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Study of seismic performance of cable-stayed-suspension hybrid bridges

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Abstract. By taking a cable-stayed-suspension hybrid bridge with main span of 1400 m as example, seismic response of the bridge under the horizontal and vertical seismic excitations is investigated numerically by response spectrum analysis and time history analysis, its seismic performance is discussed and compared to the cable-stayed bridge and suspension bridge with the same main span, and considering the aspect of seismic performance, the feasibility of using cable-stayed-suspension hybrid bridge in super long-span bridges is discussed. Under the horizontal seismic action, the effects of structural design parameters including the cable sag to span ratio, the suspension to span ratio, the side span length, the subsidiary piers in side spans, the girder supporting system and the deck form etc on the seismic performance of the bridge are investigated by response spectrum analysis, and the favorable values of these design parameters are proposed.

Keywords: cable-stayed-suspension hybrid bridge; seismic response; response spectrum analysis; time history analysis; structural design parameter

1. Introduction

Cable-stayed bridges and suspension bridges are the two dominant structural types of long-span bridges. As a combination of the two, cable-stayed-suspension hybrid bridges have attracted many researchers' attention. In the case of cable-stayed suspension bridges, the cable system is defined by presence of stays, hangers and main cable, which typically present better performances than conventional ones based on pure suspension and cable-stayed configurations. This type of bridge has a higher structural rigidity and lower cost than the suspension bridge, while it has lower compression forces in the girder, thereby gaining a higher stability than the cable-stayed bridge (Xiao and Xiang 1999a). Therefore, this can provide a better solution for long span bridges under deep-sea or soft foundation conditions (Gimsing and Georgakis 2012, Xiao and Xiang1999, Lonetti and Pascuzzo 2014).

The evolution of this type of bridge dates back to John A. Roebling's great contribution to the Brooklyn Bridge as a masterpiece in the late 19th century (Gimsing and Georgakis 2012). In his innovative work, stay cables were installed in the suspension bridge to reduce the displacement of the girder. In 1938, German engineer F. Dischinger proposed a system in which the central part of

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the span was carried by a suspension system whereas the outer parts were carried by stays radiating from the tower top (which is discussed herein and as plooted in Fig. 1). However, it had not been adopted for actual construction until the Nagisa Bridge in Japan and the Wujiang Bridge in China (both main span less than 300 m) were built recently. The result of experiments on-site proved that the good collaboration between the two structural parts resulted in an anticipated structural performance from the viewpoints of both statics and dynamics. Furthermore, the cable-stayed-suspension hybrid bridge has been brought forward as possible schemes in almost each large bridge project all over the world such as the Great Belt East Bridge in Denmark, the Gibraltar Bridge in Italy, the Messina Strait Bridge in Italy, the Izmit bridge in Turkey, the Tagus River Bridge in Portugal, the Bali Strait Bridge in Java, and some strait-crossing bridges in Japan (Gimsing and Georgakis 2012). In the 21st century, many long and particularly super long-span bridges are planned in sea-crossing projects. Many of them were built under the natural conditions unfavorable to build the traditional cable-stayed bridge or suspension bridge, such as soft soil foundation, violent typhoon, and deep-water foundation etc, and therefore the cable-stayed-suspension hybrid bridge becomes a competitive design alternative for these bridges.

Just like the suspension bridge and cable-stayed bridge, the cable-stayed-suspension hybrid bridge is also a structural system of great flexibility, and becomes susceptible to the dynamic action such as wind and earthquake etc., and the seismic performance becomes an important problem of its structural design (Wang *et al*. 2009). Until now, many investigations have been done on the dynamic characteristics and seismic performance of self-anchored cable-stayed-suspension hybrid bridges. Huang *et al*. (2007), Zhang *et al*. (2008), Wang *et al*. (2009), Han *et al*. (2011), Mu (2012) investigated the dynamic characteristics and seismic problem of a self-anchored cable-stayed-suspension hybrid bridge- the Dalian Bay Bridge with main span 0f 800 m. As for the earth-anchored cable-stayed-suspension hybrid bridges with larger span, only a few publications about the dynamic performance are found in the literature. Xiao and Xiang (1999) investigated the dynamic characteristics of a 1400 m cable-stayed-suspension hybrid bridge, and also investigated the effects of design parameters such as the cable sag to span ratio and the suspension to span ratio etc on the dynamic characteristics. Hu (2000) established the dynamic nonlinear finite element models of the cable-stayed bridge, suspension bridge and cable-stayed-suspension hybrid bridge etc with the same main span of 2000 m, and analyzed their natural frequency and vibration modes. Zen *et al*. (2002) established the spatial finite element model of a cable-stayed-suspension hybrid bridge design scheme in the Lingdingyang East channel, the dynamic characteristics was analyzed, and the inherent vibration characteristics and also the influence of girder's longitudinal restraint conditions and the subsidiary pier setting in side span on the dynamic characteristics of cable-stayed-suspension hybrid bridge were discussed. Parametric study on the dynamic behavior of a cable-stayed-suspension hybrid bridge under moving loads was conducted by Bruno *et al*. (2009). Qiu *et al*. (2010) investigated the effect of principal structural parameters on the static and dynamic behavior of a cable-stayed-suspension hybrid bridge scheme with main span of 1800 m. Konstantakopoulos and Michaltsos (2010) proposed a mathematical model to investigate the dynamic behavior of the cable-stayed-suspension hybrid bridge. Unfortunately, none has been conducted on the seismic performance of long-span earth-anchored cable-stayed-suspension hybrid bridges.

In this work, by taking a cable-stayed-suspension hybrid bridge scheme with main span of 1400 m as example, structural response of the bridge under the horizontal and vertical seismic excitations is firstly investigated numerically by response spectrum analysis and time history analysis, its seismic performance is discussed. Then, its seismic performance is compared to that

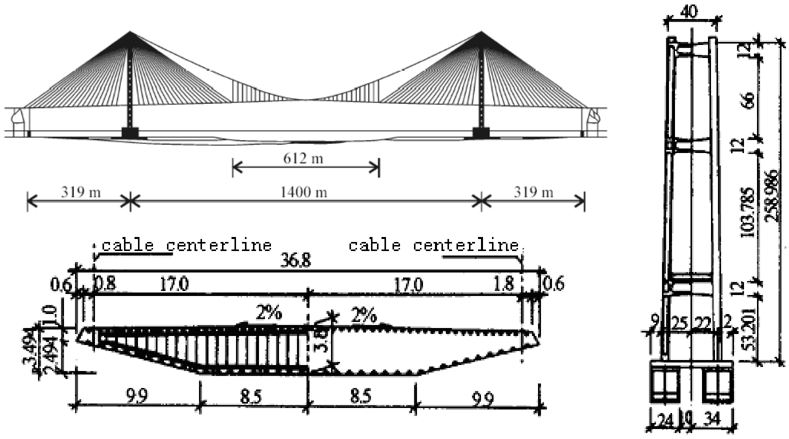

Fig.1 Elevation of the example cable-stayed-suspension hybrid bridge (Unit: m)

