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Responses of self-anchored suspension bridge to sudden breakage of hangers

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Abstract. The girder of self-anchored suspension bridge is subjected to large compression force applied by main cables. So, serious damage of the girder due to breakage of hangers may cause collapse of the whole bridge. With the time increasing, the hangers may break suddenly for their resistance capacities decrease due to corrosion. Using nonlinear static and dynamic analysis methods and adopting 3D finite element model, the responses of a concrete self-anchored suspension bridge to sudden breakage of hangers are studied in this paper. The results show that the sudden breakage of a hanger has significant effects on tensions of the hangers next to the broken hanger, bending and torsion moments of the girder, moments of the towers and reaction forces of the bearings. The results obtained from dynamic analysis method are very different from those obtained from static analysis method. The maximum tension of hanger produced by breakage of a hanger exceeds 2.2 times of its initial value, the maximum dynamic amplification factor reaches 2.54, which is larger than the value of 2.0 recommended for cable-stayed bridge in PTI codes. If two adjacent hangers on the same side of bridge break one after another, the maximum tension of other hangers exceeds 3.0 times of its initial value. If the safety factor adopted to design hanger is too small, or the hangers have been exposed to corrosion, the bridge may collapse due to breakage of two adjacent hangers.

Keywords: self-anchored suspension bridge; sudden breakage of hanger; responses; static analysis; dynamic analysis

1. Introduction

Large-span bridges, including cable-stayed bridge, suspension bridge and arch bridge, need cables to be the stay cables, main cables or hangers. With the time increasing, the elements of bridge are exposed to corrosion, and their resistance capacities decrease. Especially, the stay cables and hangers are more prone to corrosion than other elements for the diameters of their steel wires are small. Under the combination action of live loads and corrosion, stay cables and hangers may break suddenly. In china, serious corrosion and breakage of cables occurred in many bridges (Wang and Yi 2007). In 2001, eight hangers of Yibin Southgate Bridge in China broke, and the deck supported by these hangers fell in the river. Two men died in this accident. In 1995, one stay cable of Guangzhou Haiyin Bridge that was only used for 7 years broke, and it hit an oil tank

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truck. To avoid the breakage of cables due to corrosion, cables in many bridges were replaced in China. For example, all the stays in Jiujiang Bridge that was used for 10 years were replaced, because 70% of the stays were seriously corroded, and 1/3 of wires in some stays were broken.

Because the breakage of cable usually occurs suddenly, and it can cause strong vibration and large changes of internal forces of the structure, the sudden breakage may endanger the safety of the bridge.

The effects of breakage of stay cables on cable-stayed bridge have been studied by many researchers (Ruiz-Teran and Aparicio 2007, Wolff and Starossek 2008, 2010, Qu *et al*. 2009, Mozos and Aparicio 2010a, b, Cai *et al*. 2012). The studies showed that it was safe for stays when adopting the dynamic amplification factor (DAF) of 2.0 recommended by PTI (2007), but it was unsafe for deck and tower. The responses produced by breakage of stays must be calculated using dynamic analysis method.

Because the time that the breakage occurs (breakage time) has significant effects on the responses of structure, Mozos and Aparicio (2011) studied the breakage time through experiments and found that the breakage time was 0.00375s for damaged cables, and 0.0085s for undamaged cables. Ruiz-Teran and Aparicio (2009) found that the effects of breakage of stays on under-deck cable-stayed bridge were relative with the fundamental period of the structure. When the breakage time was less than 10% of the fundamental period of the damaged bridge, it had no influences on the results.

Considering the geometric and material nonlinearity, Qiu *et al*. (2009) and Kao *et al*. (2012) studied the static load-bearing capacity of self-anchored suspension bridge. The studies showed that the bridge did not collapse when five hangers broke. Because the dynamic effects of the breakage of hangers were not considered, the load-bearing capacities obtained by the studies are the upper limit values.

In recent years, more than 20 self-anchored suspension bridges have been built in China (Zhang *et al*. 2006). Their hangers are all made of parallel high strength galvanized steel wires. In Chinese codes (2002), the safety factor of hanger is 3.0 during service, and it is 1.8 during replacement of hanger. No specifications are presented for sudden loss of hangers. Because the hangers are connected with the main cables, the breakage of hangers will induce the main cable to vibrate strongly, which will further induce strong vibration and large changes of internal forces of the whole bridge. Using nonlinear static and dynamic analysis methods, the responses of a self-anchored suspension bridge with main span of 200 m due to the breakage of hangers are studied in this paper. The results can be used for reference in design and maintenance of this kind of bridge.

