Applicability Study of Travelling-wave Effect on Multi-tower Extradosed Cable-stay Bridges Using Symmetric Analyzing Method

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Abstract. Shake table test is considered to be a very intuitive and efficient way of studying structure seismic response. With more long multi span bridges been built and a larger proportional scale structure tests are towards, the capacity of shake tables and table numbers are insufficient. Sacrifice has been made when analysing bridge seismic response under multiple-support excitation by putting adjacent piers on one table.With the method used in static symmetric structure, a symmetric six-tower extradosed cable-stayed bridge under travelling wave excitation was analyzed by separating the whole bridge into symmetric and antisymmetric half bridges. The seismic loading is also dealt with symmetric method and then applied to the corresponding structure. This method is promoted from linear situation to nonlinear situation. And by adjusting Ground Peak Acceleration(PGA)and bearing constitutive relations, simulation analysis has been done. This study indicates that using symmetric analyzing method, half bridge can be used to analyze travelling wave effect effectively instead of whole bridge especially when post stiffness and PGA are in high level.

Introduction

Experiment of bridges on multi-support excitation is a strong research method of studying the law of wave passage effect. By putting side piers on one table, Jukao Yan[1] did a shake table test of a suspension bridge focused on wave passage effect using four tables. Zhou Lu [2] did a shake table test of a nine pier continuous bridge by putting four piers on one table and the middle one on the deck supported on two shake table. Technically, these cannot be called multi-support excitation.

In statics, a simpler way dealing with symmetrical structure is using symmetrical method. By putting split load of symmetrical and anti-symmetrical one on corresponding half structure, general response of the structure can be calculated simply by doing numerical superposition of the two. Research of bridge on seismic excitation with the method drawn from static has been done. Lou Menglin and Gao Shan[3] 、Lou Menglin and Li Qiang[4] did numerical simulation of a symmetrical arch bridge using symmetrical method. They've found that in elastic circumstance, this method is quite useful. As most bridges are symmetrical in shape, taking example by half-structure method used in statics, a further step is made by applying this method to dynamics with the consideration of nonlinearity.

Dynamic response of bridge structures under seismic excitation contains three aspects of nonlinearity [5]: the linearity of material, the linearity of geometry，the linearity of boundary. With a six tower extrodosed cable-stayed bridge as its main object, this paper focused the applicability of symmetric method without the consideration of nonlinearity except bearing linearity. Apparent wave velocity is a vital factor that affects structure response. However, this paper considers only the comparison of whole bridge and half bridge using symmetrical method, apparent wave velocity seems not to be a vital factor. Since the main span is 150m, with the consideration of site situation, apparent wave velocity is set to 150m/s.

Analysis of seismic response of the bridge

Bridge Overview

The bridge in this example is an extradosed multi-tower cable-stayed bridge. The pylon is 45m high, boned with pre-stressed steel-concrete box beam of corrugated steel webs, and together they are supported on six piers. The total length of the bridge is 908m, with span arrangement of 79m+5×150m+79m. The girder is 4.7m high, with the upper deck width of 37m and the lower deck width of 43.84m. The bridge is symmetrical in shape. For better seismic consideration, isolation design is used.

Simulation Model

Using SAP2000 FEA software, three 3D finite element analysis models, including full bridge, symmetrical bridge and anti-symmetrical bridge were developed to analyse seismic response of the bridge considering wave-passage effect. In the process, nonlinearities including P-Delta effect under dead load and the cable sag effect were also considered. For simplicity, the base is set to be rigid.

The bearings were simulated as nonlinear bearings using plastic-wen element, constitutive relation is shown in Fig.1. In Fig.1, K_1 represents pre-yield stiffness of the bearing while K_2 represents post-yield stiffness of the bearing. Fs represents yield force of the bearing and U_0 is yield displacement of the bearing. In this paper, by adjusting the ratio of bearing post-pre stiffness, seismic analysis can then be analyzed to a conclusion whether symmetric analyzing method works.

