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Establish Benchmark Model for Structure Damage Detection based on the Main Navigation Channel of Donghai Bridge

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ABSTRACT

Establishing a finite element Benchmark model that can accurately present structural parameters, states as well as boundary conditions of a bridge structure, based on real bridge health monitoring system, is the basis for structure damage detection and safety evaluation. In this paper, two Benchmark models are developed from the original prototype model of the Kezhushan cable-stayed bridge, which is one of the main navigation channels of Donghai Bridge. The Benchmark models are established based on the form of external loading and purpose of structural health monitoring (SHM). Dynamic characteristics, such as frequencies and mode shapes, of both the original prototype model and the Benchmark models are obtained and compared through modal analysis. An improved sensitivity-based parameter updating method is used to modify the structural parameters of the Benchmark models such that they are equivalent to the original model statically and dynamically. The updated Benchmark models can be used to replace the original model for parametric identification and condition assessment of the structure.

Keywords: structural health monitoring, structure damage detection, cable-stayed bridge, Benchmark model, model updating

1. INTRODUCTION

One of the important subjects of structural health monitoring (SHM) is the identification of structural damages. There are quite a number of damage identification techniques available in the literature, however, it is difficult to evaluate the accuracy and effectiveness of these methods because they are developed using different models and based on various sources of measurement data. Hence, in order to provide a unified research platform for the studies of damaged identification methods, standardized Benchmark models are acquired.

Benchmark models were first established for the study of building structures using numerical simulation. For example, Black and Ventura (1998) proposed a Benchmark model which was a steel frame structure scaled model with four layers. Bernal and

Gunes (2000) performed damage identification on a UBC[1]
Benchmark model using damage location vector method. Johnson and Lam (2000) and Dyke et al (2000) investigated the damage identification methods based on the ASCE Benchmark model. These Benchmark models were mainly in small scale and could not represent complicated real engineering projects.

Recently, Ni et al (2012) set up the Benchmark model of Guangzhou TV tower of China for the sharing of measurement data from the installed SHM system. This paper aims to serve the same purpose of sharing SHM data of Donghai bridge, which is located in Shanghai, China. The Kezhushan cable-stayed bridge which is one of the main navigation channels of Donghai bridge, will be used as an example. The 3D finite element model of the full bridge will first be set up as the original prototype model. Then, a 2D cable-stayed bridge model will be established for the structure under vertical excitations. Finally, this 2D cable-stayed model will be further simplified to a 2D continuous beam bridge model for the purpose of damage identification of the main girder. Both static and dynamic analysis will be performed and model updating process will be carried out to ensure the first 6 natural frequencies and mode shapes of the 2D Benchmark models agree with those of the original 3D prototype model when considering only vertical loads.

2. FINITE ELEMENT MODELING OF KEZHUSHAN BRIDGE

2.1 General Information of Kezhushan Bridge

Donghai Bridge is the only channel connecting Shanghai to Yangshan Port. The bridge is located in the East Sea of China with complex landscapes and occasionally suffered from climate change, high speed wind, thunderstorms and seawater corrosion. In order to ensure the normal operation of Donghai Bridge and improve the maintenance management level, a health monitoring system was installed. The whole bridge is divided into eight monitoring sections, where the Kezhushan Bridge is one of them.

Kezhushan Bridge is one of the main navigation channels of the Donghai Bridge, acrossing the slot of the deep sea with its east end connecting to the Kezhushan Island. The bridge is 710 meters long in total with a 610m cable-stayed bridge in the middle and 50m transition hole at each side. The main span of the cable-stayed bridge is 332m long, and the two side spans are 139m long each. It is a steel and concrete composite beam structure with double cable planes and double pylons. The main tower is a 105m high π-shaped reinforced concrete structure, and each cable plane has 64 cables arranged symmetrically in a dense fan-shaped.

2.2 Three-Dimensional (3D) Prototype Model

Dong and Sun (2010) investigated the extreme load identification and early warning of the Kezhushan Bridge based on monitoring data and established a 3D finite element model of the bridge as shown in Fig. 1. This 3D model will serve as the original prototype model in this paper.