2. Structure of a self-anchored suspension bridge and analysis methods

2.1 Structure of a self-anchored suspension bridge

Zhuanghe Jianshe Bridge built in china is a concrete self-anchored suspension bridge with main span of 200m and side span of 70 m, as shown in Fig. 1. Its stiffening girder with box cross-section is reinforced concrete, as shown in Fig. 2. Because the girder is subjected to a large compression force applied by the main cables, the tendons are not needed. The tower is reinforced concrete with box cross-section. The bridge has two main cables and each cable is made of 3937 paralleled, 5 mm in diameter, high strength galvanized steel wires. There are 65 hangers on each

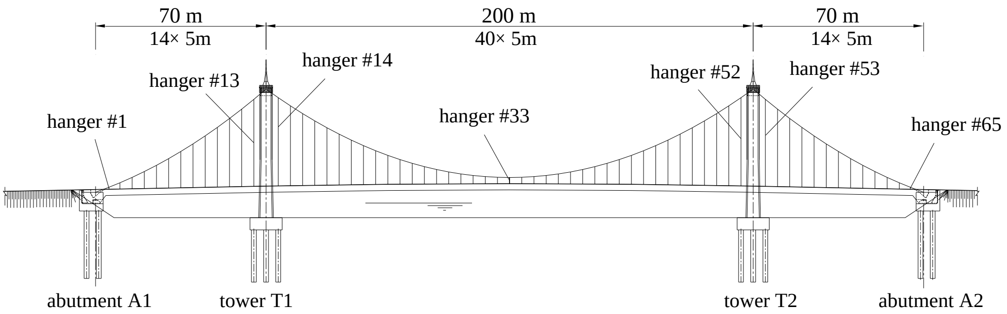

Fig. 1 Layout of Zhuanghe Jianshe Bridge

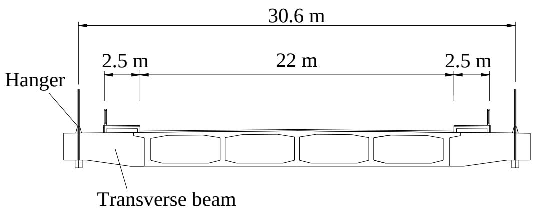

Fig. 2 Cross section of girder

side of the bridge, and the distance of the hangers along the girder is 5 m. The hangers are made of 97 paralleled, 7 mm in diameter, steel wires. The hangers are numbered from #1 to #65.

2.2 Materials

The concrete of the girder and the towers is high strength concrete with a compressive strength of 50 MPa and a modulus of elasticity of 34000 MPa. The density of the reinforced concrete is 25.5 kN/m^3. The steel of the main cables and the hangers has an ultimate tensile strength of 1570 MPa and a modulus of elasticity of 190000 MPa. The density of the steel is 78.5 kN/m^3.

2.3 Loads

Because this study is only used to investigate the responses of bridge caused by sudden breakage of hangers, the analysis of the structure under dead loads is carried out. The self-weight of girder, towers, main cables and hangers are obtained from multiplying the areas of their cross-sections by their densities. The distributed dead load on the deck except self-weight is 108 kN/m. The distributed dead load on the main cables except self-weight is 0.37 kN/m. Because the weight of clamps affects the vibration of the main cable, it is also considered in dynamic analysis. The weight of each clamp from #1 to #9 is 12 kN, the weight of each clamp from #10 to #17 is 16 kN, and the weight of each clamp from #18 to #33 is 10 kN.

2.4 Analysis model

The bridge is modeled with three dimension (3D) finite element (FE) model. In the FE model, the girder, towers and transverse beams are modeled using 3D beam elements, and their torsion

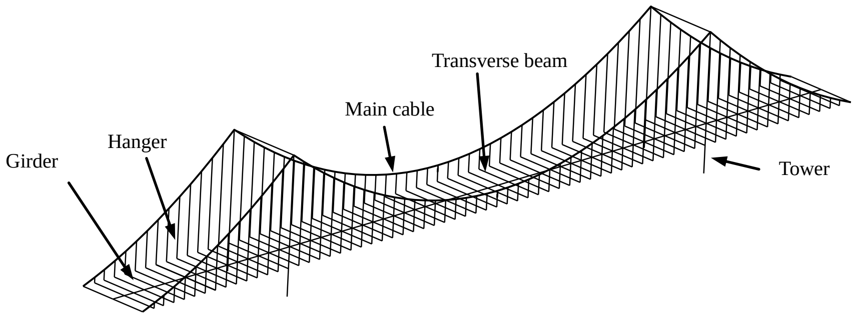

Fig. 3 FE model of the bridge

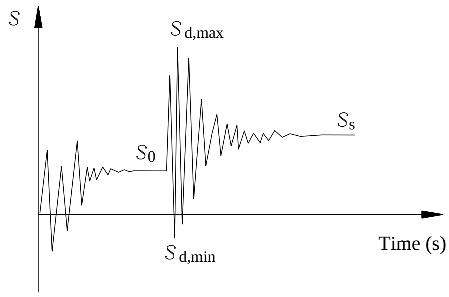

Fig. 4 Dynamic response process

stiffness and torsion mass are considered. The main cables and hangers are modeled using truss elements, and the contribution of their tensions to their stiffness is considered in the nonlinear analysis. The section of main cable between two hangers is divided into 5 elements to model the geometry configuration and local vibration of the main cables more precisely. The masses of clamps are concentrated on the nodes where the clamps are located. Considering the piles of the bridge had little effects on the analysis of sudden breakage of hanger, they are not modeled in the FE model.

