

Research on Dynamic Responses of Long-Span Suspension Bridge with CFRP Cables

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Abstract: In order to study the dynamic responses of long-span suspension bridge with CFRP cables, a suspension bridge with CFRP cables which span of 896m is designed. The dynamic responses of suspension bridge with steel cables and CFRP cables are analyzed by ANSYS software, the effects of structural design parameters on the dynamic responses are investigated. The analysis results show the basic frequency of vertical, lateral bending and twist of suspension bridge with CFRP cables were increased in contrast with suspension bridge with steel cables, applying CFRP cable has little effect on the mode shapes and frequencies of horizontal bending and longitudinal floating of stiffening girder, the central buckle could improve the dynamic behavior of suspension bridge, the frequency not always increase with the stiffness of main cables increase, the stiffness of suspender have relatively little effect on the dynamic behavior of the entire suspension bridge.

Introduction

Suspension bridge is a flexible suspension system, which composed by main cables and stiffening girder. It has been widely used in the long-span bridge due to its strong leap ability. suspension bridge is easily vibrated by environment loads which include wind loads, vehicle loads, seismic loads and so. The traditional suspension bridge use steel cables, it can meet the need of engineering of medium span bridge, the gravity of steel cables become a major factor with the increase of span, it restrict the leap ability of suspension bridge and decrease the efficiency of bearing capacity. Carbon-fibre reinforced plastic[2-5] possess the characteristics of high strength, light weight, good abrasability, non-corrosion, good durability, and high fatigue resistance, which is suitable as cables for long-span suspension bridge to solve the above problems. The dynamic behavior[6] is essential to the research on structural dynamic characteristic. It is essential to study the long-span suspension bridge with CFRP cables.

Characteristics of CFRP

CFRP[7] is a composite material of light weight and high strength, compounded by resin and carbon fiber, and take full advantage of carbon fiber and resin. The CFRP material of different manufacturers have some differences in CFRP characteristics, CFRP characteristics is shown in Table 1. According to figure 1, CFRP cables is linear variation before breakage.

Table 1 Properties of CFRP-wires and tensioning steel

Type of cable	A	B	C	steel
Bulk density(kN/mm ³)	16	16	16	77
Strength of extension(MPa)	2140	2550	2022	1570
Elasticity modulus(kN/mm ²)	137	147	137	196
Strength of extension/elasticity modulus	0.016	0.017	0.015	0.008
Relax rate in 1000 hours(%)	0.3	0.3	0.3	<2.5
Failure strain(%)	1.6	1.6	2.0	>4
Coefficient of linear Expansion($\times 10^{-6}$)	0.6	0.68	0.6	12

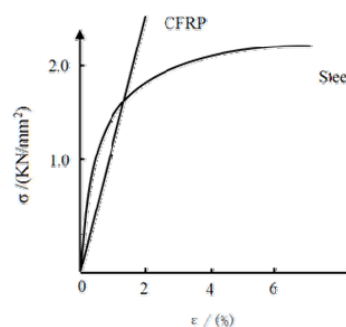


Figure 1 Stress-strain curves of CFRP cable and steel cable

Finite element analysis of suspension bridge with CFRP cables in dynamic behavior

The dynamic responses of suspension bridge is directly related with the safety of bridge. The main structural part are composed of main cables, bridge tower, the stiffening girder, suspender and anchorage. The long-span suspension bridge engineering background of this paper include, main span of the bridge is 896m, the stiffening girder use truss structural, the wide of girder is 28.2m, the truss structural is composed of main truss, top and bottom bracing, the transverse truss, use CFRP cables, the transverse space of CFRP cables is 26m, the rise-span ratio is 1/10.5, the bridge tower use portal frame in concrete structure, the height of tower is 122.1m. ANSYS software was been used to Build the finite model of the bridge. The linetype of cable use the formula[8]: $y = \frac{4f(l-x)x}{l^2}$, where y represents Y-axis, x represents X-axis, l represents the main span, f represents the rise-span ratio. The finite model of suspension bridge shown in figure 2.