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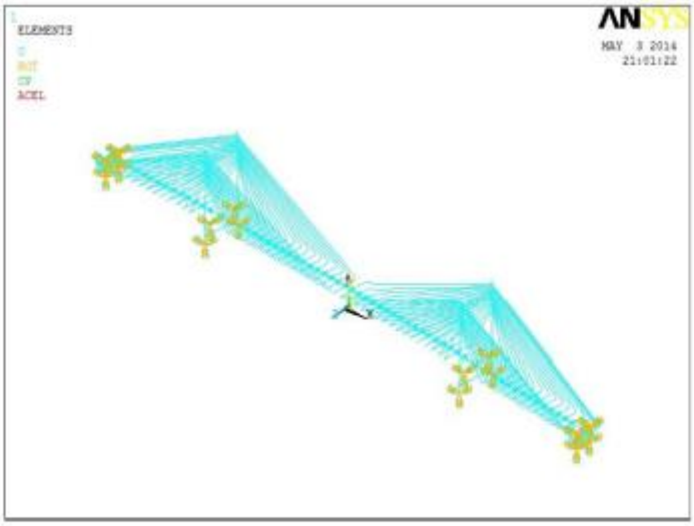


Fig. 1 Kezhushan finite element 3D model

2.3 Simplified Two-Dimensional (2D) Benchmark models

2.3.1 2D Benchmark cable-stayed bridge model

As in the daily service of the bridge, vibration of the main girder is mostly vertical vibration induced by traffic loads, a 2D Benchmark cable-stayed bridge model will be established considering vertical external excitations only, consisting of a beam, two towers and 64 cables (Huang et al, 2015). The cross section of the tower or cable in this 2D model is two times of that in the original 3D prototype model, since a pair of parallel cables or towers is combined into one. Ignoring the axial deformation of beam and tower elements in the Benchmark model, then the beam node will have just vertical DOF while the tower node has horizontal DOF, and all the nodes at the boundaries are constrained. Therefore, the entire 2D Benchmark model has 191 elements, 130 nodes and 252 DOFs, as illustrated in Fig. 2. Fig. 3 gives the numbering of elements and nodes of half of the Benchmark model and that of the other half model will be similar because of symmetry. Tables 1 and 2 summarize the lengths of beam and tower elements respectively.

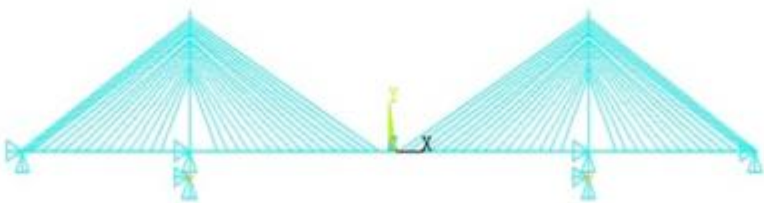


Fig. 2 2D Benchmark cable-stayed bridge model

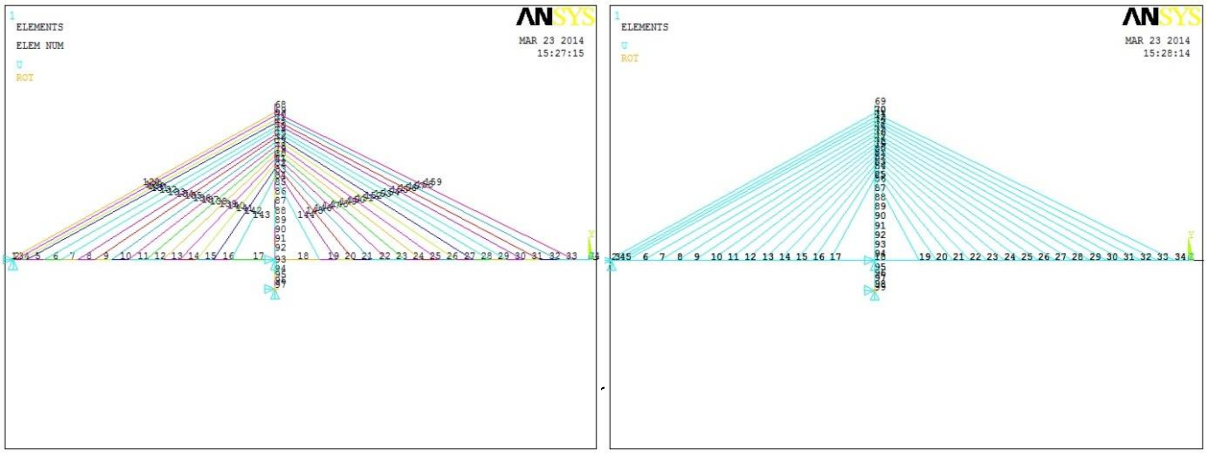


Fig. 3 Numbering of elements and nodes of half of the Benchmark cable-stayed bridge model