2.5 Analysis methods

Responses of the bridge due to sudden breakage of hangers on the bridge are analyzed by means of static and dynamic analysis using the finite element software ABAQUS V.6.8. For either static analysis or dynamic analysis, the geometric nonlinearity of the structure and effects of axial forces of the structure on the stiffness are considered, and the nonlinear procedures are carried out using iteration method. In dynamic analysis, the direct time integration method is used. The breakage time of hanger takes a value of 0.005s (Mozos and Aparicio 2010a). After a preliminary numerical study on the dynamic responses of the bridges to pulse loads, the time step of 0.01s is used to calculate the equilibrium state under dead loads, and the time step of 0.001s is used to calculate the dynamic process after the sudden breakage of hanger. The time steps allow us to achieve an important reduction in computing time and to maintain adequate accuracy in the results. A Rayleigh damping of 2% is used in the dynamic analysis.

The following analysis processes are adopted for static analysis:

(a) Using nonlinear static analysis method and adjusting the initial stresses of main cables, hangers, girder and towers, a reasonable static state of the undamaged bridge under dead loads is reached. In this state, the tensions of all hangers are nearly equal, and the moments of the girder and towers are very small.

(b) Using nonlinear static analysis method and the above reasonable static state of the bridge, removing the broken hanger and unloading its tension, the static state of the damaged bridge under dead loads is reached.

The following analysis processes are adopted for dynamic analysis, as shown in Fig. 4.

(c) Using nonlinear dynamic analysis method and adjusting the initial stresses of main cables, hangers, girder and tower, the vibration process of the bridge under dead loads is analyzed. Because of damping, the vibration attenuates with time increasing. When the maximum node displacement amplitude of the structure is less than 0.1 mm, the state of bridge is taken as the initial equilibrium state under dead loads before breakage of hanger.

(d) A hanger element is removed, and tension of the hanger is unloaded in 0.005s.

(e) The structure vibrates strongly due to the sudden breakage of the hanger, and the dynamic analysis is carried out to calculate the vibration of the structure. Because of damping, the vibration attenuates with time increasing. Until the maximum node displacement amplitude of the structure is less than 0.1 mm, the state of bridge is taken as the final equilibrium state under dead loads after breakage of a hanger.

After the sudden breakage of a hanger, the structure vibrates strongly, and the dynamic state of the bridge is identified by S_d. The calculated results show that the two static equilibrium states obtained from (a) and (b) are nearly same as the two equilibrium states obtained from (c) and (e) respectively, and the differences between them can be neglected in design. The states S_0 and S_s are used to identify the static states obtained from the static analysis.

3. Reponses due to sudden breakage of a single hanger

Considering that two hangers are not possible to break at the same time, the case of breakage of a single hanger is studied firstly. From the dynamic analysis results, it can be found that the sudden breakage of a hanger produces very strong vibration of the structure, and had very large effects on tension of the hangers next to the broken hanger, bending and torsion moments of the girder, moments of the tower and reaction forces of the bearings. To illustrate the dynamic effects of sudden breakage of hanger, dynamic amplification factor (DAF) is defined as

$$\text{DAF}=\frac{S_d - S_0}{S_s - S_0}$$

Here, S_d, S_0, S_s are responses of structure, such as tension, moment, displacement and so on.

3.1 Hanger tensions

Figures from 5 to 7 show the initial value S_0, final value S_s and maximum value $S_{d,\max}$ of tensions of the other hangers when hangers #7, #23 and #33 break, respectively. For either static analysis or dynamic analysis, it can be seen from the figures that breakage of a hanger has large effects on tensions of the hangers near the broken hanger, and has little effects on tensions of the hangers far away from the broken hanger. But the tensions obtained from dynamic analysis are