Table 1 The cross section and material properties of the example bridge

Members		*E* (Mpa)	*A* (m^2)	J_d (m^4)	*Iz* (m^4)	*Iy* (m^4)	*M* (Kg/m^3)	*Jm* ($Kg.m^2/m$)
Girder		2.1×10^5	1.2481	5.034	1.9842	137.754	14732.0	1.852×10^6
Main cable(single)	CS	2.0×10^5	0.3167	0.0	0.0	0.0	8400.0	0.0
	SS	2.0×10^5	0.3547	0.0	0.0	0.0	8400.0	0.0
Hanger(single)		2.0×10^5	0.0064	0.0	0.0	0.0	7850.0	0.0
Stay cable(single)		2.0×10^5	0.008	0.0	0.0	0.0	7850.0	0.0
Towers	C	3.3×10^4	30.0	350.0	320.0	220.0	2600.0	5.7×10^5
	TB	3.3×10^4	10.0	150.0	70.0	70.0	2600.0	4.7×10^5

Notes: *E*-elastic modulus, *A*-area, J_d-torsional moment of inertia, *Iz*-vertical bending moment of inertia, *Iy*-lateral bending moment of inertia, m-mass density, *Jm*-mass moment of inertia per unit length, *CS*-center span, *SS*-side span, *C*-tower's Column, *TB*- tower's transverse beam.

of the cable-stayed bridge and suspension bridge with the same main span, and considering the aspect of seismic performance, the feasibility of using the cable-stayed-suspension hybrid bridge in super long-span bridges is discussed. Finally, under the horizontal seismic action, the effects of structural design parameters on the seismic performance of the bridge are investigated by response spectrum analysis, and the favorable values of these design parameters are proposed.

2. Description of the example bridge

The example earth-anchored cable-stayed-suspension hybrid bridge consists of a main span of 1400 m and two side spans of 319 m as shown in Fig. 1, which was proposed in the east channel of Lingding Strait in China (Xiao 2000). The central span consists of the cable-stayed portion of 788 m and the suspension portion of 612 m. The lateral spacing of two main cables is 34 m, the cable sag to span ratio is 1/10, and the interval of hangers is 18 m. The stay cables are anchored to the girder at 18 m intervals in the central span and 14 m in the side spans. The deck is a steel streamlined box steel girder of 36.8 m wide and 3.8 m high. The towers are door-shaped frames with three transverse beams, and their height above ground is about 259 m. The cross section and material properties of the bridge are given in Table 1.

3. Finite element model and dynamic characteristic of the example bridge

3.1 Finite element modeling

The example bridge is is simplified as a three-dimensional skeleton finite element model with 814 elements and 567 nodes as plotted in Fig. 2, in which the bridge deck is modeled by the single-girder model, the bridge deck and towers are modeled by 3D beam elements, and the hangers, main cables and stay cables are modeled by 3D bar elements, and rigid diaphragms are provided to model the connections between the bridge deck and the hangers and stay cables. The pavement and the railings on the steel box girder were simulated by mass elements without stiffness. The cable-stayed-suspension hybrid bridge exhibits strong geometric nonlinearity due to: (1) the combined effects of axial force and bending moment in the girder and towers; (2) the nonlinear behavior of cables caused by cable sag and gravity effects; and (3) the bridge geometry change due to large displacements. All sources of geometric nonlinearities are considered in the following analysis. The common equivalent modulus approach is used to account for the sag effect of inclined stay cables. The gravity stiffness of main cables under the dead load action is approximately accounted by a gemotric stiffness of bar element. A geometric stiffness matrix for beam element is used to take into account the combined effects of axial force and bending moment in the girder and towers. The Corotational (CR) formulation is employed to solve the geometric nonliear problems with large displacement, large rotation but small strain. Both the outer and inner boundary conditions are added to the finite element model. The nodal restrictions in the desired directions are imposed at the bottom of the tower, ends of the girder, ends of the main cable, and points at the auxiliary piers. In a fully floating deck system, the girder and the tower are free of linkage in the vertical (Y) and the longitudinal (X) directions at the intersection points, while are coupled in the lateral (Z) direction to simulate the effect of the wind-resisting bearing.

3.2 Dynamic characteristics

On the computed equilibrium position of the example bridge in completion, based on the subspace iteration method, the first 60 modes of the example bridge are calculated by MIDAS/Civil software. Table 2 shows the girder’s modal properties of the first 20 modes of the example bridge.

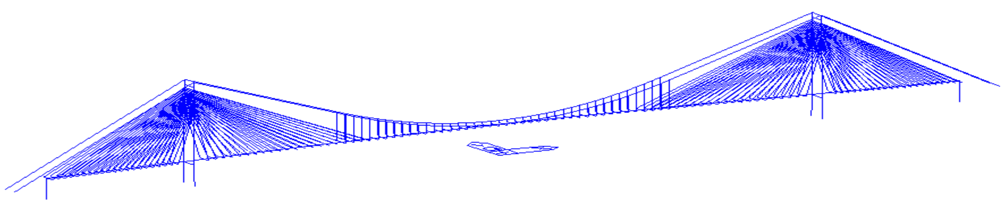

Fig. 2 3D finite element model of the example bridge

Table 2 The girdre's modal properties of the example bridge

Mode	Frequency (Hz)	Modal shape*
Vertical bending	0.1858	1-S
	0.0970	1-AS
	0.2171	2-S
	0.1837	2-AS
	0.3100	3-S
	0.2849	3-AS
Lateral bending	0.0621	1-S
	0.1467	1-AS
	0.3009	2-S
	0.1810	2-AS
Torsion	0.3359	1-S
	0.3657	1-AS

Note: *S*=symmetric; *AS*=anti-symmetric; the value denotes the mode number.