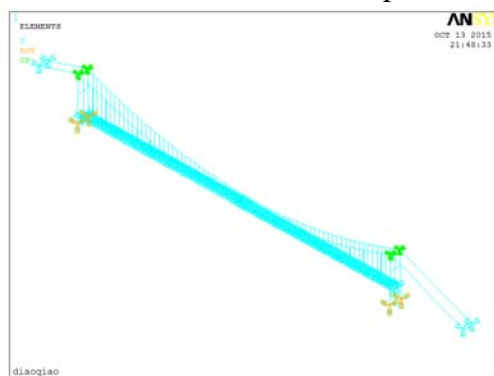


Figure 2 Finite model of suspension bridge

Modal analysis is necessary to study the dynamic characteristics of the structural. Through the Modal analysis of suspension bridge with CFRP cables, the first ten natural frequencies and mode shapes are gained. The main steps of modal analysis include: firstly, have static analysis on the finite model. The effect of large deformation and prestressing should consider in static analysis. Secondly, have modal analysis on the finite model. Thirdly, mode expansion. The last, post processing and view results. The first six mode of vibration about suspension bridge is shown in figure 3, the preceding 10 primary modal analysis results are listed in table 3. The modal characteristic are described with abbreviations: H-horizontal, V-vertical, L-Longitudinal, B-bending, T-torsion, F-floating, S-symmetric, A-anti-symmetric, SG-stiffening girder, MC-main cables. According to the results in figure 3 and table 3, the main mode shapes of the first ten mode shapes of suspension bridge with CFRP cables are the vibration of girder and cable. The first six mode shapes are the vibration of girder, the first order vibration is the lateral bending of symmetrical, the fundamental frequency is 0.069555Hz.

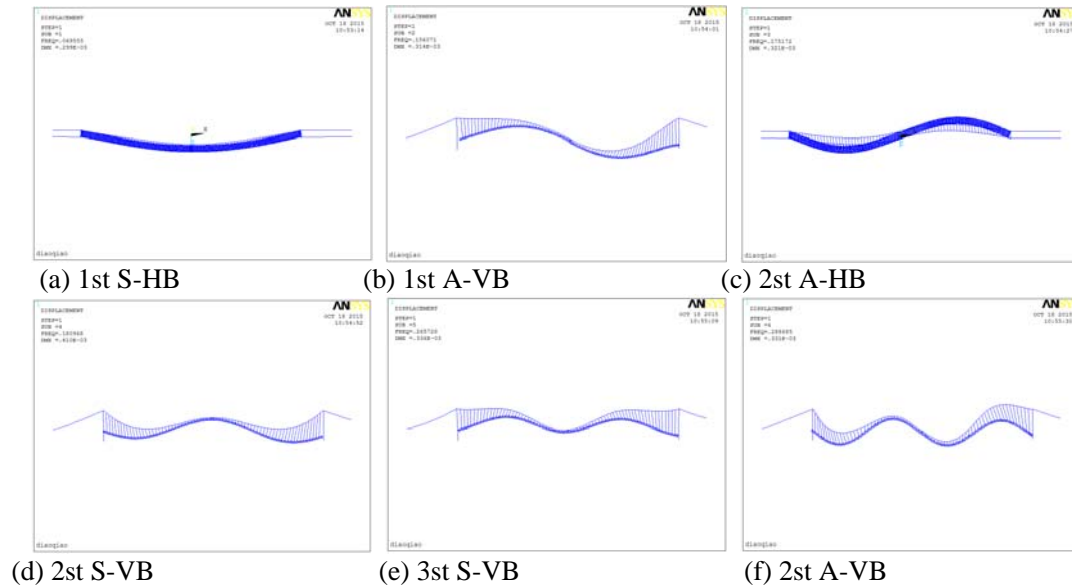


Figure 3 Mode of vibration about suspension bridge

Table 3 Fundamental frequency and mode of suspension bridge with CFRP cables

Mode No.	Frequency (Hz)	Mode shape description	Period (s)
1	0.069555	1st S-HB	14.38
2	0.15607	1st A-VB	6.41
3	0.17517	2st A-HB	5.71
4	0.18097	2st S-VB	5.53
5	0.26573	3st S-VB	3.76
6	0.28869	2st A-VB	3.46
7	0.31492	2st S-HB	3.18
8	0.383	4st S-VB	2.61
9	0.38997	1st S-T	2.56
10	0.46619	2st S-T	2.15

Dynamic responses comparison between suspension bridge with CFRP cables and steel cables

The paper remain the parameters of the bridge unchanged, use the equivalent stiffness method[7] to calculate the cross-sectional area of the steel cable, analyze the dynamic responses of suspension bridge with steel cables. The equivalent stiffness method: $E_1 A_1 = E_2 A_2$, where, E_1, E_2 represent elasticity modulus of CFRP and steel separately, A_1, A_2 represent cross-sectional area of CFRP cable and steel cable separately. The fundamental frequency and mode of suspension bridge with steel cables are listed in table 4. The fundamental frequency and mode of several suspension bridges are listed in table 5.