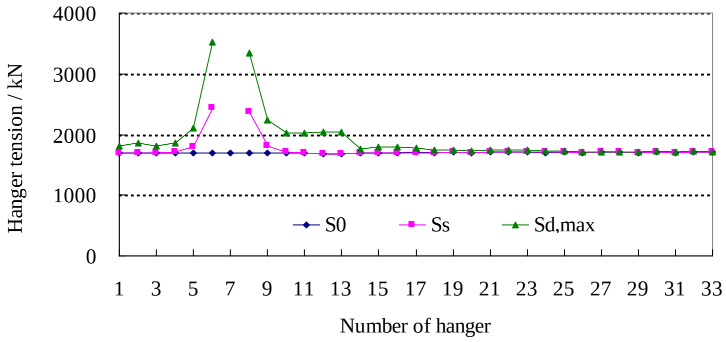

Fig. 5 Hanger tensions in the case of breakage of hanger #7

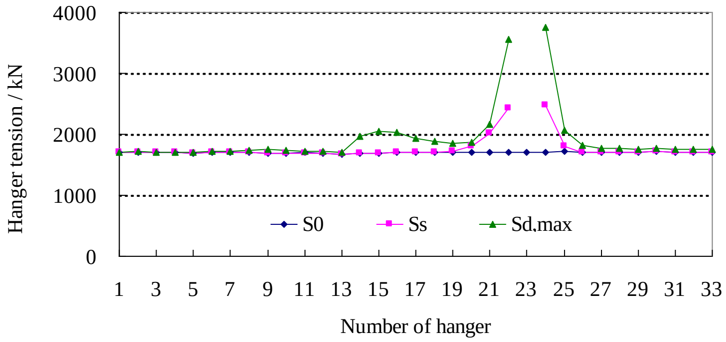

Fig. 6 Hanger tensions in the case of breakage of hanger #23

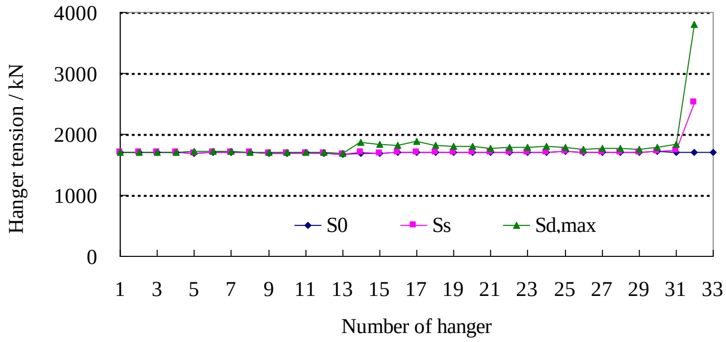

Fig. 7 Hanger tensions in the case of breakage of hanger #33

much larger than those from static analysis, and there are more hangers whose tensions change markedly when using dynamic analysis method.

To obtain the maximum values of tension ratios $S_{d,\max}/S_0$ and S_s/S_0 of every hanger, maximum tension $S_{d,\max}$ and final tension S_s of each hanger are calculated when every one of the other hangers breaks. Fig. 8 shows the maximum values of tension ratios $S_{d,\max}/S_0$ and S_s/S_0 of the

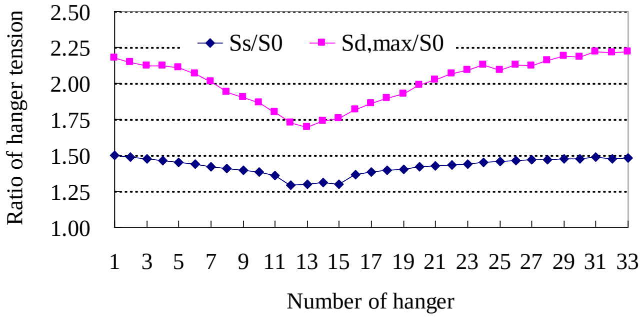

Fig. 8 Ratios of hanger tensions produced by breakage of hanger to the initial values

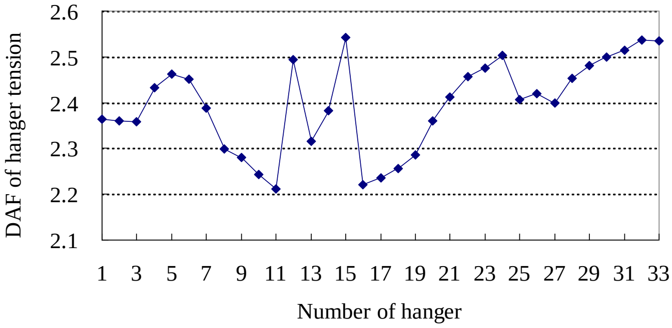

Fig. 9 DAFs of hanger tension

hangers. The tension ratio $S_{d,\max}/S_0$ of hanger #30 is the largest, that is 2.22. However, the tension ratio S_s/S_0 of hanger #30 is only 1.48, which is only 66.7% of the tension ratio $S_{d,\max}/S_0$.

Although DAFs of tensions of the hangers far away from the broken hanger are very large, the changes of their tensions are much less than those of the hangers next to the broken hanger and do not affect the safety of the bridge. For each hanger, the hanger tension DAF is calculated from its tensions S_s and $S_{d,\max}$, which are produced by breakage of one hanger adjacent to it. The hanger tension DAFs of the hangers from #1 to #33 are shown in Fig. 9. If a hanger has two adjacent hangers, only the DAF calculated from the larger value of $S_{\mathrm{d,max}}$ is given in the figure. The DAFs of hanger tensions range from 2.21 to 2.54, and they are larger than the value of 2.0 recommended for cable-stayed bridge in PTI codes.

The dynamic effects on hanger tensions are so marked that the maximum tension reaches 2.2 times of the initial value. So, the breakage of a hanger can endanger the safety of the bridge seriously. If the breakage of a hanger is for the reason of corrosion, the other hangers may be also exposed to corrosion, and their resistance capacities decrease too. The breakage of one hanger may induce one-by-one breakage of the other hangers, and the bridge may collapse after several hangers break.

3.2 Internal forces of girder

The analysis results show that breakage of a hanger has little effects on axial forces, bending moments about vertical axis of girder cross-section (lateral moment) and horizontal shear forces of the stiffening girder. The maximum axial force produced by breakage of a hanger is only 3% of the initial value. The maximum horizontal shear force produced by breakage of a hanger only generates shear stress of 0.016 MPa. The maximum lateral moment produced by breakage of a hanger only generates bending stress of 0.353 MPa. But the bending moments about horizontal axis of girder cross-section (vertical moment), torsion moments and vertical shear forces of girder produced by breakage of a hanger are very large, and they are introduced in detail as the following.

