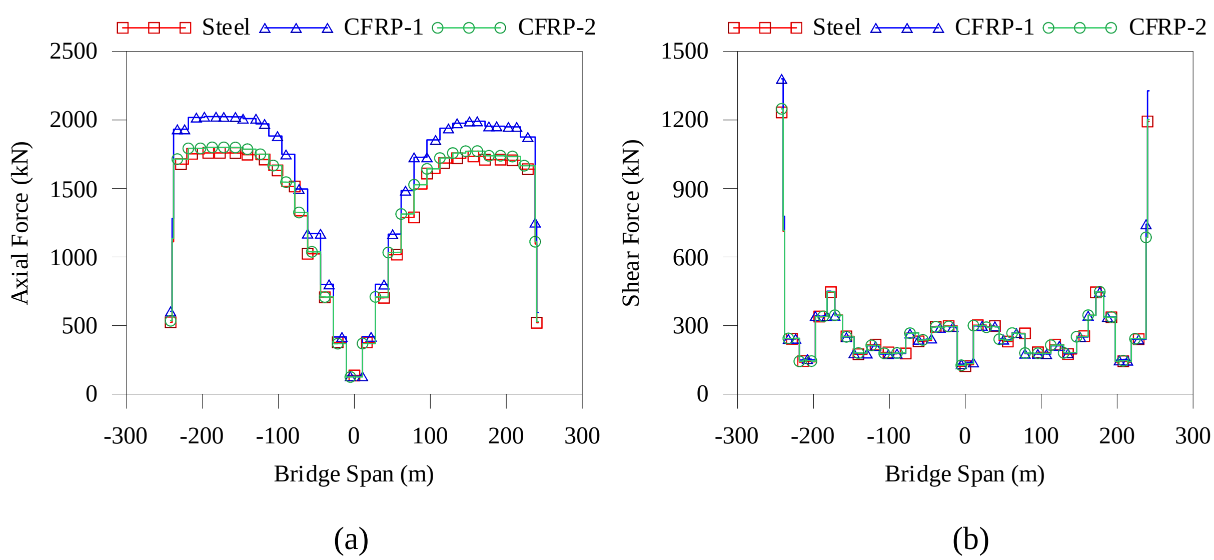
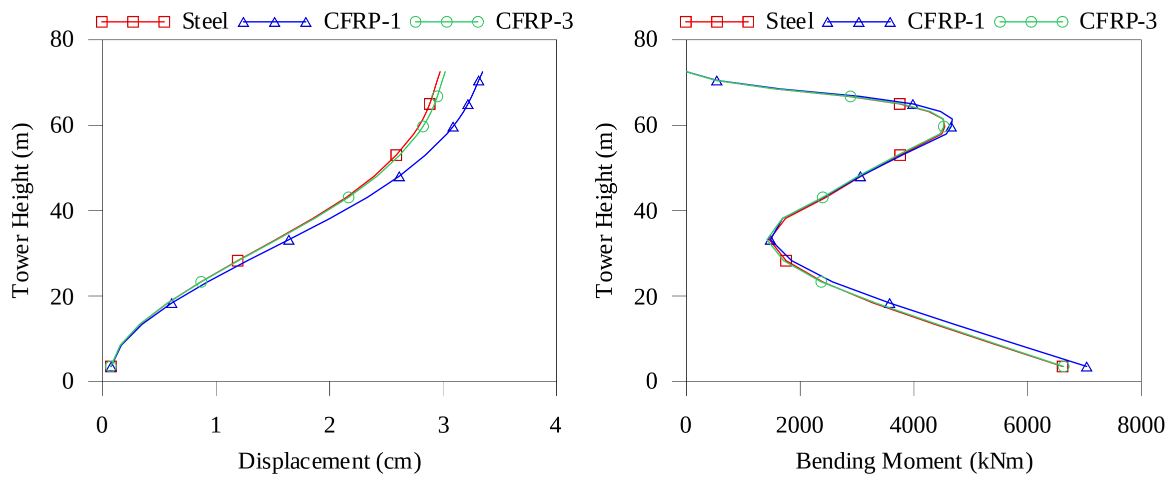


Figure 4 Changing of (a) axial forces and (b) shear forces along the bridge deck

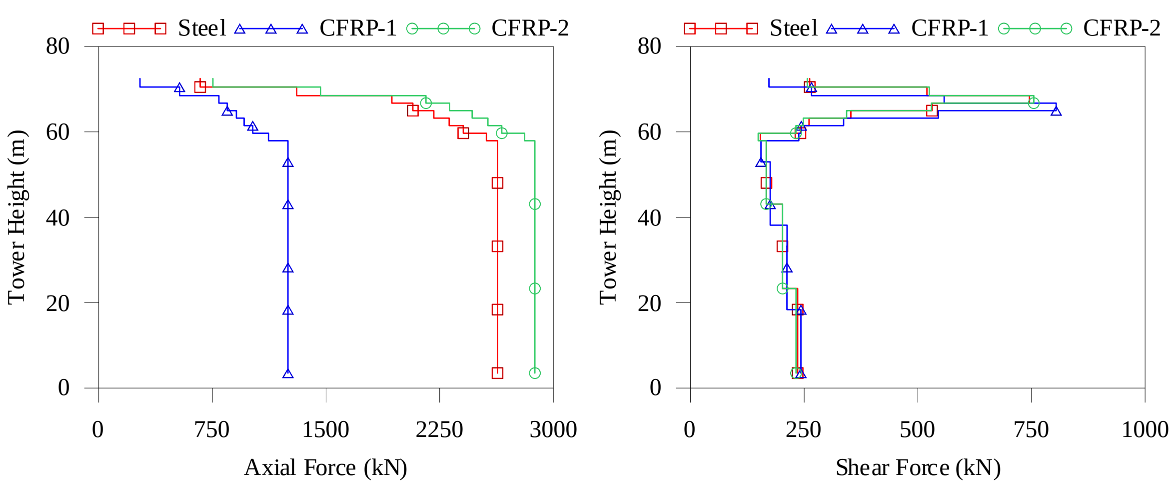
Figure 5 illustrates the mean of displacements and bending moment values of the tower. As seen in figure, displacement and bending moment values obtained steel and CFRP cable bridges are nearly equal when these values compared with each other.



(a) (b)

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 cable bridges for bridge tower are given in Figure 6. The maximum axial force acquired as 2878 kN for CFRP-2. The case of equivalent cable strength is more favorable than that of equivalent cable stiffness for the axial force obtained along the bridge tower. The shear force values are almost equal, as can be seen in Figure 6.



(a) (b)

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

CONCLUSION

This paper presents the stochastic seismic analysis of a cable stayed bridge subjected to earthquake ground motion using CFRP cables in lieu of steel to investigate the feasibility of the CFRP cables for the cable-stayed bridges. Cable properties of the Jindo Bridge are schemed by using both principle of equivalent cable stiffness and cable strength methods to obtain the cross-sectional areas of CFRP cables. It is concluded from this study that the using of CFRP cables is feasible for cable stayed bridges.

Based on the results of this research, it can be said that CFRP cables might use application of cable-stayed 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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