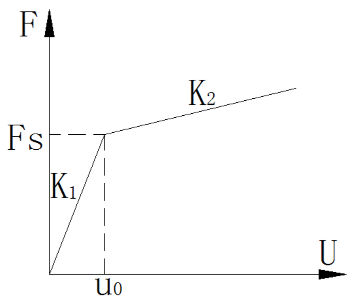


Fig.1 Restoring force model of Friction Pendulum System bearing

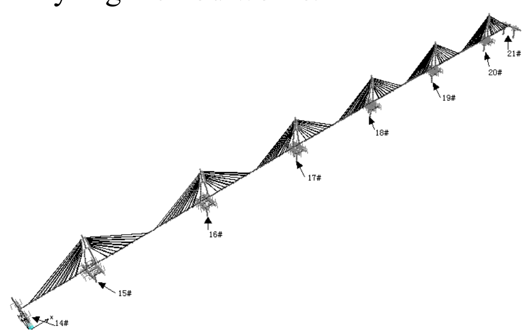
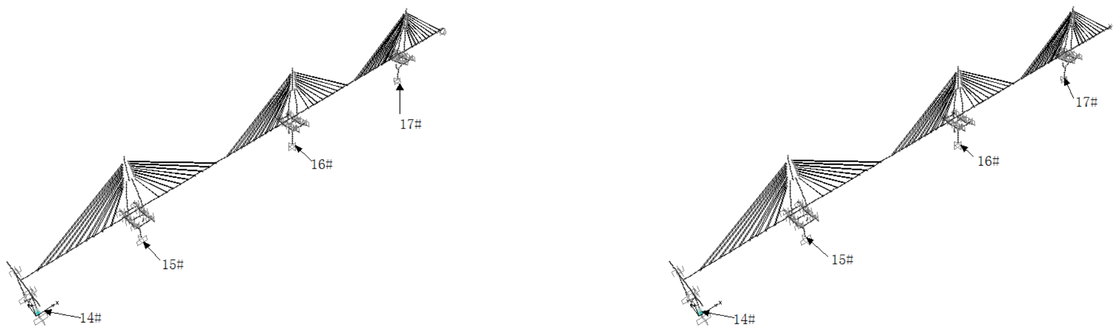


Fig.2 FEA Model of six-tower Extrodosed Cable-Stayed Bridge



Symmetric half of the bridge   Antisymmetric half of the bridge

Fig.3 FEA Model of half structure of six-tower Extrodosed Cable-Stayed bridge

Assuming the wave travels from Pier 14# to Pier 21#(Fig.2 and Fig.3), the excitation on each base is $u_1(t) \sim u_8(t)$. With guide in statics, excitation on Pier 14# to Pier 17# under anti-symmetrical structure is $u_1s(t)=\frac{u_1(t)+u_8(t)}{2}$, $u_2s(t)=\frac{u_2(t)+u_7(t)}{2}$, $u_3s(t)=\frac{u_3(t)+u_6(t)}{2}$, $u_4s(t)=\frac{u_4(t)+u_5(t)}{2}$; whereas $u_1r(t)=\frac{u_1(t)-u_8(t)}{2}$, $u_2r(t)=\frac{u_2(t)-u_7(t)}{2}$, $u_3r(t)=\frac{u_3(t)-u_6(t)}{2}$, $u_4r(t)=\frac{u_4(t)-u_5(t)}{2}$ under symmetrical structure.

Seismic response under wave passage effect with different post-pre stiffness ratio of bearings

In this paper, Chi-Chi wave was selected in analysis with post-pre stiffness of bearings range from 0.0002 to 0.02[0.0002 0.001 0.005 0.01 0.02]. In the analysis, bearing deformation and moment of pier bottom were selected as the parameters of interest. Direct Displacement Method was applied in the analysis with its displacement integrated from acceleration time-history curve. However, excited by direct displacement may differ from acceleration excitation pattern. Wilson [6] pointed that one important reason is that linear acceleration load corresponds to cubic displacement load, thus smaller time increment is needed in DD Method or higher order method should be applied. While time-history data is recorded in dot data with finite time interval, time-history displacement integrated by recorded acceleration curve coordinate with recorded one. But it's not the same story backward. Normally, reducing time interval will be helpful because it will reduce the difference between differential value of time-history displacement with the recorded acceleration curve. 0.005s was selected as the time interval in this paper.

Table 1 demonstrates the results of full bridge response and superposition response of symmetric and anti-symmetric structure using symmetric analyzing method (Due to space limitation, stiffness ratio of 0.02 is displayed here). The apparent velocity in this example is 150m/s.

Table 1 Comparison of whole bridge response and overlap of half bridges peak response with bearings in different post-pre stiffness ratios

Seismic Response	Location	Peak Value(Post-pre stiffness equals 0.02)		
		Superposition	Full bridge	Deviation
Bearing Deformation(m)	14#PTB	2.100408	2.11134	-0.518152
	15#PTB	1.863055	1.84432	1.0154381
	16#PTB	1.332705	1.29473	2.9327259
	17#PTB	1.044973	1.05818	-1.248926
	18#PTB	0.977652	1.02121	-4.265707
	19#PTB	1.391587	1.39472	-0.224775
	20#PTB	1.649228	1.64302	0.3774742
	21#PTB	1.768608	1.74395	1.4137422
Moment of pier bottom (kN·m)	14# PB	150039.1	160761	-6.669725
	15# PB	1964122.1	1979229	-0.763278
	16# PB	1570168.8	1463368	7.2982250
	17# PB	1253565.9	1373765	-8.749620
	18# PB	1209628.3	1275957	-5.198404
	19# PB	1791043.4	1799281	-0.457842
	20# PB	1714164.8	1805856	-5.077439
	21# PB	153888.85	167501	-8.126871