3.2.1 Vertical moments of girder

Figures from 10 to 12 show the changes of vertical moments of girder due to breakage of hangers #7, #14 and #23 respectively. The figures include the maximum moments $S_{d,\max}$, the minimum moments $S_{\mathrm{d,min}}$ in the process of vibration, and final moments S_s of damaged bridge reduced by initial moments S_0 of undamaged bridge respectively. It can be seen from the curve S_s - S_0 that breakage of a hanger has marked effects on moments of the girder only in the region of about 10m near the broken hanger, and moments of the girder in other region are very small, which are only about -12.3% to 2.2% of the maximum value obtained by static analysis. From the curves $S_{d,\max}$- S_0 and $S_{d,\min}$- S_0, it can be seen that breakage of a hanger has marked effects on moments of the girder in whole region of the girder when using dynamic analysis. Especially, every cross-section of the girder has not only positive moment but also negative moment due to vibration, which is very different from the results obtained by static analysis. Additionally, in Fig. 10 and Fig. 12, the maximum positive moment is at the position of the broken hanger, and the maximum negative moment is far away from the broken hanger. So the static analysis method can not obtain the actual vertical moments of girder produced by sudden breakage of hangers.

3.2.2 Torsion moments of girder

The torsion moments of girder produced by breakage of hangers #7, #14 and #23 are shown in Figs. 13, 14 and 15 respectively. Because the breakage of a hanger in one span has little effects on the torsion moments of girder in the other span, the figures only present the torsion moments of girder in the span where the hanger breaks. When using static analysis, breakage of a hanger has marked effects on torsion moments of the girder only in the region near the broken hanger, and torsion moments of the girder in other regions are nearly zero. But torsion moments of girder in

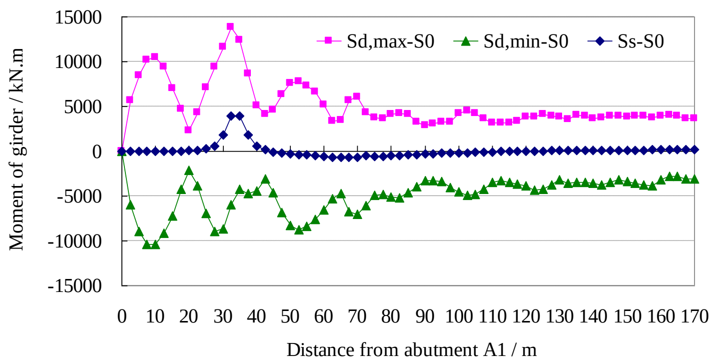

Fig. 10 Moments of girder produced by breakage of hanger #7

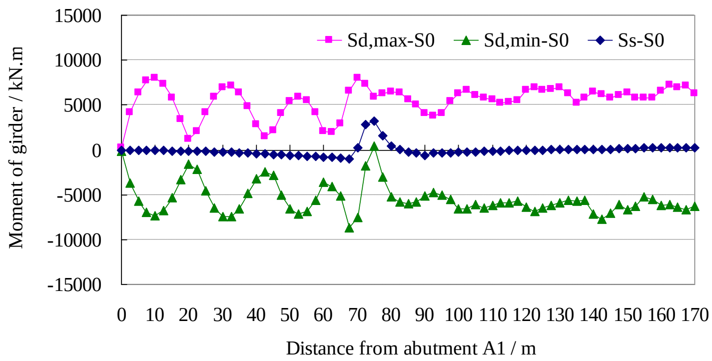

Fig. 11 Moments of girder produced by breakage of hanger #14

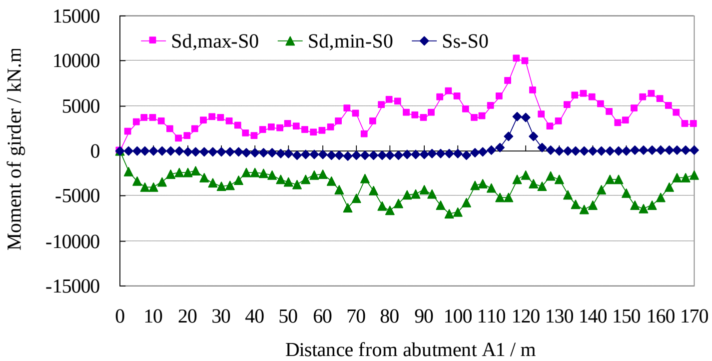

Fig. 12 Moments of girder produced by breakage of hanger #23

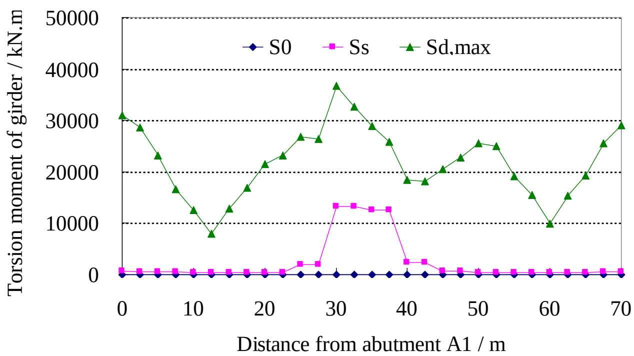

Fig. 13 Torsion moments of girder produced by breakage of hanger #7

the whole span are very large when using dynamic analysis. The ratios of the maximum torsion moment obtained by dynamic analysis to the maximum torsion moment obtained by static analysis are 2.8, 2.3 and 2.1 respectively.