Table1 Lengths of beam elements

Beam element number	Element length (m)
1-2	1.5
3-4	3.0
5-16	9.0
17-18	23.5
19-33	9.0
34	15

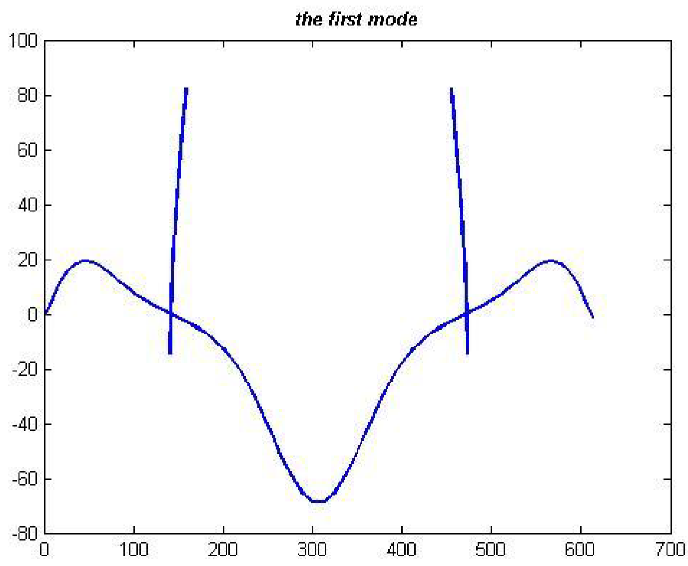
Table2 Lengths of tower elements

Tower element number	Element length (m)	Tower element number	Element length (m)
68	4.4	78	2.2
69	2.0	79	2.1
70	2.0	80	2.3
71	1.9	81	2.4
72	2.2	82	2.6
73	1.9	83	4.4
74	2.1	84	2.1
75	2.0	85	4.8
76	2.2	86-96	5.0
77	2.1	97	1.5

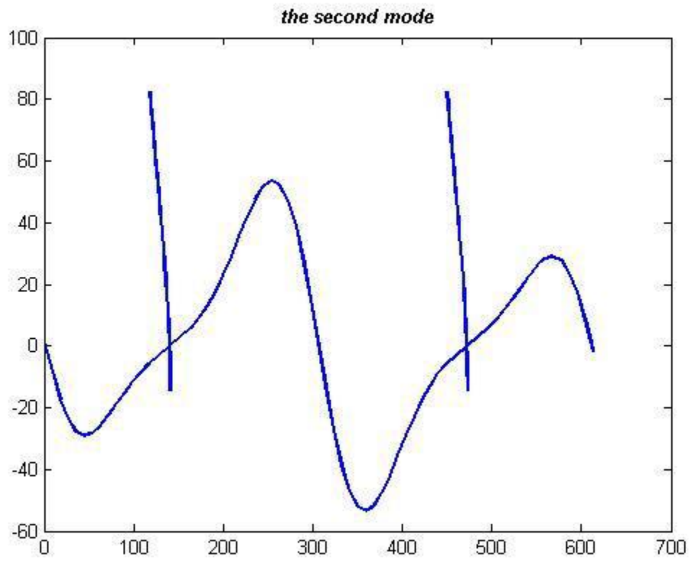
After integrating the overall stiffness and mass matrices of the finite element model, the natural frequencies and mode shapes can be obtained. The first 6 natural frequencies of both the original 3D model and the 2D Benchmark model are listed in Table 3 for comparison, and the corresponding first 6 mode shapes are plotted in Fig. 4

Table 3 Comparison of the first 6 natural frequencies of the 2D cable-stayed bridge model and the 3D prototype model.