Note：PTB(Pier-Top-Bearing)；PB(Pier-Bottom)。

Fig.4 and Fig.5 show that with the growth of bearing's post-pre stiffness ratio, bearing deformation as well as pier moment superposed by symmetric and anti-symmetric structure comes closer to those thrived from full bridge model. One reason might be that, the samaller the post-pre stiffness ratio, the larger degree of nonlinearity the structure has, the larger deviation of full bridge method and symmetric analyzing method.

To testify whether it is that ration affect the deviation, linear analysis was done. In which, the stiffness of the bearing applied equivalent stiffness. When all bearings had same stiffness, which means the structure were in perfect symmetric condition, deviation of bearing deformation was low enough(with maximum value of -0.125%). However, deviation of pier-bottom moment was a bit high, especially pier 14# and Pier21#. As this bridge is a seismic isolation design, bearing deformation is relative displacement between deck and pier. Which is controlled mainly by the mode of the structure.

However, it is self-vibration of the pier that matters in pier 14# and Pier21# (About 75%). The stiffness of piers in the middle is high enough, that the deviation is relatively normal.

As to asynchronous excitation in different pier base, bearings on top of each pier might be in different stiffness section, due to the short yield displacement, for most time, bearings were in lower stiffness section. Bearing deformation deviation stayed low (limited below 15.6% under post-pre ratio of 0.0002). When post-pre ratio equaled 0.02, bearing deformation deviation was limited below 4.3% while pier-bottom moment deviation was limited below 8.2%.

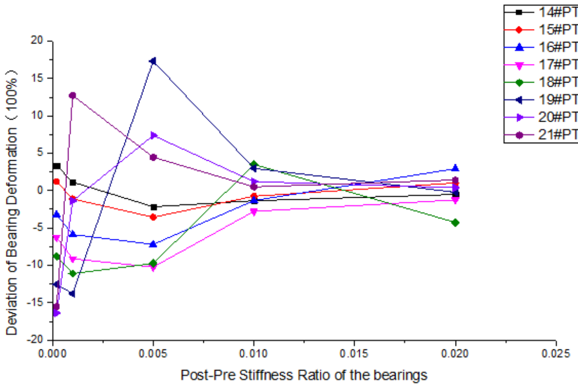


Fig.4 Bearing Displacement Deviation between full bridge response and overlap of symmetric and Antisymmetric bridge response under travelling wave excitation

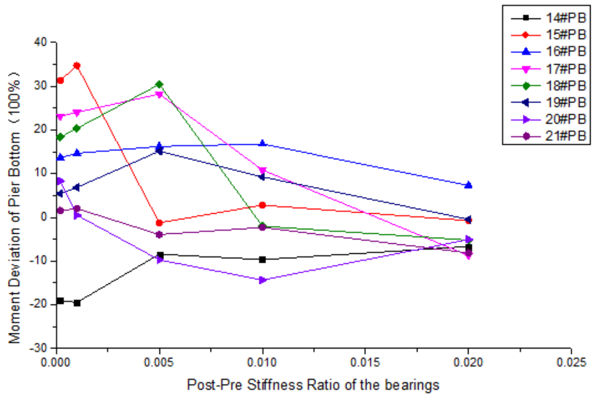
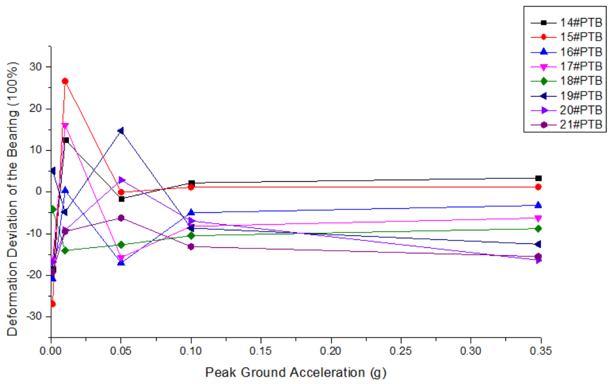
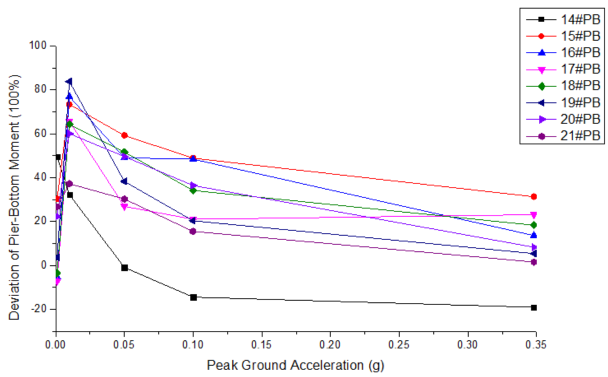