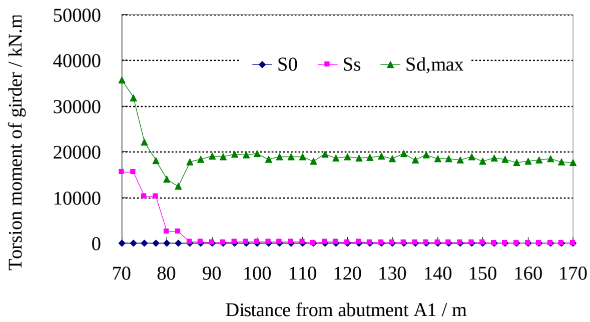

Fig. 14 Torsion moments of girder produced by breakage of hanger #14

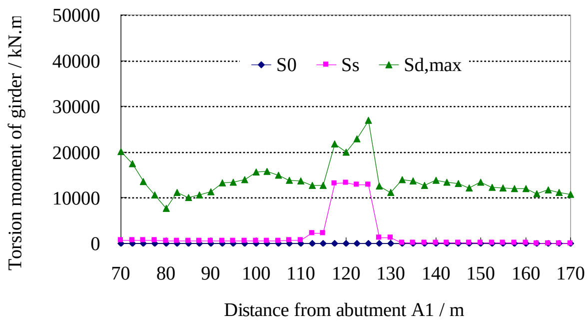

Fig. 15 Torsion moments of girder produced by breakage of hanger #23

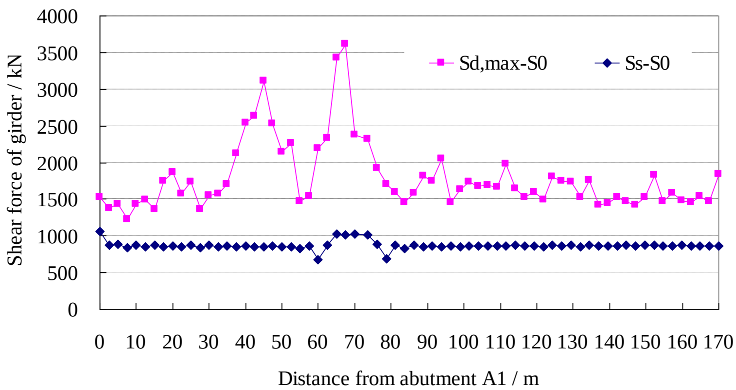

Fig. 16 Maximum vertical shear forces of girder

3.2.3 Vertical shear forces of girder

The maximum vertical shear forces of girder produced by sudden breakage of hangers are presented in Fig. 16. In the figure, $S_{d,\max}$ or S_s is the maximum value of the vertical shear forces in girder cross-section produced by breakage of any one of all the hangers. When using static analysis, the maximum vertical shear forces in most sections along the girder produced by breakage of a hanger are nearly same, and the average value is about 864 kN. The maximum

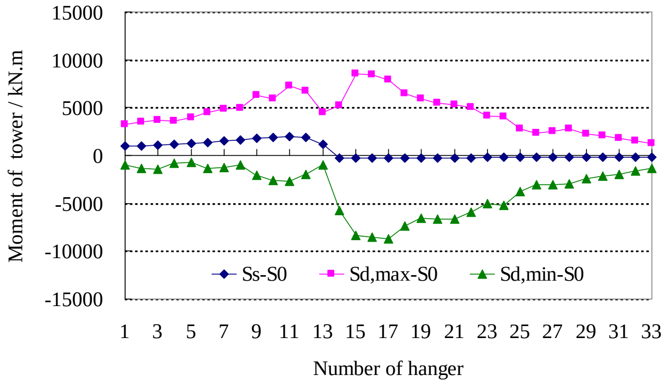

Fig. 17 Moments of the left column of tower T1 produced by sudden breakage of the hangers on the left side

vertical shear forces obtained by dynamic analysis are much larger than those obtained by static analysis, and the maximum ratio of the shear forces obtained by the dynamic and static analysis is 3.54.

3.3 Internal forces of tower

The analyzed results show that, except bending moments about transversal axis of tower cross-section (longitudinal moments), internal forces of tower produced by breakage of hangers are very small. The longitudinal moments at bottom of the left column of tower T1 produced by sudden breakage of every one of hangers from #1 to #33 on the left side are presented in Fig. 17. When using static analysis, the moment of tower produced by breakage of a hanger is very small, especially when the hangers in main span break. The moments of tower obtained by dynamic analysis are much larger than those obtained by static analysis, especially when the hangers in main span break. Except the two hangers next to the tower, the moments of tower produced by the breakage of the hangers near the tower are larger than those produced by the breakage of the hangers far away from the tower.