Table 4 Fundamental frequency and mode of suspension bridge with CFRP cables

Mode No.	Frequency (Hz)	Mode shape description	Period (s)
1	0.068218	1st S-HB	14.66
2	0.15056	1st A-VB	6.64
3	0.17295	2st A-HB	5.78
4	0.17583	2st S-VB	5.69
5	0.25097	3st S-VB	3.98
6	0.2802	2st A-VB	3.57
7	0.30297	2st S-HB	3.30
8	0.33072	1st S-T	3.02
9	0.33589	1st S-T	2.98
10	0.3544	2st S-T	2.82

Table 5 Fundamental frequency and mode of several suspension bridges [5-6]

Bridge name	Main span(m)	Type of stiffening girder	Frequency(Hz)	Period(s)	Mode shape description
Runyang yangtze river bridge	1490	Steel box girder	0.0498	20.08	1st S-HB
Jiangyin yangtze river bridge	1385	Steel box girder	0.0521	19.19	1st S-HB
Hong Kong Tsingma bridge	1377	Steel truss girder	0.068	14.71	1st S-HB
Yichang Yangtze river bridge	960	Steel box girder	0.0705	14.18	1st S-HB
Humen bridge	888	Steel box girder	0.0921	10.86	1st S-HB
Haicang bridge	648	Steel box girder	0.122	8.20	LF

According to the results in table 3 and table 4, in contrast with suspension bridge with steel cables, the fundamental frequency of suspension bridge with CFRP cables increased, and the low order improve more than high order, the result can illustrate that suspension bridge with CFRP cables possess good dynamic responses. According to the results in table 5, the fundamental frequency increase with the main span increase, the fundamental frequency of suspension bridge with steel cables get close to the Yichang Yangtze river highway bridge, the result illustrate the accuracy of the finite model in this paper.

Analyze the effects of structural design parameters of suspension bridge with CFRP cables on the dynamic responses

The paper use simple variable method to analyze the dynamic responses of suspension bridge with CFRP cables models which possess different structural parameters.

Effects of central buckle

Central buckle is a effective measure to improve the entire stiffness of suspension bridge. Modal analysis of the effects of central buckle is shown in table 6 which list the fist ten mode shapes only.

Table 6 Dynamic responses of suspension bridge with central buckle or suspender

Mode No.	Central buckle		Suspender	
	Frequenc y(Hz)	Mode shape description	Frequenc y(Hz)	Mode shape description
1	0.069555	1st S-HB	0.069106	1st S-HB
2	0.15607	1st A-VB	0.13605	1st A-VB
3	0.17517	2st A-HB	0.16507	1st A-HB
4	0.18097	2st S-HB	0.1809	2st S-VB
5	0.26573	3st S-VB	0.26445	3st S-VB
6	0.28869	2st S-VB	0.28137	2st A-VB
7	0.31492	2st S-HB	0.31347	2st S-HB
8	0.383	4st S-VB	0.37079	4st S-VB
9	0.38997	1st S-T	0.41336	1st S-T
10	0.46619	2st S-T	0.41593	2st S-T

The fundamental frequency of model that have suspender is 0.0691Hz, but the fundamental frequency of model that have central buckle is 0.0695Hz, it improve a lot by comparison, the reason is that central buckle restrict the longitudinal displacement of suspension bridge, and make the entire stiffness of the bridge improve.

Effects of the stiffness of main cable

The stiffness of main cable is the product of cross-sectional area and elasticity modulus, the elasticity modulus of the material is unchanged, so the stiffness of the cable depend on the cross-sectional area. The paper use relative stiffness coefficient η_1 to represent the change of stiffness, $\eta_1 = \frac{EA}{E_0A_0}$, where E_0A_0 represents the standard stiffness, EA represents the changed stiffness. Modal analysis of the effects of the stiffness of the cable are shown in table 7 which list the first ten mode shapes only.

According to the results in table 7, most of the fundamental frequency of the bridge increase with η_1 increase, but the lateral bending of symmetrical of second order and the torsion of second order are increase at first and then decrease. The change of the stiffness of cable leads to the gravity of the bridge increase and make the original balance of the bridge break. In conclusion, the fundamental frequency of suspension bridge not always increase with the stiffness of the main cable increase.