Fig.5 Pier Bottom Bending Moment Deviation between full bridge response and overlap of symmetric and Antisymmetric bridge response under travelling wave excitation

Seismic response under different PGA

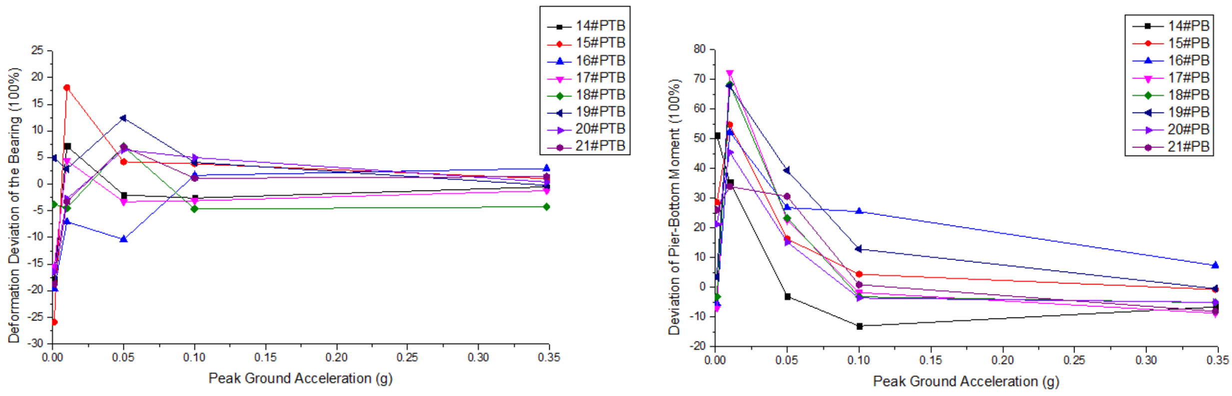


(a)Bearing Displacement Deviation between full bridge response and overlap of symmetric and Antisymmetric bridge response under travelling wave excitation



(b) Pier Bottom Bending Moment Deviation between full bridge response and overlap of symmetric and Antisymmetric bridge response under travelling wave excitation

Fig.6 Response Deviation of Concerning Parts with Post-Pre Stiffness of 0.0002



(a)Bearing Displacement Deviation between full bridge response and overlap of symmetric and Antisymmetric bridge response under travelling wave excitation

(b) Pier Bottom Bending Moment Deviation between full bridge response and overlap of symmetric and Antisymmetric bridge response under travelling wave excitation

Fig.7 Response Deviation of Concerning Parts with Post-Pre Stiffness of 0.02

Figure 7 to Figure 8 show deviation of critical response of bearing deformation and pier-bottom moment under post-pre stiffness of 0.0002 and 0.02, respectively.

With Figure 6 and Figure 7, it can be seen that whatever post-pre stiffness ratio, 0.0002 or 0.02, with the growth of PGA, the less difference between results draw from full bridge model and that from superposition of symmetric and anti-symmetric structure.

Conclusions

Based on an extradosed multi-tower cable-stayed bridge, seismic analysis of full bridge and half bridge using symmetric analyzing method was done. By adjusting post-pre stiffness ratio of the bearing in different PGA, conclusions are draw as follows:

Deviation may appear with different excitation pattern—acceleration mode and displacement mode. That deviation can be scaled down with the use of smaller time interval of displacement mode. When bearings apply same stiffness in linear analysis, results draw from full bridge model is very close to those from symmetric analyzing method. Which indicates, that symmetric analyzing method is acceptable to linear structure.

Bearing's post-pre stiffness ratio and PGA value do affect the accuracy of symmetric analyzing method. The higher the ratio and PGA value, the more accuracy the method has. Which means, this method is more acceptable to lower nonlinearity. But in another aspect, when PGA value or the ratio stays in a high state, this method has a high validating effect. Under this circumstance, symmetric analyzing method can be acceptable.

Focusing on two important responses—bearing deformation and pier-bottom moment, full bridge model as well as symmetric and anti-symmetric model had been set to testify the accuracy of using symmetric analyzing method in half structures. It has been found that, symmetric analyzing method can be used to analyze wave-passage effect of multi-span bridges with isolation design under the circumstance of relatively high post-pre stiffness ratio of bearing or high PGA. With the huge development of shake-table tests, more bridges with multi spans are going to be tested. Due to limited shake tables, this kind of method might be of a great help.

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