Damage Simulation of Cable of Long-span Concrete Cable- stayed Bridge

Bin Zeng¹, a, Zhenwei Zhou², b, Bo Wen², c, Qing Xu¹, d, Yanchao Shao¹, e, Liyuan Huang², f, Chunfeng Wan², g, *

¹Central Research Institute of Building and Construction Co., Ltd, Beijing 100088, China
²Key Laboratory of Concrete and Prestressed Concrete Structure of Ministry of Education, Southeast University, Nanjing 210096, China
azengbin@cribc.com, bzzwdndx@613.com, cbowennj@hotmail.com, da_qing01@foxmail.com, esyc-mail@163.com, fhuangliyuan_seu@126.com, gwan@seu.edu.cn

Keywords: cable-stayed bridge, Sutong bridge, cable loss, damage simulation, condition assessment

Abstract: Stayed cable is a key part of the force system in terms of cable-stayed bridge, whose safety performance can be influenced by damaged cable. In this paper, an effective area method is utilized to simulate the damaged cable. Both the single and double damages are studied, the corresponding cable loss is estimated; and the changes of the mid-span deflection and first-order frequency are discussed. Moreover, the numerical example is carried out by taking the Sutong bridge as the background. The results are demonstrated that it is realistic and possible to simulate the cable loss by using the reduced effective area of cable. Furthermore, the deflection of the main span has an evident change when the damaged cable is farther away from pylons; nevertheless, the cable loss has a slight effect on the first-order frequency.

1. Introduction

The cable is the key force component of the cable-stayed bridge, and it is also the most vulnerable member of the cable-stayed bridge structural system. Among the damages found in cable-stayed bridge, most of the diseases appeared on the cable. The damaged cables have a negative effect on the safety, integrity, static and dynamic characteristics of the cable-stayed bridge structural system. Therefore, to detect the damaged cable early and take measures immediately can effectively avoid the adverse impact and ensure the safe operation of the bridge structural system. Cable tension is an important content of the entire bridge structure status assessment, and it is also the significant basis of structure currently stress state analysis and bridge structure health status evaluation [1-4]. Generally speaking, there are three primary techniques for estimating cable tension forces: direct measurement method; magnetic method; and vibration-based method. Due to the easy operation, the vibration-based method is more widely employed in practical applications [2].

In this paper, an effective area method is applied to simulate the damaged cable. In this simulation, the three-dimensional FE model of Sutong bridge was established and the initial state of each cable tension under the dead load was calculated. Both the single and double cable damages
were further studied. Corresponding results have verified the effective area method is an applicable method which can be applied to simulate the cable loss accuracy. Subsequently, the distribution laws of the cable tension distribution are identified. The changes laws of deflection in mid-span and first-order frequency were also discussed.

2. Numerical simulation

2.1 Model Establishment.

The Sutong bridge is a very famous cable-stayed bridge that spans the Yangtze River in China between Nantong and Changshu, a satellite city of Suzhou, in Jiangsu Province. The diagrammatic sketch of the Sutong Bridge is shown in Figure 1, it can be seen from that Sutong bridge has a main span of 1,088 m, two side spans are 300 m each, and there are also four small cable spans. The girder is supported by a total of 272 stay cables in double fan-type planes which are connected to two concrete pylons.

![Figure 1 Diagrammatic sketch of the cable-stayed Sutong Bridge.](image)

Figure 1 Diagrammatic sketch of the cable-stayed Sutong Bridge.

For simplicity, in order to study the influence of cable loss on the performance of cable-stayed bridge, a three-dimensional FE model of the bridge is established using ANSYS software is shown in Figure 2. In this simulation, the main span is set to a closed box section and the torsional stiffness of the section is relatively large. Thus the “fish spurs” single beam model can be used for simplified reasonably. Moreover, the stiffness and mass are all concentrated on the middle node during the process of modeling, and the main girder and the cable towers are simulated by the beam4 unit (three-dimensional beam unit), the corresponding cables are simulated by the link10 unit. All of the nodes and the cables are rigidly connected and the main beam is evenly divided into 522 units. It should be pointed out that only the prestressed structure and stay cables are taken into account in terms of the dead load.

![Figure 2 The numerical model of Sutong Bridge.](image)
2.2 Damage Simulation.

