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Model Test on Steel Box Girder Damage Identification of Cable-stayed Bridges

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Abstract: Based on dynamic characteristics analysis, a whole bridge model test research on damage identification of cable-stayed bridges was executed. The damage test cases are designed, and the damage identification test is carried out by taking the curvature variation coefficient of modal flexibility as the damage identification index. In the design of this experiment, the optimization of cable tensions and the sensor placement optimization were discussed and the suitable methods are chosen. The sensitivity of variation coefficient of modal curvature is verified by experimental results. The influence of vibration mode order on the curvature variation coefficient of mode flexibility is discussed, and the appropriate order is given.

Keywords: cable-stayed bridge, damage identification, variation coefficient of flexibility curvature, whole bridge model test.

1. Introduction

Since the 1990s, many large bridge projects have been built around the world. In the long-term use of the bridge structure, various structural damages occur, and the causes of damage are diverse. There are both human factors and natural disasters, as well as the damage and deterioration of the bridge structure caused by the increasing traffic volume. If these problems are not discovered and dealt with in time, catastrophic accidents will occur in extreme cases. Therefore, it is necessary to monitor and evaluate the overall state of the damage structure of the bridge in real-time[1].

In order to ensure the safe operation of large-scale bridge structures, a feasible damage identification method should be established. Domestic and foreign scholars have proposed various methods of damage identification and assessed the sensitivity of damage identification indicators[2-6]. In recent years, Zhouhong Zong[7] made progress in the research of uncertainty damage identification method and finite element model confirmability method. Yanqiang Li[8] used Tikhonow normalization method and model correction method to obtain the main beam stiffness reduction coefficient as the damage factor. Damage identification of the main beam. The damage identification method based on the change of flexibility has become a research hotspot because of its stability and accuracy. The structural model test is often used as a relatively reliable research method because of its intuitiveness [8]. During model test and data analysis, the modal flexibility curvature coefficients are adopted as the damage index to identify the damage of the bridge, and some test results are presented in the paper.

2 Whole Bridge Model Test

2.1 Model design and fabrication

2.1.1 Project overview

The superstructure of the test bridge is a three-span of 295+620+295m semi-floating steel box girder cable-stayed bridge (Figure1). The main beam is an orthotropic plate streamlined flat steel box girder. The longitudinal slope of the steel box girder bridge deck is 2.8%, the beam height is 3m (in-box size), and the width is 30.1m (including wind nozzle). The cable adopts a 1670 MPa parallel steel cable stay cable, and the whole bridge has a total of 168 stay cables, six specifications. The tower is in the shape of a diamond with C50 marine durable concrete with a total height of 204m.

2.1.2 Test model

According to the experimental purpose of damage identification, the dynamic elastic model is selected to design the scale model. Through analysis, it is determined that the main beam and the cable tower are made of Q345 steel. The cable stays with high-strength steel strands, the model scale ratio is 1/100, the test model bridge length is 12.1m, and the steel box beam length is 12.08m. The length of the top of the pier is 0.01m each sides, and a total of 88 stay cables are provided, as shown in Figure 1. According to the similarity theory, similar conditions exist in the static test model that satisfies the full geometric similarity:

$$C = C_x = C_y = C_z \tag{1}$$

Which represents the similar corresponding position under the load; C is the ratio of the size of the model structure to the actual size, that is, the geometric similarity ratio. The similarity theory determines the similar relationship of the required physical quantities as shown in Table 1. Considering the decrease in the stiffness caused by the decrease in the elastic modulus of the stay cable, the cable area is adjusted to some extent. On the basis of satisfying the similar relationship, the main beam section is simplified into a regular box shape, and the bridge section is simplified into an equal section (as shown in Fig. 2), and reduce the number of cable. In the design of the counterweight, the density of the test model material should theoretically reach 16.67 times and 100 times of the real bridge material. In practice, it is difficult to achieve this requirement, and the mass should be added to make the generalized (or equivalent) density of the model meet the similar requirements [10,11], finally combined with the calculation results and the actual situation, the counterweight is applied to the steel box shape at 50kg/m. The full bridge model is shown in Figure 3.