As seen in Table 2, some features on the dynamic characteristics of cable-stayed-suspension hybrid bridge can be concluded as follows: (1) the fundamental frequency is very small, and correspondingly the fundamental period is very long, which demonstrates that cable-stayed-suspension hybrid bridge is a structural system with great flexibility; (2) the symmetric lateral bending mode comes firstly, and then the longitudinal floating-vertical bending coupled mode is followed, the frequency ratio of the fundamental symmetric in-plane and out-of- plane modes is 2.992:1, which indicates the out-of-plane structural stiffness is less than that in plane, and the bridge becomes more susceptible to the lateral and longitudinal actions such as wind and earthquake; (3) the fundamental torsional frequency is higher than those of the lateral and vertical bending modes, the bridge has great torsional stiffness; (4) the vibration frequency distributes densely within a narrow frequency band, and the coupling among modes is remarkable, and therefore the CQC method should be used for modal combination in seismic response analysis of cable-stayed-suspension hybrid bridge.

4. Seismic response analysis of the example bridge

4.1 Earthquake ground motion

4.1.1 Seismic response spectrum

According to the guidelines for seismic design of highway bridges (JTGT B02-01-2008) (Ministry of Communications 2008) and the geological condition of bridge site, a standard response spectrum of Class Ⅲ field is taken, the basic design acceleration of ground motion is assumed as 0.1 g, the characteristic period is 0.45s, and structural damping ratio is 3%. Under the earthquake action E1, the design horizontal seismic acceleration response spectrum is plotted in Fig. 3, and for the vertical design seismic acceleration response spectrum, it is taken as 65% the horizontal seismic acceleration response spectrum.

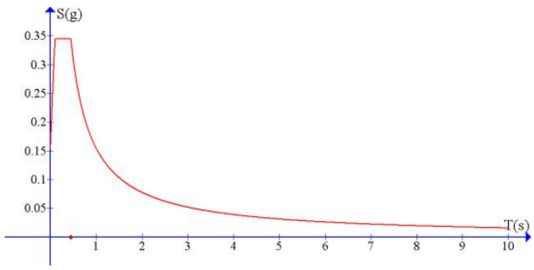

Fig. 3 The horizontal seismic design acceleration response spectrum under E1 seismic action

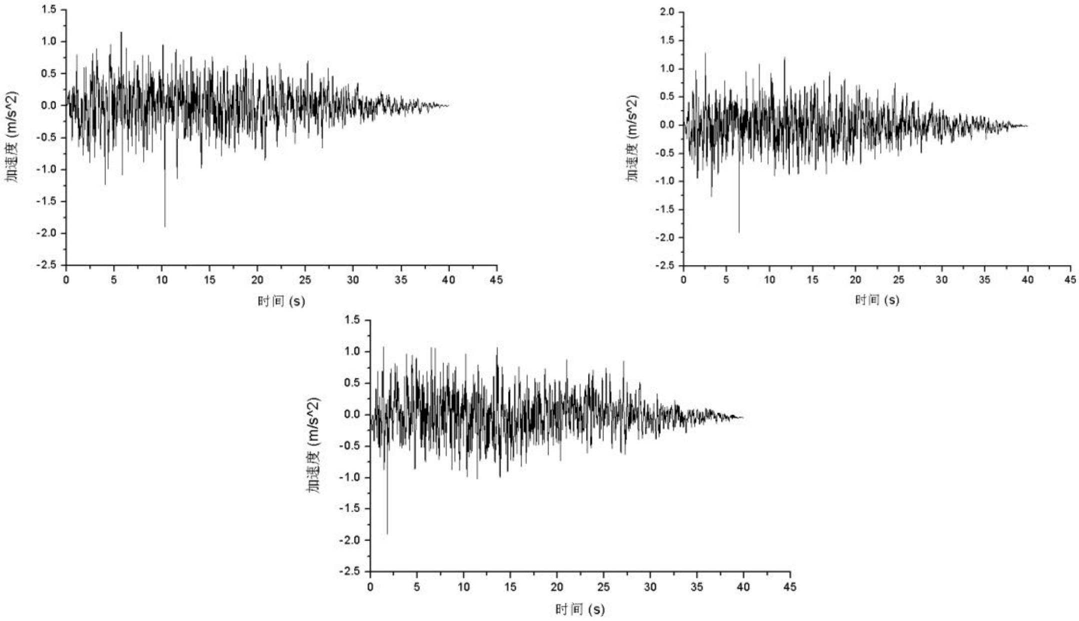

Fig. 4 Three artificial seismic acceleration time curves under E1 seismic action

4.1.2 The artificial seismic acceleration time curves

By taking the above design response spectrum as target spectrum, three artificial earthquake acceleration time history curves as shown in Fig. 4 are generated by the trigonometric series superposition method, which are the seismic excitation of nonlinear time history analysis of seismic response as follows.

4.2 Response spectrum analysis

Under the longitudinal, lateral and vertical seismic excitations, structural response of the example bridge is investigated numerically by multimode response spectrum analysis. Due to the dense distribution of natural frequencies of the bridge, and the modal coupling effect is remarkable, and therefore the CQC method is used for modal combination. In the response spectrum analysis, the first 60 modes are involved, the effective mass of mode participation in every direction is all greater than 90% the total structural mass. Due to the paper length limitation, only the maximum seismic responses are given as follows.

Table 3 The maximum seismic response under longitudinal seismic excitation

Member	Bending moment (kN.m)	Shear force (kN)	Axial force (kN)	Displacement (mm)	
				Longitudinal	Vertical
Tower	1.488×10^6	1.09×10^4	1.425×10^4	910	-
Girder	2.339×10^5	1.237×10^4	2.528×10^4	840.6	344.8
Main cable	-	-	4.880×10^6	841.5	387.0

Note: the tower's bending moment and shear force are both in longitudinal direction, and for the girder, they are in vertical direction.

Table 4 The maximum seismic response under lateral seismic excitation

Member	Bending moment (kN.m)	Shear force (kN)	Axial force (kN)	Displacement (mm)
Tower	2.576×10^5	2.0797×10^4	4.855×10^4	148.5
Girder	1.559×10^6	9.717×10^3	-	617.2
Main cable	-	-	4.881×10^6	611.6

Note: the bending moment, shear force and displacement are all in lateral direction.

4.2.1 Longitudinal seismic excitation

Under the longitudinal seismic excitation, the towers are undergoing the longitudinal vibration, and the girder and main cables are undergoing the longitudinal and vertical vibration. Table 3 gives the maximum seismic responses of the girder, tower and main cables. The maximum vertical bending moment, shear force and axial force of the girder all occurs at the deck supports in the towers, and for the tower, the maximum longitudinal bending moment and axial force occurs at the tower bottom end. At the tower top end, the longitudinal displacement reaches the maximum value, and for the girder and main cables, the maximum longitudinal and vertical displacements both occurs at the midpoint of main span, and structural displacements of the girder and main cables are very identical. As compared to the girder, greater seismic response is encountered in the tower, and especially in the tower bottom end.