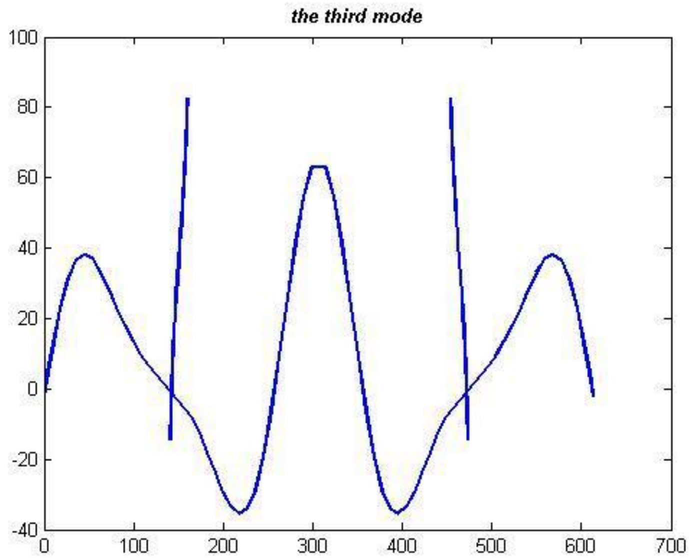
Mode	3D prototype model (Hz)	2D cable-stayed bridge model (Hz)	Error
1	0.3979	0.4018	0.98%
2	0.5079	0.5403	6.38%
3	0.8124	0.7985	-1.71%
4	0.9215	0.9832	6.70%
5	1.0320	1.1104	7.60%
6	1.2253	1.3027	6.32%