In general, broken wires can be seen as a reduction of the effective area [5]. Assume that the stress area of the cable under the intact condition is \( A \), and the effective area after damage is \( A^* \). Then the damage degree is represented by the variable \( D \) and can be expressed as Equation (1).

\[
D = \frac{A - A^*}{A}
\]  

(1)

Theoretically, \( D=0 \) means the cable has been no damaged, and \( D=1 \) means the cable was completely destroyed.

3. Identification Results

In order to simplify the analysis, the two cables in the same position that is stressed together as a set of objects. Considering that two towers of the bridge are symmetrical, thus 68 groups of the 1# tower are selected for analysis. The distribution of the initial state in each cable under dead load as showed in Figure 3. In this paper, the single damage degree of stayed cable is simulated by 10%, 30%, 50%, respectively. In addition, due to the evaluation and analysis of the performance state of cable-stayed bridge is determined by many factors, such as cable tension frequency, and mid-span deflection. In this research, the cable tension after damage is identified firstly, the first-order frequency and the mid-span deflection will be discussed accordingly.

![Figure 3 The distribution diagram of the Sutong Bridge under dead load.](image)

3.1 Single Damage.

Numerical simulation of several different single damage scenarios was employed to evaluate accuracy of the area reduction method. Changes of cable tension are obtained and shown in Figure 4. There will be a sharp point in damaged cable and the tension of closely cable will be slightly increased. The results have also clearly shown loss rate of cable is close to the reduction of effective area. For instance, the identified cable loss is reached 9.428% since the area is reduced by 10%. Moreover, the tendency of cable tension distribution is consistent wherever the cable was damaged.
Figure 4 The identified cable tension results when single cable loss: (a) is 10% cable loss; (b) is 30% cable loss; (c) 50% cable loss.

Figure 5 Deflection changes in the main span. Figure 6 Mode 1 changes with single damage.

Distribution curves of the changes of the mid-span deflection and first-order frequency are shown in Figure 5 and Figure 6, respectively. In Figure 5, one of the positive values indicates an increase in deflection, the other is the negative value which indicates a decrease in deflection. It can be noted that the distribution laws of the deflection under different double damage degrees are basically the same. Furthermore, the deflection changes will be more obvious when the damaged
cables are more farther from the pylon. Ultimately, it can be also found from Figure 6 that the influence of the frequency is increases with the increase of cable damage degrees. Nevertheless, this influence is slight which can be ignored.

3.2 Double Damages.

In this section, the maximum effect of the two cable damages on the cable tension is considered. For example, the maximum effect on the S1 cable tension is the loss of the S2-S3 cable. Therefore, typical results are shown in Figure 7, which pertains to loss changes in local closely double damages because of a 50% loss. It can be found that a double damage can also be accurately simulated by the area reduction method. Although there is a certain error during simulation than that of the area reduction, in any case, the maximum error is within the allowable range which is still acceptable.

Similar discussions can be made for the cases with closely double cable damage scenarios. In Figure 8, it can be clearly seen that when a 50% cross-section loss occurs in double cables, the tendency of the deflection changes in the mid-span is almost the same as those of the single damage cases. It also should be noted that it will be resulted in a significant effect on the deflection when the damaged cable is far away from the pylons, which should be regarded with some care. In addition, the influence of frequency is still quite small even the 50% double losses were occurred.
4. Conclusions

This work has been described in this paper pertained to an effective area method to simulate the cable loss for health monitoring of cable-stayed bridge. Finite element model of the bridge was employed for the evaluation of the effective area method. Several different damage scenarios were considered in the simulation, including single and double cable damage scenarios. The influences of the cable tension, mid-span deflection and frequency are discussed accordingly. Some important results can be summarized.

The cable loss is in line with the area reduction rate, which indicates the feasible to use the area reduction instead of the cable loss in simulation. As well as both the single damage and double damages have an obvious negative effect on the deflection of mid-span which should be given enough attention. Besides, cable loss has a litter effect on the first-order frequency even the double losses is reached 50%.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (No. 51578558); open fund of National Engineering Research Center on Diagnosis and Rehabilitation of Industrial Building (No. 2016YZAKy01); the National Key Research and Development Program of China (No. 2016YFC0701309); the National Natural Science Foundation of China (No. 51578140); a Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD, No. CE02-2-8); Postgraduate Research & Innovation Program of Jiangsu Province and Fundamental Research Funds for Southeast University (No. KYLYX15_0084).

References