4.2.2 Lateral seismic excitation

Under the lateral seismic excitation, the tower, girder and main cables are all undergoing the lateral vibration, and the maximum seismic response are given in Table 4. The girder maximum lateral displacement happens at the midpoint of main span, and but its maximum lateral bending moment and shear force occur at the junction of the girder and tower. The tower bends laterally, its maximum lateral bending moment and shear force also occur at the junction of the girder and tower, and there exists the maximum axial force at the tower bottom end. The main cables move laterally along with the girder, their maximum lateral displacements are basically the same. As compared to the tower, greater seismic response is achieved in the girder, and the girder section near the tower becomes the key section, which should be paid more attention to its seismic design.

4.2.3 Vertical seismic excitation

Under the vertical seismic excitation, the tower bends longitudinally, and the girder and main cables move longitudinally and meanwhile deflect vertically, the maximum seismic responses are given in Table 5. As for the girder, the maximum vertical displacement, bending moment and also shear force occur at the midpoint of main span, and there exists the maximum axial force at the

Table 5 The maximum seismic response under vertical seismic excitation

Member	Bending moment (kN.m)	Shear force (kN)	Axial force (kN)	Displacement (mm)	
				Longitudinal	Vertical
Tower	3.535×10^4	-	1.361×10^5	41.2	-
Girder	9.132×10^4	4.295×10^3	2.289×10^4	7.1	317.8
Main cable	-	-	4.862×10^6	40.3	308.8

Note: the tower bending moment and shear force are both in longitudinal direction, and for the girder, they are in vertical direction.

Table 6 The seismic response peak values under longitudinal seismic excitation

Member	Bending moment (kN.m)	Shear force (kN)	Axial force (kN)	Displacement (mm)	
				Longitudinal	Vertical
Tower	1.868×10^6	1.808×10^4	2.630×10^4	1063	-
Girder	3.071×10^5	1.285×10^4	2.878×10^4	898	434.9
Main cable	-	-	4.902×10^6	850.4	383.1

Table 7 The seismic response peak values under lateral seismic excitation

Member	Bending moment (kN.m)	Shear force (kN)	Axial force (kN)	Displacement (mm)
Tower	2.587×10^5	2.181×10^4	4.063×10^4	181.4.
Girder	1.571×10^6	9.976×10^3	-	768.0
Main cable	-	-	4.905×10^6	628.1

junction of the girder and tower. The inertial forces of the girder and main cables under the vertical seismic excitation are transferred to the foundation through the towers and anchorages, the axial force in the tower is thus increased remarkably, and along with the longitudinal bending of the towers, large longitudinal bending moment exists at the tower bottom end.

Through the comparison of the results given in Tables 3, 4 and 5, it can be found that structural seismic responses under the longitudinal and lateral seismic excitations are both much greater than those under the vertical seismic excitation, the horizontal seismic excitation produces the maximum internal force in the girder at the junction of the girder and tower, and for the tower, it produces the maximum internal force at the tower bottom end and also the junction of the girder and tower, and therefore special attention should be paid to the seismic design of these sections.

4.3 Nonlinear time history analysis

To investigate the effect of structural nonlinearity on the seismic response of cable-stayed-suspension hybrid bridge, the seismic response of the bridge under the horizontal and vertical earthquake ground motions is conducted by nonlinear time history analysis, and the peak displacement and internal force of the tower, the girder and main cables are given in Tables 6, 7 and 8 respectively. In the analysis, structural geometric nonlinearity is considered, and three acceleration time history curves of horizontal earthquake ground motions plotted in Fig. 4 are taken as seismic input, and the peak values are taken from the seismic response curves.

Table 8 The seismic response peak values under vertical seismic excitation

Member	Bending moment (kN.m)	Shear force (kN)	Axial force (kN)	Displacement (mm)	
				Longitudinal	Vertical
Tower	3.547×10^4	-	1.567×10^5	53.4	-
Girder	9.225×10^4	4.690×10^3	2.260×10^4	9.7	500.7
Main cable	-	-	4.914×10^6	40.5	307.7

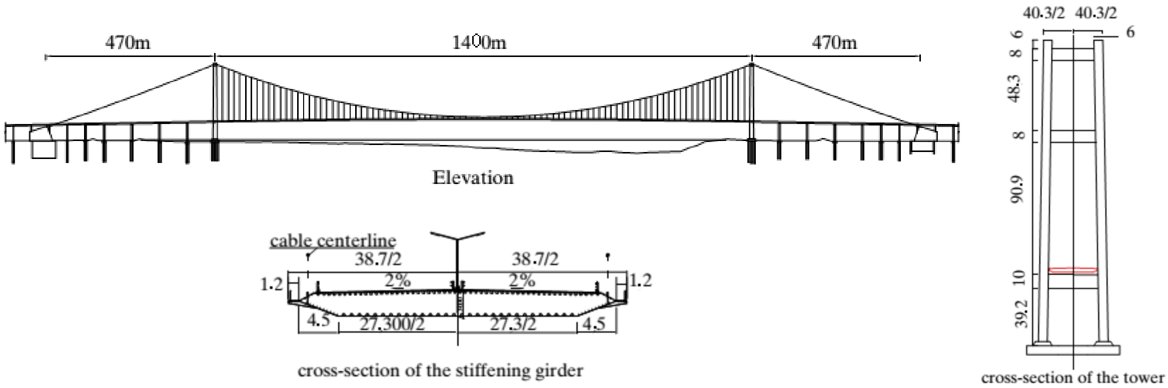

Fig. 5 1400 m suspension bridge scheme (Unit: m)

It can be found from the nonlinear time history analysis that the peak values and their positions of seismic response of the tower, girder and main cables are basically consistent to those of response spectrum analysis, and the results are proved to be valid. In general, the seismic responses obtained by nonlinear time history analysis are greater than those of response spectrum analysis. As compared to the linear response spectrum analysis, with introducing the nonlinear effect, structural stiffness is reduced, and thus greater response is achieved under the same seismic excitation. Therefore for long-span cable-stayed-suspension hybrid bridge, the nonlinear time history analysis is proposed to accurately predict its seismic response.

5. Comparison of the seismic performance with other bridge structures

In order to investigate the applicability of cable-stayed-suspension hybrid bridge in super long-span bridge with main span above 1000 m, a suspension bridge scheme and a cable-stayed bridge scheme both with 1400 m main span are assumed respectively, their dynamic characteristics is analyzed firstly, and then their seismic responses under the same seismic excitation are analyzed by the multimode response spectrum method.