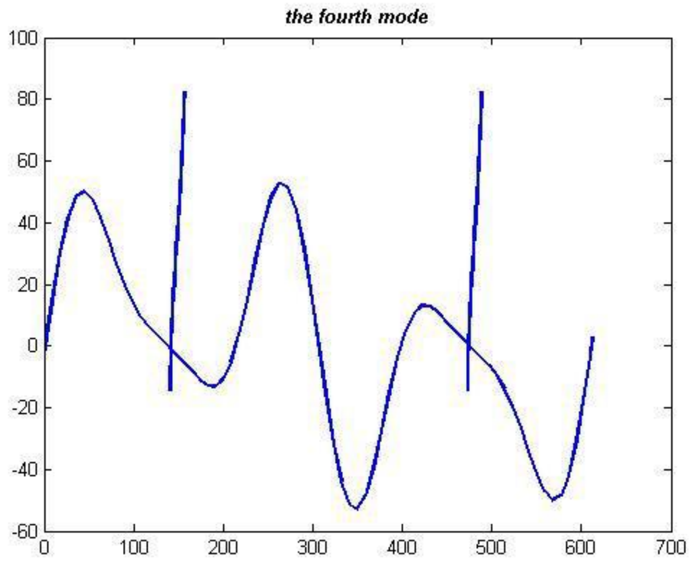
1st mode



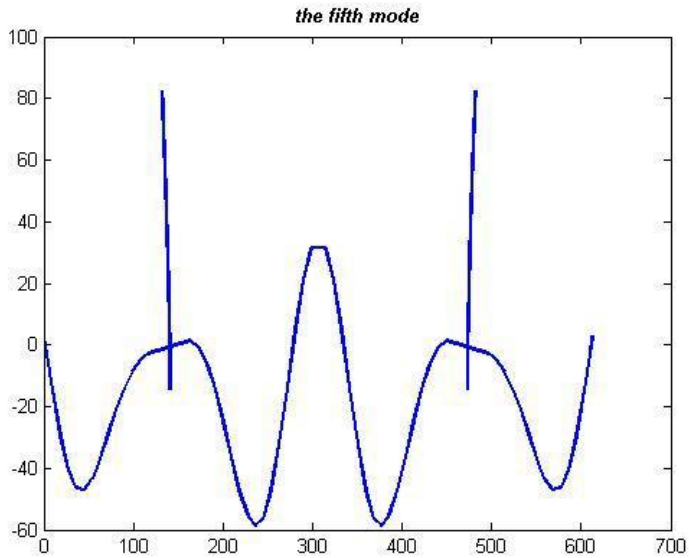
2nd mode



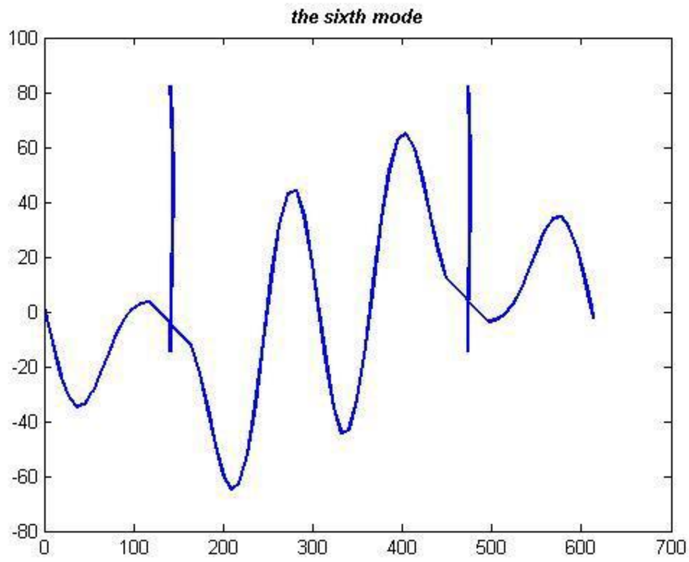
3rd mode



4th mode



5th mode



6th mode

Fig.4 Mode shapes obtained by 2D Benchmark cable-stayed bridge model

It can be seen from Table 3 and Fig. 4 that the dynamic characteristics of the 2D Benchmark cable-stayed bridge model agree with that of the original 3D prototype model, and therefore, no model updating process is required.

2.3.2 2D Benchmark continuous beam bridge model

If the focus of damage identification is on the main girder, the 2D cable-stayed bridge model can be further simplified to a 2D continuous beam bridge model with elastic supports, where cables and piers are replaced by vertical springs, as shown in Fig. 5. The finite elements were defined between adjacent elastic supports and each node has 2 DOFs, namely vertical and angular displacements, if axial deformation of beam and tower elements is ignored. Therefore, there are 67 elements, 68 nodes and 132 DOFs in total of this Benchmark model. (Chu, 2011)

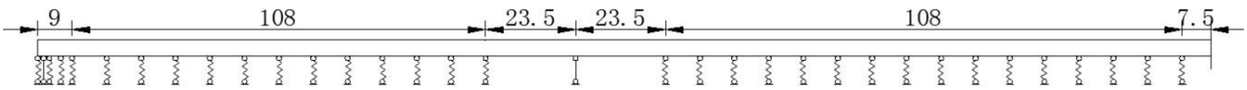


Fig. 5 The 2D Benchmark continuous beam bridge model (left-half-span)

As in this model, cables are replaced by springs, the stiffness of girder elements will be changed due to the fraction of cable force in the longitudinal direction. Thus, model updating needs to be carried out to modify the spring stiffness such that the dynamic characteristics of the 2D Benchmark continuous beam bridge model will be similar to that of the original 3D prototype model.

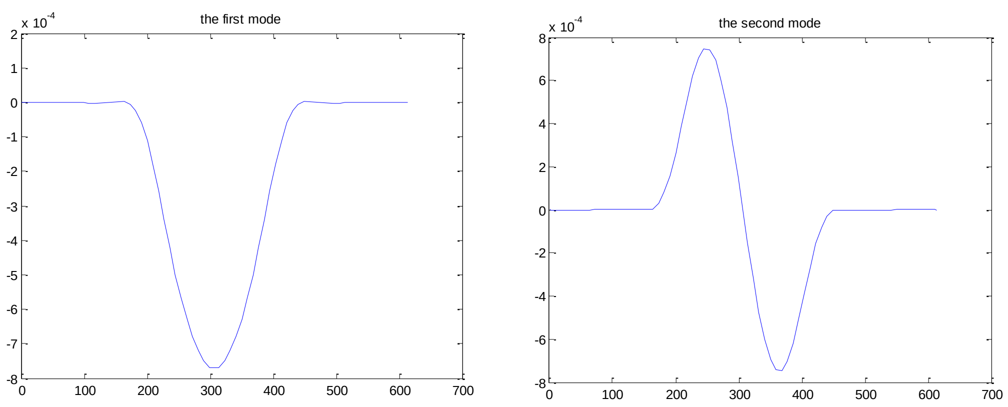
There are different types of model updating methods available in the literature. In this paper, sensitivity-based parameter updating method proposed by Zhang (2001) will be used. The first 6 natural frequencies of the updated 2D continuous beam bridge model are summarized in Table 4, comparing to the corresponding frequencies of the 3D prototype model.

Table 4 Comparison of the first 6 natural frequencies of the 2D continuous beam bridge model and the 3D prototype model

Mode	3D prototype model (Hz)	2D continuous beam bridge model (Hz)	Error
1	0.3979	0.3827	3.82%
2	0.5079	0.5295	4.25%
3	0.8124	0.802	1.28%
4	0.9215	0.9982	8.32%
5	1.0320	0.9982	3.28%
6	1.2253	1.172	4.35%

It can be seen from Table 4 that most of the natural frequencies of the updated model were obtained with errors less than 5%, while the frequency of the 4th mode has a slightly higher error but is still within the reasonable range in civil engineering practice.