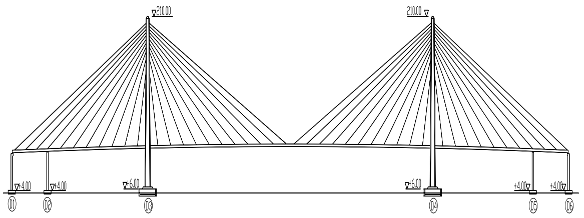

Figure 1. The bridge elevation

Table.1 Main resemble parameters of the model

Similarity	geometric	area	density	Stiffness	frequency
Cable	100	100^2	0.01	100	0.1
Main beam	100	100^2	0.01	100	0.1
Bridge tower	100	100^2	0.0597	597	0.1

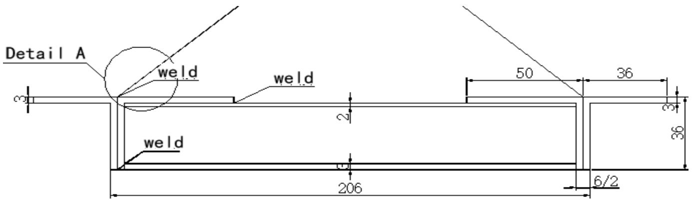

Figure 2. Cross-section of main girder model

Figure 3. Model of the whole bridge

2.2 Technical preparation of the test

2.2.1 Cable force optimization of the model

Based on the principle of reasonable internal force state of the bridge, adjusting the cable force using the cable force optimization method based on the influence matrix, that is, a set of cable force is found to make the cable-stayed bridge reach the deterministic load, and the optimal internal force effect target is achieved. In the specific operation, the cable force is adjusted according to the strain value of the thin iron piece connected in series with the cable. Considering the complexity of the cable force optimization of the actual cable-stayed bridge model, the actual tuning is based on the influence matrix method of the cable-stayed bridge linear control.

2.2.2 Optimal placement of sensors

In order to make full use of the sensor, the sensor layout needs to be optimized in the laboratory. Here, the optimal placement criteria of the sensor based on the modal confidence of the annealing algorithm adopted by Peng Wei [12]. The sensor used in the test is a DH610V accelerometer, a total of 16. The final arrangement of the 16 accelerometers is shown in Table 2.

Table.2 Location of acceleration sensor

Sensor No.	Point coordinates/m	Channel number	Sensitivity /(m/s^2)
1	0.24	2-1	0.308
2	0.94	2-2	0.308
3	1.47	2-3	0.305
4	2.32	2-4	0.306
5	3.49	2-5	0.3
6	4.43	2-6	0.302
7	5.25	2-7	0.316
8	6.05	2-8	0.319
9	6.34	2-9	0.298
10	7.16	2-10	0.318
11	7.95	2-11	0.331
12	8.8	2-12	0.325
13	9.5	2-13	0.31
14	10.31	2-14	0.318
15	11.08	2-15	0.327
16	11.87	2-16	0.322

After the bridge model has been revised and debugged, its accuracy meets the requirements.

2.3 Experimental design of the experiment cases

In this experiment, the damage identification of single damage and multiple damages was investigated. The simulated damaged cross-sections are three sections: 1/2 side-span, 1/4 middle-span, 1/2 middle-span. The damaged area of each cross-section is located at the top, bottom, and both the top and bottom of box girder respectively. The test cases are as follows:

Case1: 1/2 side-span, damage 1/1, 1/2, 1/3, 1/6；
Case2: 1/4 middle-span, damage 1/1, 1/2, 1/6;
Case3: 1/2 middle-span, damage 1/1, 1/2, 1/6;
Case4: 1/2 side-span and 1/2 middle-span damaged simultaneously, damage 1/1, 1/2, 1/6;
Case5: 1/2 side-span and 1/4 middle-span damaged simultaneously, damage 1/1, 1/2, 1/6;
Case6: 1/2 side-span, 1/4 middle-span and 1/2 middle-span damaged simultaneously, damage 1/1, 1/2, 1/6.

3 Modal-based Flexibility Curvature Matrix Principle

3.1 Modal flexibility curvature

Through the equation of motion of multi degree of freedom, undamped, free vibration system, the vibration mode is normalized to the mass matrix to obtain the flexibility matrix, and as the modal order increases, the influence of the higher-order mode on the matrix will gradually decrease. Then, a precise modal flexibility matrix can be obtained by a number of low-order modal parameters.