5.1 Suspension bridge scheme

By taking the Runyang Bridge built in China as prototype, a suspension bridge scheme with main span of 1400 m and two side spans of 470 m is designed as shown in Fig. 5. The cable's sag to span ratio is 1/10, the lateral distance of two main cables is 34.3 m, and the interval of hangers

Table 9 The cross-sectional and material properties of the suspension bridge scheme

Member		*E* (Mpa)	*A* (m^2)	J_d (m^4)	*Iz* (m^4)	*Iy* (m^4)	*M* (Kg/m^3)	*Jm* ($Kg.m^2/m$)
Girder		2.1×10^5	1.2481	5.034	1.9842	137.754	14732.0	1.852×10^6
Main cable(single)		2.0×10^5	0.4735	0.0	0.0	0.0	8062.0	0.0
Hanger(single)		2.0×10^5	0.0022	0.0	0.0	0.0	7850.0	0.0
Tower	C	3.3×10^4	30.0	350.0	320.0	220.0	2600.0	5.7×10^5
	TB	3.3×10^4	10.0	150.0	70.0	70.0	2600.0	4.7×10^5

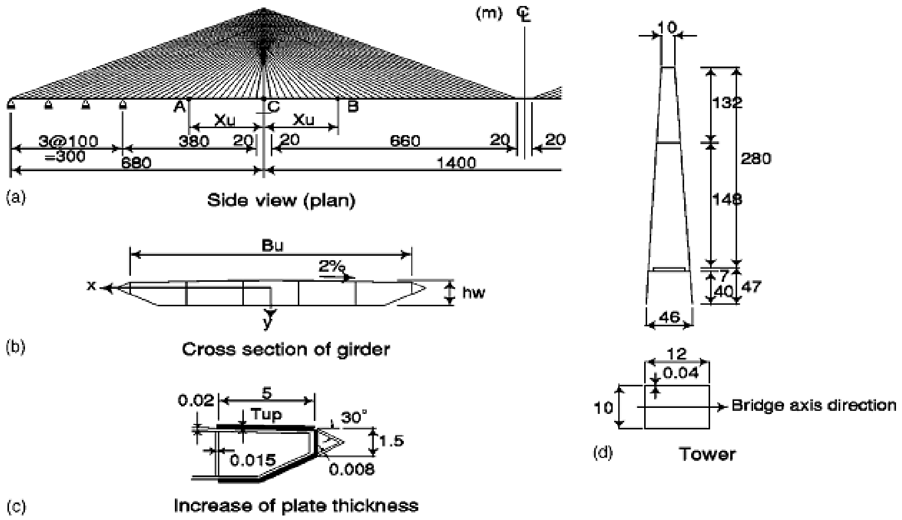

Fig. 6 1400 m cable-stayed bridge scheme (Unit: m)

is 16 m. The deck is a streamlined steel box girder, the net height of the girder at the bridge centerline is 3 m and the girder is 36.3 m wide (excluding the inspection and maintenance sidewalk), while the inspection and maintenance sidewalk is 1.2 m wide. The tower is a door-shaped frame with 3 transverse beams, its height is about 210 m from the ground level. The cross-sectional and material properties of the suspension bridge scheme are given in Table 9.

5.2 Cable-stayed bridge scheme

Fig. 6(a) shows the side view of a cable-stayed bridge scheme (Nagai *et al*. 2004). The center and side spans are assumed to be 1,400 and 680 m respectively. For the side span, three intermediate piers are installed at a distance of 100 m in order to increase in-plane flexural rigidity of the bridge. The deck shown in Fig. 6(b) is a streamlined steel box girder of 35 m wide and 3.5 m high, and is suspended by diagonal stays anchored to the girder at 20 m intervals. As shown in Fig. 6(c) at the edge of the cross section, the thickness of the plate is increased to cope with the large bending moment from wind load in the girder near the tower. The required distance for reinforcement from the tower is defined as Xu seen in Fig. 6(a), which is 80 m herein. Fig. 6(d) shows a front view and the assumed cross section of the tower. Its height from deck level is 280 m, which is one-fifth of the center span length. Table 10 gives the cross-sectional and material

Table 10 The cross-sectional and material properties of the cable-stayed bridge scheme

Member	E (Mpa)	A (m^2)	J_d (m^4)	Iz (m^4)	Iy (m^4)	M (Kg/m^3)	Jm ($Kg.m^2/m$)
Girder	2.1×10^5	1.761	3.939	8.330	193.2	14673.0	2.957×10^6
	(2.1×10^5)	(2.046)	(4.432)	(9.739)	(261.1)	(13705.0)	(3.712×10^6)
Stay cable	2.0×10^5	0.0087~0.038	0.0	0.0	0.0	7850.0	0.0
Tower	2.1×10^5	1.76	30.67	39.27	40.32	10773.0	8.574×10^5

Note: Values in parentheses are reinforced values.

Table 11 Comparison of modal frequency(Hz)

Modes	Suspension bridge	Cable-stayed bridge	The example bridge	Modal shape
Vertical bending	0.1442	0.1822	0.1858	1-S
	0.1163	0.2117	0.0970	1-AS
Lateral bending	0.0533	0.0571	0.0621	1-S
	0.1248	0.1666	0.1467	1-AS
Torsion	0.2811	0.4169	0.3359	1-S
	0.2703	0.5491	0.3657	1-AS

Table 12 Comparison of seismic response peak values of the towers of different bridge structural system

Bridge type	Seismic excitation	Bending moment (kN.m)	Shear force (kN)	Axial force (kN)	Displacement (mm)	
					Longitudinal	Lateral
Suspension bridge	Longitudinal	1.061×10^6	1.005×10^4	9.686×10^3	641.3	-
	Lateral	2.461×10^5	1.599×10^4	3.407×10^4	-	105.9
	Vertical	3.182×10^4	-	1.060×10^5	27.1	-
Cable-stayed bridge	Longitudinal	3.495×10^6	3.526×10^4	5.967×10^4	1199.1	-
	Lateral	3.405×10^5	3.026×10^4	6.378×10^4	-	185.6
	Vertical	7.433×10^4	-	2.882×10^5	34.1	-
Cable-stayed-suspension hybrid bridge	Longitudinal	1.488×10^6	1.090×10^4	1.425×10^4	910	-
	Lateral	2.576×10^5	2.079×10^4	4.855×10^4	-	148.5
	Vertical	3.535×10^4	-	1.361×10^5	41.2	-

Note: under the longitudinal and vertical excitations, the tower bending moment and shear force are both in longitudinal direction; under the lateral excitation, the bending moment and shear force are both in lateral direction.

properties of the cable-stayed bridge scheme.

5.3 Comparison of the dynamic characteristics

On the computed equilibrium position of the above suspension and cable-stayed bridge schemes in completion, structural dynamic characteristics is analyzed by MIDAS/Civil software, and the fundamental frequencies of these three bridges are compared in Table 11.