The first 6 mode shapes of the updated 2D continuous beam bridge model are illustrated in Fig. 6. It is observed from the figure that the transition part of the mode shape is not very smooth, because the vertical displacements were connected without considering the rotational angle. Also, although the wave crest and trough of the 4th and 5th mode shapes is not obvious, the flow of the shape is the same as that of the 3D prototype model shown in Fig. 4. In summary, Table 4 and Figure 6 prove the dynamic equivalence between the 2D Benchmark continuous beam bridge model and the 3D prototype model.



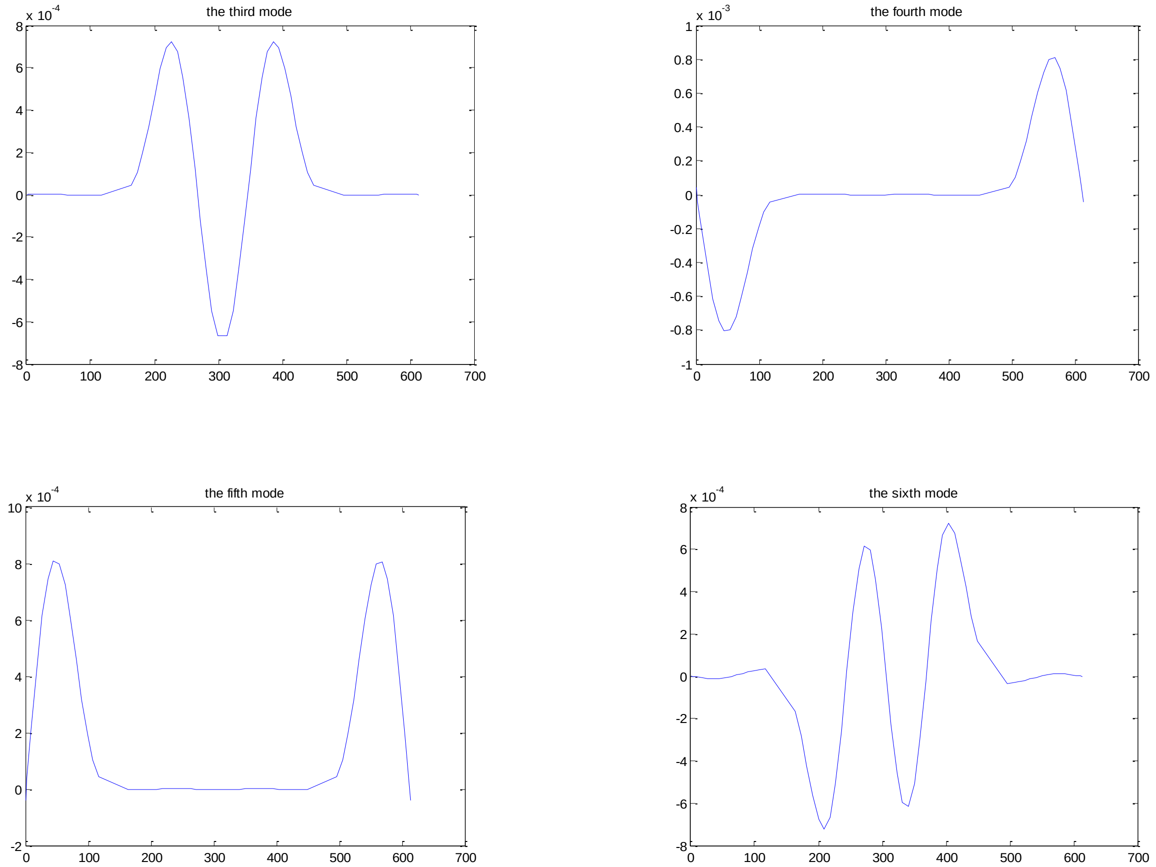


Fig.6 Mode shapes obtained by 2D Benchmark continuous beam bridge model

4. CONCLUSION

This paper established Benchmark models for the purpose of structural health monitoring, based on the Kezhushan cable-stayed bridge. The 3D finite element model of the full bridge was first set up as the original prototype model. Then, a 2D Benchmark cable-stayed bridge model was established for the structure under vertical excitations. Finally, this 2D Benchmark cable-stayed model was further simplified to a 2D Benchmark continuous beam bridge model for the purpose of damage identification of the main girder. Both static and dynamic analysis were performed and model updating process was carried out to ensure the first 6 natural frequencies and mode shapes of the 2D Benchmark models agree with those of the original 3D prototype model when considering only vertical loads.

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