According to the each column element in the modal flexibility matrix to calculate the mean value and the central difference, the flexibility curvature of the kth calculation point is:

$$F_k'' = \frac{\left(F_{i,k+1}^d - 2F_{i,k}^d + F_{i,k-1}^d\right)}{l_{k-1,k}\, l_{k,k+1}} \quad (k = 2,3,4,\cdots,n-1) \tag{2}$$

Where $l_{k-1,k}$, $l_{k,k+1}$ are the distance between the k-1th calculated point and the kth calculated point and between the kth calculated point and the k+1th calculated point.

3.2 Variation coefficient of flexibility curvature

Based on the principle of modal curvature matrix, this paper defines the coefficient of curvature variation coefficient β to characterize the damage location of the structure. According to the definition of coefficient of variation, the mean value of the structure flexibility curvature $\bar{X}$ is:

$$\bar{X}_{ik} = F_{i,k-1}'' + F_{i,k}'' + F_{i,k+1}'' \big/ 3 \tag{3}$$

The variance of the structural flexibility curvature is:

$$S_{ik}^2 = \frac{1}{2}\left[\left(F_{i,k-1}'' - \bar{X}_{ik}\right)^2 + \left(F_{ik}'' - \bar{X}_{ik}\right)^2 + \left(F_{i,k+1}'' - \bar{X}_{ik}\right)^2\right] \tag{4}$$

The standard deviation is:

$$S_{ik} = \sqrt{S_{ik}^2} \tag{5}$$

The variation coefficient of structural flexibility curvature is:

$$\beta_{ik} = S_{ik} \big/ \bar{X}_{ik} \tag{6}$$

Where $F_{i,\ k-1}$, $F_{i,\ k}$, $F_{i,\ k+1}$ is the compliance curvature value of the damage point and the adjacent point.

4 Test Results

4.1 Identification of large damage of box girder

4.1.1 Single damage identification

Under the condition of single damage, the test values obtained through the test are converted to the curve of the flexibility curvature coefficient of each node are as follows:

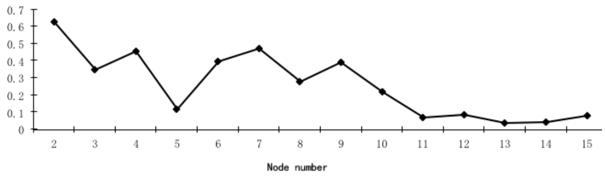

Figure 4. Variation coefficient of modal flexibility curvature on 1/2 side-span

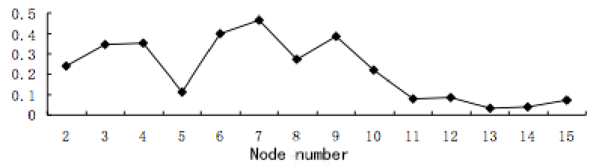

Figure 5. Variation coefficient of modal flexibility curvature on 1/4 middle-span

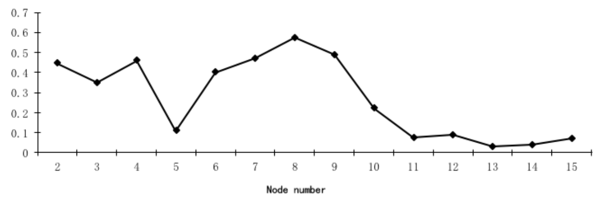

Figure 6. Variation coefficient of modal flexibility curvature on 1/2 middle-span

It can be seen from figure 4 that it is obvious that the values of the coefficient of curvature mutation of nodes 2 and 3 are large, which can indicate that 1/2 side-span section has been damaged. Similarly, figure 5 shows that 1/4 middle-span section damage can be identified. As can be seen from figure 6, the values of the coefficient of curvature mutation of the nodes 7, 8, and 9 are higher, and the value of the node 9 is larger than the node 7, and the damage at the 1/2 middle-span section can be clearly indicated.