As found in Table 11, as compared to the suspension bridge with similar main span, the natural frequencies of cable-stayed-suspension hybrid bridge are significantly increased, especially the vertical bending and torsional frequency, and it is concluded that in the case of same main span, cable-stayed-suspension hybrid bridge has greater structural stiffness. With comparison of cable-stayed bridge with same main span, except that the fundamental symmetric vertical and lateral bending frequencies of cable-stayed-suspension hybrid bridge are slightly increased, the other fundamental frequencies are all decreased, especially the torsional frequency, which indicates that under the same main span, the overall stiffness of cable-stayed-suspension hybrid bridge is less than that of cable-stayed bridge. In all, the cable-stayed-suspension hybrid bridge has good stiffness characteristics, its structural stiffness is between the suspension bridge and cable-stayed bridge.

5.4 Comparison of the seismic performance

As found in Table 12 and Table 13, under the same main span and seismic excitations, the maximum seismic response occurs in the cable-stayed bridge, and whereas the minimum seismic response happens in the suspension bridge, and as for the cable-stayed-suspension hybrid bridge, it is between the cable-stayed bridge and suspension bridge and but more close to the suspension bridge. Therefore as viewed from the seismic performance, the cable-stayed-suspension hybrid bridge is similar to the suspension bridge, and superior to the cable-stayed bridge, and therefore it is suitable to be employed in super long-span bridges with main span of ultra kilometer.

6. Parametric study on the seismic performance of cable-stayed-suspension hybrid bridge

To investigate comprehensively the seismic performance of cable-stayed-suspension hybrid bridge, under the horizontal seismic action, the effects of structural design parameters including the cable sag to span ratio, the suspension to span ratio, the side span length, the subsidiary piers in side spans, the girder supporting system and the deck form etc(Zhang 2007; Sun *et al*. 2013) on the seismic performance of the bridge are investigated by multimode response spectrum analysis,

Table 13 Comparison of seismic response peak values of the girders of different bridge structural system

Bridge type	Seismic excitation	Bending moment(kN.m)	Shear force(kN)	Axial force(kN)	Displacement(mm)		
					Longitudinal	Lateral	Vertical
Suspension bridge	Longitudinal	1.467×10^5	4.366×10^3	1.971×10^4	610.0	-	205.5
	Lateral	1.148×10^6	8.442×10^3	-	-	631.2	-
	Vertical	6.597×10^4	2.915×10^3	4.453×10^3	0.9	-	189.1
Cable-stayed bridge	Longitudinal	1.056×10^6	2.955×10^4	4.044×10^4	1258.1	-	686.9
	Lateral	3.328×10^6	2.703×10^4	-	-	753.7	-
	Vertical	1.799×10^5	7.701×10^3	1.678×10^4	24.3	-	192.6
Cable-stayed-suspension hybrid bridge	Longitudinal	2.339×10^5	1.237×10^4	2.528×10^4	840.6		344.8
	Lateral	1.559×10^6	9.717×10^3	-		617.2	
	Vertical	9.132×10^4	4.295×10^3	2.289×10^4	7.1		317.8

Note: under the longitudinal and vertical excitations, the girder bending moment and shear force are both in vertical direction; under the lateral excitation, the bending moment and shear force are both in lateral direction.

Table 14 Effect of the cable sag to span ratio on the seismic response of tower

The cable sag to span ratio	Seismic excitation	Bending moment (kN.m)	Shear force (kN)	Axial force (kN)	Displacement(mm)	
					Longitudinal	Lateral
1/9	Longitudinal	1.499×10^6	1.154×10^4	1.504×10^4	1308	-
	Lateral	2.297×10^5	1.828×10^4	4.233×10^4	-	158.5
1/10	Longitudinal	1.488×10^6	1.09×10^4	1.425×10^4	910	-
	Lateral	2.576×10^5	2.079×10^4	4.855×10^4	-	148.5
1/11	Longitudinal	1.331×10^6	1.921×10^4	1.050×10^4	904	-
	Lateral	3.024×10^5	2.381×10^4	5.638×10^4	-	138.4

Table 15 Effect of the cable sag to span ratio on the seismic response of girder

The cable sag to span ratio	Seismic excitation	Bending moment (kN.m)	Shear force (kN)	Axial force (kN)	Displacement(mm)		
					Longitudinal	Lateral	Vertical
1/9	Longitudinal	2.641×10^5	1.417×10^4	2.635×10^4	892.1		557.0
	Lateral	1.583×10^6	9.448×10^3	-	-	635.7	-
1/10	Longitudinal	2.339×10^5	1.237×10^4	2.528×10^4	840.6	-	344.8
	Lateral	1.559×10^6	9.717×10^3	-	-	617.2	-
1/11	Longitudinal	2.259×10^5	1.119×10^4	2.474×10^4	673.8	-	473.2
	Lateral	1.501×10^6	9.157×10^3	-	-	599.9	-

and the favorable values of these design parameters are proposed.

6.1 The cable sag to span ratio

It is to be noted that the cable sag to span ratio herein is defined with respect of the suspension portion. The cable sag has important influence on the tower height and the inclination angles of stay cables, which are closely related to the tensile forces in main cables and stay cables, and ultimately affects structural stiffness of the bridge. Based on the example bridge, two bridge schemes with the cable sag to span ratio of 1/9 and 1/11 are assumed respectively, their seismic responses are analyzed, and the results are shown in Table 14 and Table 15 respectively.

It is found that the cable sag to span ratio has important influence on structural seismic response, especially under the longitudinal seismic excitation. Under the longitudinal seismic excitation, with the decrease of cable sag to span ratio, the longitudinal displacement, bending moment and axial force of tower decrease, and the shear force reaches the minimum value at the cable sag to span ratio of 1/10; similarly, the longitudinal displacement, vertical bending moment, shear force and axial force of girder reduces gradually, and the minimum vertical displacement occurs at the cable sag to span ratio of 1/10. Under the lateral seismic excitation, with the decrease of the cable sag to span ratio, the tower’s lateral displacement decreases, but its lateral bending moment, shear force and axial force increase significantly; meanwhile the lateral displacement and bending moment of girder reduce gradually. On the whole, better seismic performance of the bridge is achieved at the cable sag to span ratio of 1/10.