3.4 Tensile stress of main cable

The analytical results show that tensile stress of main cables produced by breakage of a hanger is very small. The maximum tensile stress produced by breakage of a hanger is 9.5 MPa, which is only 2.2% of the initial stress. So, the effects of breakage of a hanger on the main cables can be ignored in design.

3.5 The reaction forces of bearings at tower

The reaction forces of the two bearings at tower T1 produced by sudden breakage of every one of the hangers from #1 to #33 on the left side are shown in Fig. 18 and Fig. 19. When using static analysis method, the reaction forces produced by sudden breakage of the hangers far from the tower are very small, and only breakage of the two hangers next to the tower has marked effects. The maximum increment of reaction force of the left bearing is about 0.75 times of tension of the

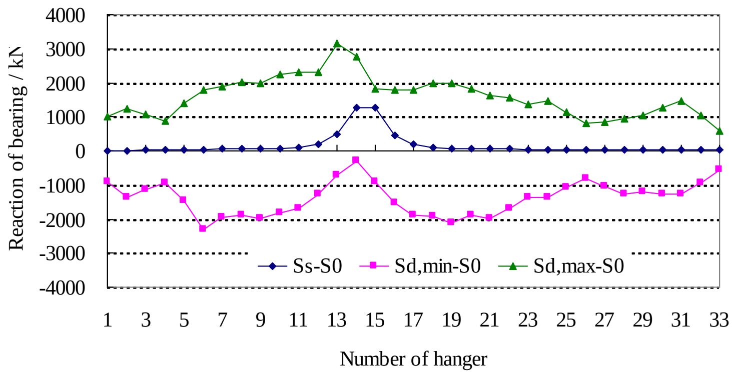

Fig. 18 Reaction forces of the left bearing at tower T1

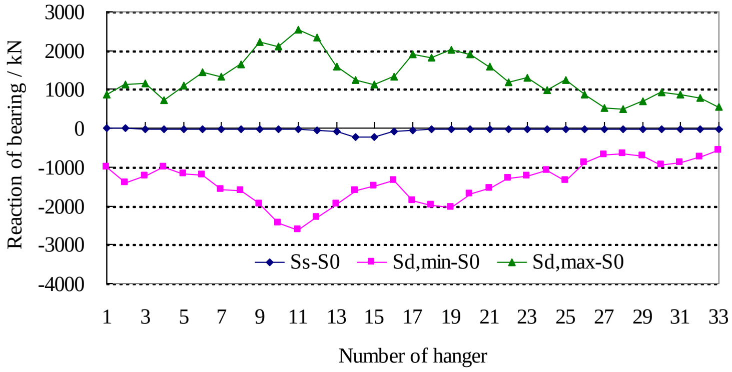

Fig. 19 Reaction forces of the right bearing at tower T1

broken hanger, and the maximum decrement of reaction force of the right bearing is about 0.13 times of tension of the broken hanger.

When using dynamic analysis method, breakage of every hanger can change markedly the reaction forces of the two bearings, that is because breakage of any one hanger can induce strong vertical and torsion vibrations, and vibrations further induce large changes of reaction forces of the bearings. The maximum increment of reaction force of the left bearing is produced by breakage of hanger #14, and it is 2.22 times of tension of the broken hanger. The maximum decrement of reaction force of the right bearing is produced by breakage of hanger #6, and it is 1.38 times of tension of the broken hanger. Both the maximum increment and the maximum decrement of reaction force of the right bearing are produced by breakage of hanger #11, and they are 1.51 and 1.54 times of tension of the broken hanger respectively. So the reaction forces of bearings produced by breakage of a hanger can not be ignored. Additionally, the reaction forces of bearings due to torsion of girder are related to the distance between the two bearings, and the reaction forces increase with the distance decreasing. A relatively large distance is adopted in the bridge analyzed in this paper.