4.1.2 Multiple damage identification

The results of multiple damage identification are as follows:

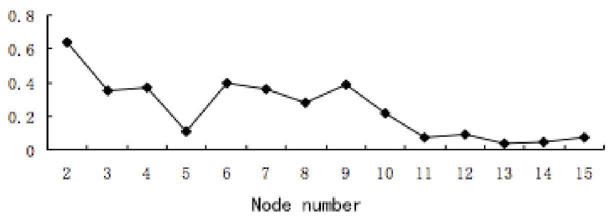

Figure 7. Variation coefficient of modal flexibility curvature on 1/2 side-span and 1/4 middle-span

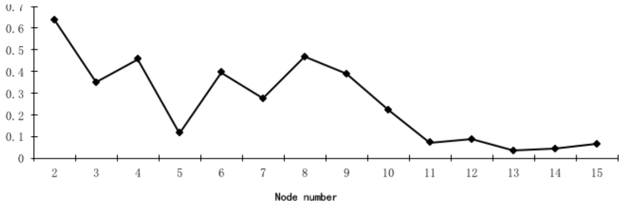

Figure 8. Variation coefficient of modal flexibility curvature on 1/2 side-span and 1/2 middle-span

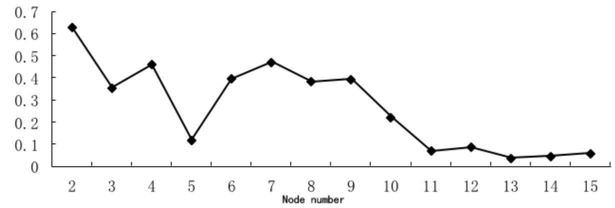

Figure 9. Variation coefficient of modal flexibility curvature on 1/2 side-span, 1/4 middle-span and 1/2 middle-span

It can be seen from figure 7 that the values of the flexibility curvature coefficient of the nodes 2 and 3 are significantly larger, indicating that the 1/2 side-span section damage occurs, the values of the flexibility curvature coefficient of the nodes 6, 7 are also large, and the damage of the 1/4 middle-span section can be identified. Similarly, the damage of 1/2 side-span and 1/2 middle-span can be recognized from figure 8. For the three damage case in figure 9, according to the above analysis method, it can be clearly seen that the values of the flexibility curvature coefficient of nodes 2, 3, 6, 7, 8, and 9 associated with 1/2 side-span, 1/4 middle-span, and 1/2 middle-span are significantly larger than others. So it can be determined that the damage at 1/2 side-span, 1/4 middle-span, and 1/2 middle-span can be basically recognized.

4.2 Identification of small damage of box girder

The identification of large damage in the damage identification of cable-stayed bridges is easier than the small damage identification, especially for the damage identification of the main girder box girder of cable-stayed bridges. In this paper, the method of prefabricated damage segment is used to simulate the local damage location and degree of the main beam. The thicknesses of 1.5mm, 2.0mm and 2.5mm are selected to simulate the main beam damage 1/2, 1/3 and 1/6 respectively. Due to the limitation of space, only the observation and analysis of the strain change of the top and bottom plates of the main beam section are selected, and single damage, two damages and multiple damages are selected to illustrate the problem. The comparison of local damage identification in each working condition is as shown:

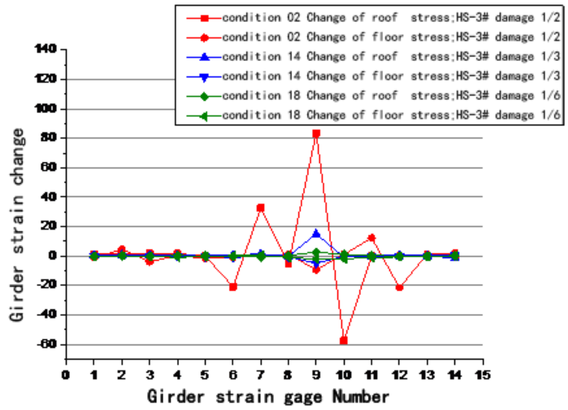

Figure 10. Comparisons of local damage on 1/2 side-span

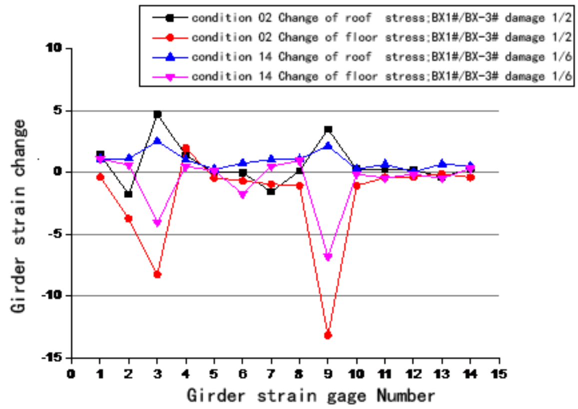

Figure 11. Comparisons of local damage on 1/2 side-span and 1/2 middle-span

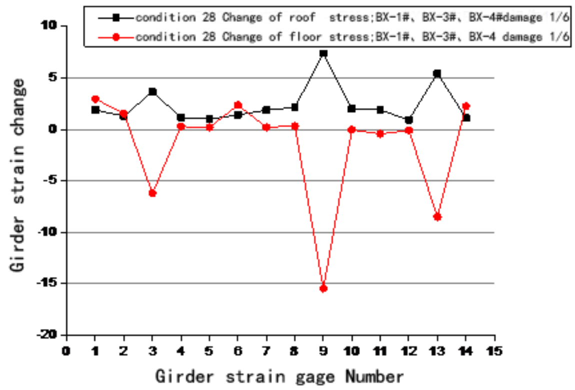

Figure.12 Comparisons of local damage on 1/2 side-span, 1/4 middle-span and 1/2 middle-span

It can be seen from figure 10 to figure 12 that the local small damage recognition effect of the top and bottom plates of the three working conditions is basically the same as the recognition effect of the simultaneous damage of the top and bottom plates, which shows that it is applicable to arrange the acceleration sensor on the actual cable-stayed bridge to identify the damage of the bottom plate and the top plate by using the index based on the modal flexibility curvature variation coefficient. This may have significance for identifying damage of the box girder top plate which located under the deck pavement and damage of the box girder bottom plate where is difficult to install the sensor.

4.3 Influence of modal order on modal flexibility curvature coefficient

For the damage identification of the main beam of the cable-stayed bridge, the selection of the modal order may have a certain influence on the calculation of the modal compliance. The damage of 1/4 middle-span was selected for study. The mean value of each element of the matrix of the damage matrix of the section was also analyzed to calculate the coefficient of variation of flexibility curvature. The model flexibility diagrams of different orders are as follows:

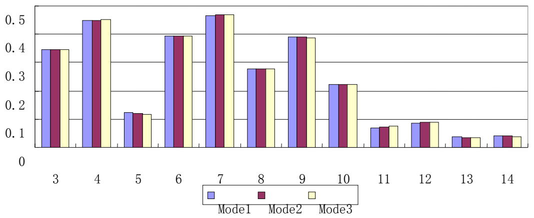

Figure 13. Comparisons of model 1-3 on the damage

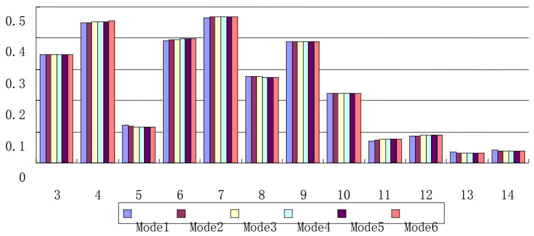

Figure 14. Comparisons of modal 1-6 on the damage

It can be seen from figure 13 and figure 14, the value of the modal flexibility mutation coefficient does not change with the increase of the order from the fourth order, indicating that the modal flexibility variation coefficient index calculated by the first four modal parameters is used to identify the damage is enough.

5 Conclusions

Most structural damage identification studies are based on finite element model simulations, and there are few studies using model tests. In this paper, model tests are used to identify the damage of cable-stayed bridges, and a new damage identification index based on modal flexibility curvature coefficient is proposed. The following research conclusions are obtained:

(1) Based on the similarity theory, the similarity relationship of the cable-stayed bridge model is derived. According to the similarity relationship, the model's fabrication and detailed structure are processed more concisely, which provides a feasible idea for the cable-stayed bridge model.

(2) Based on the study of modal flexibility curvature, modal flexibility curvature difference and modal flexibility curvature variation coefficient, it can be shown that, in this paper, the sensitivity of damage identification index of cable-stayed bridge based on variation coefficient of modal flexibility curvature is higher than other indexes.

(3) A small number of low-order modes can be used to calculate the variation coefficient of modal flexibility curvature to identify structural damage. This also proves that the flexibility of the structure is inversely proportional to the square of the modal frequency. The higher the order is, the smaller the contribution to modal flexibility is.

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