Table 16 Effect of the suspension to span ratio on the seismic response of tower

The suspension to span ratio	Seismic excitation	Bending moment (kN.m)	Shear force (kN)	Axial force (kN)	Displacement(mm)	
					Longitudinal	Lateral
0.3	Longitudinal	1.119×10^6	9.491×10^3	1.347×10^4	828.0	-
	Lateral	2.294×10^5	1.839×10^4	4.433×10^4	-	150.9
0.437	Longitudinal	1.488×10^6	1.09×10^4	1.425×10^4	910	-
	Lateral	2.576×10^5	2.079×10^4	4.855×10^4	-	148.5
0.5	Longitudinal	1.966×10^6	1.173×10^4	1.466×10^4	925.9	-
	Lateral	2.736×10^5	2.237×10^4	4.968×10^4	-	132.8

Note: The suspension to span ratio of 0.437 is for the example bridge.

Table 17 Effect of the suspension to span ratio on the seismic response of girder

The suspension to span ratio	Seismic excitation	Bending moment (kN.m)	Shear force (kN)	Axial force (kN)	Displacement(mm)		
					Longitudinal	Lateral	Vertical
0.3	Longitudinal	2.328×10^5	1.322×10^4	2.122×10^4	816.29	-	397.97
	Lateral	1.511×10^6	9.263×10^3	-	-	599.9	-
0.437	Longitudinal	2.339×10^5	1.237×10^4	2.528×10^4	840.6	-	344.8
	Lateral	1.559×10^6	9.717×10^3	-	-	617.2	-
0.5	Longitudinal	2.668×10^5	1.442×10^4	2.477×10^4	875.4	-	342.7
	Lateral	1.595×10^6	9.724×10^3	-	-	619.6	-

6.2 The suspension to span ratio

Increasing or shortening the suspension length enables the cable-stayed-suspension hybrid bridge to behave as the suspension bridge or cable-stayed bridge respectively. Based on the example bridge, two bridge schemes with the suspension to span ratio of 0.3 and 0.5 respectively are assumed, their seismic responses under the horizontal seismic excitation are analyzed and given in Table 16 and Table 17.

As seen in Tables 16 and 17, the suspension to span ratio has also remarkable influence on structural seismic response under the longitudinal seismic excitation, and however the seismic response under the lateral seismic excitation is slightly affected. Under the longitudinal seismic excitation, with the increase of the suspension to span ratio, the longitudinal displacement, bending moment, shear force and axial force of tower increase significantly; similarly, the longitudinal displacement, vertical bending moment, shear force and axial force of girder also increase remarkably, whereas the vertical displacement decreases. Under the lateral seismic excitation, with the increase of the suspension to span ratio, the tower lateral displacement decreases slightly, but its lateral bending moment, shear force and axial force increase significantly; however the seismic response of girder is slightly influenced by the suspension to span ratio.

With the increase of the suspension to span ratio, the bridge behaves as the suspension bridge, structural stiffness decreases, and therefore structural seismic response increases. Viewed from the aspect of seismic performance, small suspension to span ratio is favorable to the cable-stayed-suspension hybrid bridge.

Table 18 Effect of the side span length on the seismic response of tower

The side span length (m)	Seismic excitation	Bending moment (kN.m)	Shear force (kN)	Axial force (kN)	Displacement(mm)	
					Longitudinal	Lateral
394	Longitudinal	1.709×10^6	1.781×10^4	1.672×10^4	1300	-
	Lateral	2.465×10^5	2.464×10^4	5.699×10^4	-	144.8
314	Longitudinal	1.488×10^6	1.09×10^4	1.425×10^4	910	-
	Lateral	2.576×10^5	2.079×10^4	4.855×10^4	-	148.5

Note: The side span length of 314m is for the example bridge.

Table 19 Effect of the side span length on the seismic response of girder

The side span length (m)	Seismic excitation	Bending moment (kN.m)	Shear force (kN)	Axial force (kN)	Displacement(mm)		
					Longitudinal	Lateral	Vertical
394	Longitudinal	2.465×10^5	1.064×10^4	2.101×10^4	1519.4	-	531.4
	Lateral	1.267×10^6	8.234×10^3	-	-	559.1	-
314	Longitudinal	2.339×10^5	1.237×10^4	2.528×10^4	840.6	-	344.8
	Lateral	1.559×10^6	9.717×10^3	-	-	617.2	-

6.3 The side span length

To investigate the effect of side span length on the seismic performance of the bridge, a bridge scheme with side span of 394 m (which is symmetric to the cable-stayed portion in main span) is assumed based on the example bridge, its seismic response is analyzed and compared to the example bridge in Tables 18 and 19.

With the increase of side span length, the longitudinal seismic response of tower increase significantly, while the lateral seismic response is little affected. Similarly, the longitudinal seismic response of girder also increases significantly, and however the lateral seismic response reduces. Therefore, the side span length has significant influence on structural longitudinal seismic response, and for the lateral seismic response, the effect is small, and short side span is more favorable to improve the seismic performance of cable-stayed-suspension hybrid bridge.

6.4 The subsidiary piers in side span

In order to improve the vertical stiffness of cable-stayed-suspension hybrid bridge, several subsidiary piers are commonly set in side spans. Based on the example bridge, two bridge schemes with one and two subsidiary piers in each side span are assumed, their seismic responses under the horizontal seismic excitation are given in Tables 20 and 21.

As can be seen in Tables 20 and 21, when the side span is provided with the subsidiary piers, due to the enhancement of vertical stiffness, the longitudinal seismic response of tower and girder is significantly reduced, and with the increase of subsidiary piers in side span, and the longitudinal seismic effect is further decreased. The lateral displacements of girder and tower are also decreased significantly with increasing the number of subsidiary piers in side span, and however structural seismic internal force is slightly increased. Therefore considering the seismic performance, setting the subsidiary pier in side span is favorable to cable-stayed-suspension hybrid

Table 20 Effect of the subsidiary piers in side span on the seismic response of tower

Number of subsidiary piers	Seismic excitation	Bending moment (kN.m)	Shear force (kN)	Axial force (kN)	Displacement (mm)	
					Longitudinal	Lateral
2	Longitudinal	1.498×10^6	9.943×10^3	1.467×10^4	847.3	-
	Lateral	2.339×10^5	2.369×10^4	4.569×10^4	-	129.9
1	Longitudinal	1.404×10^6	1.01×10^4	1.498×10^4	903.8	-
	Lateral	2.816×10^5	2.411×10^4	4.903×10^4	-	131.0
0	Longitudinal	1.488×10^6	1.09×10^4	1.425×10^4	910.0	-
	Lateral	2.576×10^5	2.079×10^4	4.855×10^4	-	148.5

Note: The number of subsidiary piers of 0 is for the example bridge.