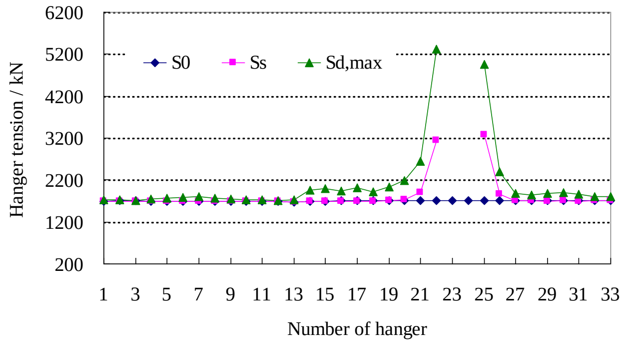

Fig. 20 Hanger tensions due to breakage of hangers #23 and #24 for case 1

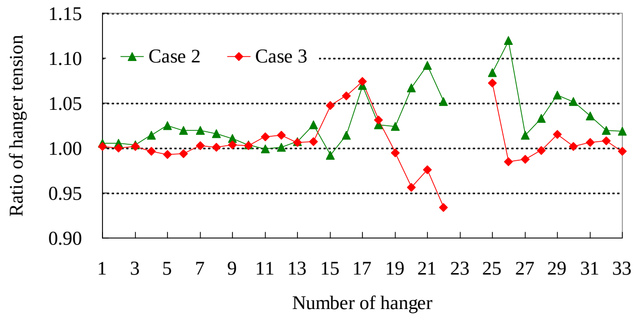

Fig. 21 Ratio of hanger tensions obtained from case 2 and case 3 to case 1

4. Reponses due to sudden breakage of two adjacent hangers on the same side of the bridge

It is known from the above analysis that sudden breakage of one hanger markedly increased tensions of the hangers next to the broken hanger. Although two adjacent hangers are impossible to break at the same time, they are very possible to be exposed to serious corrosion, and their resistance capacities may decrease simultaneously. If one of them breaks suddenly, the other hanger may break because its tension increases too much. The effects of breakage of two adjacent hangers on the same side of the bridge are studied and the following analysis processes are adopted.

(f) Using nonlinear dynamic analysis method and adjusting the initial stresses of main cables, hangers, girder and tower, the vibration process of the bridge under dead loads is analyzed. Because of damping, the vibration attenuates with time increasing. When the maximum node displacement amplitude of the structure is less than 0.1 mm, the state of bridge is taken as the initial static equilibrium state under dead loads before breakage of one hanger.

(g) A hanger element is removed, and its tension is unloaded in 0.005s.

(h) The dynamic analysis is carried out to calculate the vibration of the structure due to the sudden breakage of the hanger. At a certain time during the vibration, one of the two hangers next to the broken hanger is removed, and its tension is unloaded in 0.005s. The dynamic analysis continues. Because of damping, the vibration attenuates with time increasing. Until the maximum node displacement amplitude of the structure is less than 0.1mm, the final state of bridge is taken as the static equilibrium state under dead loads after breakage of two hangers.

The case in which hanger #24 breaks after sudden breakage of hanger #23 is studied in detail. To investigate the effects of the time when hanger #24 breaks on the responses, the following 3 cases are adopted in the study.

Case 1: Hanger #24 breaks when the vibration due to breakage of hanger #23 nearly ceases.

Case 2: Hanger #24 breaks when its tension reaches the maximum value.

Case 3: Hanger #24 breaks when its tension reaches the minimum value.

The tensions of the hangers except hangers #23 and #24 are presented in Fig. 20 for case 1, including the initial value S_0, final value S_s and maximum value $S_{d,\max}$. The tensions of the hangers near the broken hangers are changed largely, and tensions of the hangers far away from the broken hangers are changed little. Especially, the maximum tensions of hangers #22 and #25 are 1267 kN and 1179 kN respectively, which are 3.11 and 2.90 times of their initial values respectively. If the hangers are design by Chinese codes, the hanger will break even if they are not exposed to corrosion. So the breakage of two adjacent hangers on the same side of the bridge can induce the other hangers break one by one, and induce the collapse of the whole bridge.

Fig. 21 presents the ratios of maximum tensions of case 2 and case 3 to those of case 1. The different time when the second hanger breaks makes the tensions different, and the maximum tension obtained in case 2 is larger than the value obtained in case 1 by 12%. The maximum tensions obtained in case 2 are larger than those in the other two cases for the most hangers.

5. Conclusions

For self-anchored suspension bridge, its main cables are anchored directly to two ends of its stiffening girder, and the stiffening girder subjected to a very large compression force is supported by hangers. So the hangers are very important for the safety of the whole bridge. With the time increasing, the resistance capacities of the hangers decrease due to corrosion, and the hangers may break suddenly. The study on the responses of a self-anchored suspension bridge to breakage of hangers reaches the following conclusions.

(1) The sudden breakage of a hanger produces very strong vibration and large changes of internal forces of the bridge. During the vibration, the maximum tension of hanger reaches 2.22 times of the initial value. The maximum increment of reaction force of bearing is 2.22 times of the tension of the broken hanger, and the maximum decrement of reaction force of bearing is 1.54 times of tension of the broken hanger. The breakage of a hanger produces very large bending moments and torsion moments of girder. The tension of main cable and internal forces of tower except longitudinal moments are affected little.

(2) If two adjacent hangers on the same side of bridge break one after another, the maximum tension of their adjacent hanger reaches 3.11 times of its initial value. If the safety factor adopted to design hanger is too small, or the hangers have been exposed to corrosion, the bridge will collapse due to breakage of two adjacent hangers. So inspection and maintenance of the hangers should be paid more attention to avoid breakage of two adjacent hangers due to corrosion, and the safety factor of hanger adopted in design should take into account the dynamic influences of breakage of hangers.

(3) After breakage of a hanger, only tensions of the hangers next to the broken hanger increase markedly, tensions of the other hangers changed little and do not govern the design. The maximum

the DAF of the hangers next to the broken hanger reaches 2.54, which is larger than the value of 2.0 recommended for cable-stayed bridge in PTI codes. The internal forces of girder and towers and the reaction forces of bearings obtained by dynamic analysis method are very different from those obtained by static analysis method. So the dynamic analysis method should be used for analysis of the responses of self-anchored suspension bridge due to breakage of hangers.

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