Table 7 Dynamic responses of suspension bridge with different η_1

Mode No.	η_1									
	0.5	0.8	1	1.5	2	0.5	0.8	1	1.5	2
	Frequency (Hz)	Mode shape description	Frequency (Hz)	Mode shape description	Frequency (Hz)	Mode shape description	Frequency (Hz)	Mode shape description	Frequency (Hz)	Mode shape description
1	0.068221	1st S-HB	0.069208	1st S-HB	0.069555	1st S-HB	0.069989	1st S-HB	0.070146	1st S-HB
2	0.14947	1st A-VB	0.15449	1st A-VB	0.15607	1st A-VB	0.15789	1st A-VB	0.15842	1st A-VB
3	0.1619	2st A-VB	0.17397	2st A-VB	0.17517	2st A-HB	0.17705	2st A-HB	0.1781	2st A-HB
4	0.17119	2st A-HB	0.17639	2st S-VB	0.18097	2st S-VB	0.18636	2st S-VB	0.18859	2st S-VB
5	0.21884	1st S-VB	0.24754	3st A-VB	0.26573	3st S-VB	0.28996	4st A-VB	0.29044	4st A-VB
6	0.28233	4st A-VB	0.28708	4st A-VB	0.28869	2st A-VB	0.30435	3st A-VB	0.31332	3st A-VB
7	0.31364	2st S-HB	0.3149	2st S-HB	0.31492	2st S-HB	0.31433	2st S-VB	0.33091	2st S-VB
8	0.32485	1st A-T	0.36796	1st S-T	0.383	4st A-VB	0.38991	1st S-T	0.39937	1st S-T
9	0.37314	5st S-VB	0.37995	5st S-VB	0.38997	1st S-T	0.42713	5st A-VB	0.44026	5st S-VB
10	0.46473	2st S-T	0.46642	2st S-T	0.46619	1st S-T	0.46417	1st A-VB	0.46155	2st S-T

Effects of the stiffness of suspender

The stiffness of the suspender depend on the cross-sectional area. The paper use relative stiffness coefficient η_2 to represent the change of stiffness, $\eta_2 = \frac{EA}{E_0A_0}$, where E_0A_0 represents the standard stiffness, EA represents the changed stiffness. Modal analysis of the effects of the stiffness of suspender is shown in table 8 which list the fist ten mode shapes only.

Table 8 Dynamic responses of suspension bridge with different η_2

Mode No.	η_2									
	0.5		0.8		1		1.5		2	
	Frequency (Hz)	Mode shape description	Frequency (Hz)	Mode shape description	Frequency (Hz)	Mode shape description	Frequency (Hz)	Mode shape description	Frequency (Hz)	Mode shape description
1	0.069545	1st S-HB	0.069555	1st S-HB	0.069555	1st S-HB	0.06955	1st S-HB	0.070146	1st S-HB
2	0.15586	1st A-VB	0.15604	1st A-VB	0.15607	1st A-VB	0.15606	1st A-VB	0.15842	1st A-VB
3	0.17523	2st A-HB	0.17521	2st A-HB	0.17517	2st A-HB	0.17506	2st A-HB	0.1781	2st A-HB
4	0.18078	2st A-VB	0.18093	2st A-VB	0.18097	2st A-VB	0.18101	2st A-VB	0.18859	2st A-VB
5	0.26427	3st S-VB	0.26541	3st S-VB	0.26573	3st S-VB	0.26598	3st S-VB	0.29044	3st S-VB
6	0.28761	4st A-VB	0.28847	4st A-VB	0.28869	2st A-VB	0.28881	4st A-VB	0.31332	4st A-VB
7	0.31507	2st S-HB	0.31499	2st S-HB	0.31492	2st S-HB	0.31473	2st S-HB	0.33091	2st S-HB
8	0.38068	5st S-VB	0.38248	5st S-VB	0.383	4st S-VB	0.38346	5st S-VB	0.39937	5st S-VB
9	0.38875	1st S-T	0.38972	1st S-T	0.38997	1st S-T	0.39011	1st S-T	0.44026	1st S-T
10	0.46688	2st S-T	0.46654	2st S-T	0.46619	2st S-T	0.46517	2st S-T	0.46155	2st S-T

According to the results in table 8, the fundamental frequency of suspension bridge change little with the stiffness of the suspender change, the relative variation ratio is 0.5% only, when the relative stiffness coefficient change from 1.5 to 2, so the stiffness of the suspender change have little effect on the dynamic responses of suspension bridge.

Conclusions

The research results show the basic frequency of vertical, lateral bending and twist of suspension bridge with CFRP cables were increased in contrast with suspension bridge with steel cables, applying CFRP cable has little effect on the mode shapes and frequencies of horizontal bending and longitudinal floating of stiffening girder. The central buckle make the entire stiffness of suspension bridge increase, it restrict the longitudinal displacement of the bridge also, so the central buckle could improve the dynamic behavior of suspension bridge, the frequency not always increase with the stiffness of main cables increase. The stiffness of suspender have relatively a small effect on the dynamic behavior of the entire suspension bridge.

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