Table 21 Effect of the subsidiary piers in side span on the seismic response of girder

Number of subsidiary piers	Seismic excitation	Bending moment (kN.m)	Shear force (kN)	Axial force (kN)	Displacement (mm)		
					Longitudinal	Lateral	Vertical
2	Longitudinal	1.615×10^5	9.550×10^3	2.084×10^4	749.1	-	321.1
	Lateral	1.840×10^6	9.967×10^3	-	-	534.6	-
1	Longitudinal	1.927×10^5	1.013×10^4	2.063×10^4	770.6	-	321.6
	Lateral	1.936×10^6	1.012×10^4	-	-	597.5	-
0	Longitudinal	2.339×10^5	1.237×10^4	2.528×10^4	840.6	-	344.8
	Lateral	1.559×10^6	9.717×10^3	-	-	617.2	-

Table 22 Effect of the girder supporting system on the seismic response of tower

The girder supporting system	Seismic excitation	Bending moment (kN.m)	Shear force (kN)	Axial force (kN)	Displacement (mm)	
					Longitudinal	Lateral
Floating	Longitudinal	3.834×10^6	1.111×10^4	1.5750×10^4	1542.9	-
	Lateral	2.574×10^5	2.088×10^4	4.861×10^4	-	148.2
Semi-floating	Longitudinal	1.488×10^6	1.090×10^4	1.425×10^4	910	-
	Lateral	2.576×10^5	2.079×10^4	4.855×10^4	-	148.5

Table 23 Effect of the girder supporting system on the seismic response of girder

The girder supporting system	Seismic excitation	Bending moment (kN.m)	Shear force (kN)	Axial force (kN)	Displacement (mm)		
					Longitudinal	Latera	Vertical
Floating	Longitudinal	3.435×10^5	1.263×10^4	2.122×10^4	1545.9	-	509.6
	Lateral	1.543×10^6	9.568×10^3	-	-	615.9	-
Semi-floating	Longitudinal	2.339×10^5	1.237×10^4	2.528×10^4	840.6	-	344.8
	Lateral	1.559×10^6	9.717×10^3	-	-	617.2	-

bridge, however the favorable number of subsidiary piers needs to consider other factors such as the static performance, construction and economic conditions etc.

6.5 The girder supporting system

For the example bridge, the girder supporting system is semi-floating, there exits vertical

Table 24 Effect of the deck form on the seismic response of tower

The deck form	Seismic excitation	Bending moment (kN.m)	Shear force (kN)	Axial force (kN)	Displacement (mm)	
					Longitudinal	Lateral
Steel-concrete hybrid	Longitudinal	2.388×10^6	7.035×10^3	7.602×10^3	874	-
	Lateral	3.506×10^5	2.448×10^4	4.317×10^4	-	141.9
Steel	Longitudinal	1.488×10^6	1.09×10^4	1.425×10^4	910	-
	Lateral	2.576×10^5	2.079×10^4	4.855×10^4	-	148.5

Table 25 Effect of the deck form on the seismic response of girder

The deck form	Seismic excitation	Bending moment (kN.m)	Shear force (kN)	Axial force (kN)	Displacement (mm)		
					Longitudinal	Lateral	Vertical
Steel-concrete hybrid	Longitudinal	4.070×10^5	1.976×10^4	3.640×10^4	769.3	-	254.1
	Lateral	2.416×10^6	1.009×10^4	-	-	350.7	-
Steel	Longitudinal	2.339×10^5	1.237×10^4	2.528×10^4	840.6	-	344.8
	Lateral	1.559×10^6	9.717×10^3	-	-	617.2	-

supports between the girder and tower. Based on the example bridge, a bridge scheme is assumed, in which the girder is floating longitudinal and no vertical supports are provided between the girder and tower, its seismic response under the horizontal seismic excitation is analyzed and compared to that of the example bridge as shown in Tables 22 and 23.

It can be seen that the girder supporting system has little influence on the lateral seismic responses of the girder and tower, and however for the longitudinal seismic response, the effect is significant. Under the case of floating system, the longitudinal seismic responses of the girder and tower are greatly increased, especially the longitudinal displacement, and therefore favorable longitudinal constraint should be provided to reduce the seismic response. As result, the floating system is not favorable for the cable-stayed-suspension hybrid bridge, and favorable longitudinal constraints should be provided between the girder and tower.

6.6 The deck form

For cable-stayed-suspension hybrid bridge, different structural materials can be used in the suspension and cable-stayed portions, for example, the concrete girder in the cable-stayed portion and the light steel box girder in the suspension portion, structural performance can be improved and also the materials in the deck, cables and anchorages can be greatly saved. Based on the example bridge, a bridge scheme with steel-concrete hybrid girder is assumed, in which the concrete girder is employed in the cable-stayed portion and the light steel box girder is employed in the suspension portion, its seismic response is analyzed and compared to the example bridge as shown in Tables 24 and 25.

It is found that as the hybri girder is employed, structural displacement is decreased significantly, and however its internal force is increased, which indicates that the steel-concrete hybrid girder is helpful to improve structural stiffness and further the seismic performance. Therefore considering the seismic performance, the steel-concrete hybrid girder is favorable to cable-stayed-suspension hybrid bridge.

7. Conclusions

In this work, by taking a cable-stayed-suspension hybrid bridge with main span of 1400 m as example, seismic response of the bridge under the seismic excitations is investigated numerically by response spectrum analysis and time history analysis, its seismic performance is discussed and compared to the cable-stayed bridge and suspension bridge with the same main span. Under the horizontal seismic action, the effects of structural design parameters including the cable sag to span ratio, the suspension to span ratio, the side span length, the subsidiary piers in side spans, the girder supporting system and the deck form etc on the seismic performance of cable-stayed-suspension hybrid bridge are investigated by response spectrum analysis. Some conclusions can be drawn as follows:

(1) Under the horizontal seismic action, the maximum internal forces occur at the junctions of the girder and tower and also the tower bottom ends , and therefore more attentions should be paid to the seismic design of these sections.

(2) Due to its strong gemetric nonlinearity, the nonlinear time history analysis should be conducted to accurately predict the seismic response of cable-stayed-suspension hybrid bridge.

(3) The seismic performance of cable-stayed-suspension hybrid bridge is between the cable-stayed bridge and suspension bridge, however it is more close to the suspension bridge and superior to the cable-stayed bridge. Therefore, the cable-stayed-suspension hybrid bridge is suitable to long-span bridges with ultra-kilometer main span.

(4) Better seismic performance is achieved for the cable-stayed-suspension hybrid bridge with the cable sag to span ratio of 1/10, the suspension to span ratio between 0.4 to 0.5, short side spans and setting subsidiary piers in side spans, semi-floating system and the hybrid deck form.

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