SEISMIC VULNERABILITY ANALYSIS OF CABLE-STAYED BRIDGE DURING ROTATION CONSTRUCTION

Wang Sukang, Sun Quansheng,Yu Haitao and Wang Hongyang

Department of Civil Engineering, Northeast Forestry University, Harbin， 150040, China; wangsukang2021@126.com

ABSTRACT

Due to the swivel construction, the structural redundancy of cable-stayed bridge is reduced, and its seismic vulnerability is significantly higher than that of non-swirling construction structure and its own state of formation. Therefore, it is particularly important to study the damage changes of each component and stage system during the swivel construction of cable-stayed bridge under different horizontal earthquakes. Based on the construction of Rotary Cable-stayed Bridge in Haxi Street, the calculation formula of damage exceeding probability is established based on reliability theory, and the damage calibration of cable-stayed bridge components is carried out, and the finite element model of cable-stayed bridge rotating structure is established. The vulnerable parts of the main tower and the stay cable components of the cable-stayed bridge are identified and the incremental dynamic analysis is carried out. Finally, the seismic vulnerability curves of the main tower section, the stay cable and the rotating system are established. The results of the study show that the vulnerable areas of the H-shaped bridge towers are the abrupt changes in the main tower section near the upper and lower beams, and the vulnerable diagonal cables are the long cables anchored to the beam ends and the short cables near the main tower. At the same seismic level, the damage exceedance probability of main tower vulnerable section of cable-stayed bridge under transverse earthquake is greater than that under longitudinal earthquake, the damage exceedance probability of vulnerable stay cables under transverse seismic action is less than that under longitudinal seismic action. On the premise of the same damage probability, the required ground motion intensity of the system can be reduced by 0.35g at most compared with the component. Under the same seismic intensity, the system damage probability is 6.60 % higher than the component damage probability at most. The research results have reference significance for the construction of rotating cable-stayed bridges in areas lacking seismic records.

KEYWORDS

Bridge engineering, Rotational cable-stayed bridge, Earthquake, Vulnerability analysis, System damage

INTRODUCTION

Earthquakes are accidental loads and may occur at all stages of bridge construction. The unfinished Mingshi Strait Bridge in Japan in 1995 was struck by an earthquake of magnitude 7.2, which resulted in displacement of the main tower foundation and the anchor ingot of the main cable, and the mid-span elevation of the stiffening girder by 1.27 meters [1]. In 1999, a strong earthquake with magnitude 7.3 occurred in Jixian County, Taiwan, which resulted in the main tower damage, cable damage and shear failure of the anti-seismic pin and tie of the Jilu Bridge under construction near the epicentre [2]. In the 2008 Wenchuan earthquake, the main girder of the Miaoziping Minjiang Bridge under construction was dropped [3]. The possibility of seismic damage in bridge construction. For the rotating cable-stayed bridge, in the construction process, it not only shows the characteristics

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of its flexible bridge, but also has the characteristics of architecture, when the earthquake comes, the redundancy is extremely low and the vulnerability is strong. Through seismic vulnerability analysis of swivel cable-stayed bridge during construction, corresponding theoretical support is provided for design and construction in order to effectively reduce or avoid structural damage caused by earthquake during bridge construction.

Seismic vulnerability analysis of cable-stayed bridge is based on continuous beam and rigid frame bridge. With the continuous construction of long-span cable-stayed bridge, near-field seismic cable-stayed bridge and fault zone cable-stayed bridge in China, the seismic damage of cable-stayed bridge in operation stage reminds us to pay attention to the seismic analysis of cable-stayed bridge, for cable-stayed bridges in potential seismic areas without relevant seismic records, the theoretical analysis method of vulnerability becomes particularly important.

According to the statistics of 30 highway bridges damaged by earthquake by Japanese scholar Kubo [4], the seismic performance of bridges is analyzed by numerical evaluation method. The influence factors such as foundation type, pier height, main beam form and anti-falling beam structure are considered respectively, the vulnerability degree of bridges is judged by designing damage index. Shinozuka [5] obtained a simplified formula by counting the vulnerability of several typical reinforced concrete bridges. Using this formula, the vulnerability curve of similar bridges can be obtained without pushover analysis and dynamic time history analysis. Jong-Su [6] and other scholars used the idea of parameter analysis in the study of seismic vulnerability analysis of urban curved box girder viaducts, and obtained that piers and bearings were vulnerable components, and the damage probability of bearings was higher than that of piers. Karthik et al. [7] considered the influence of the change of seismic design concept on the seismic performance of bridges, and discussed the change of vulnerability curve of the same bridge in the three seismic concepts. Do-Eun [8] analyzes the seismic vulnerability of piers under the premise of corrosion of steel bars in piers. It is concluded that the corrosion of steel bars affects the constitutive relationship of steel bars and core confined concrete in piers, affects the probabilistic demand model, and then affects the change of vulnerability curve. Wu Shaofeng and Shang Guanping [9] studied the vulnerability of longitudinal and transverse ground motions of some single-pylon cable-stayed bridges. The finite element model was established by MIDAS software, and plastic hinge was set up at the weak position of each member. The vulnerability curves of the members and the whole bridge are obtained. Feng Qinghai [10] takes an extra-large cable-stayed bridge as the research object, only the geometric nonlinear factors of the structure are considered, the vulnerable section of the main tower is the bottom section of the main tower and the cross-section of the main tower above and below the cross-beam. GuYin [11] and other scholars studied the seismic vulnerability of low-pylon cable-stayed bridge based on performance. Aiming at the vertical and horizontal seismic input and considering the vertical seismic, incremental dynamic analysis was carried out on the finite element model of cable-stayed bridge, and the vulnerability curve was drawn by calculating the damage probability, the IDA method is feasible and the analysis idea is clear. Shen Guoyu [12] used the “Artificial neural network-orthogonal design method” to calculate the structural capacity, which not only improves the analysis efficiency, but also simplifies the calculation method. Huang Shengnan [13] adjusted the amplitude of the ground motion records and did a nonlinear dynamic analysis of the structure, with the gradual increase of the seismic intensity, the seismic response of the key components is obtained, the IDA curve is drawn, and the vulnerability curve is further obtained. Wang Chongchong [14] did not consider the vulnerability of the main girder and stay cable in the vulnerability analysis of long-span cable-stayed bridge for highway and railway as Ji Zhengdi did. After the time history analysis along the tower height and pier height under the action of multiple seismic waves, the weak section can be clearly located and IDA analysis can be carried out in a directional manner, which reduces the workload of finite element calculation. In the seismic vulnerability analysis of offshore cable-stayed bridge, Gu Qiong [15] considered the influence of chloride ions on the time-varying deterioration of materials. After determining the constitutive relationship of deteriorated materials, the finite element model was established for theoretical analysis, which was consistent with the analysis conclusions of Wu Shaofeng and other scholars, the damage probability of the system was greater than any single component. Thus, the seismic vulnerability analysis of cable-stayed bridge system is necessary. Fabio et al. [16] considered the structural uncertainties by defining a random variable, and used the time-history analysis method to analyze the seismic vulnerability of cable-stayed bridges. Chao [17] and other scholars put forward the vulnerability of offshore cable-stayed bridge under the combined action of marine environment and earthquake, and put forward the change of the overall vulnerability of cable-stayed bridge when considering the pile-soil interaction, the propagation of ground motion in different sand, the erosion of seawater on pile foundation and the change of pile depth. In order to obtain the most suitable ground motion evaluation parameters, Jun [18] and other scholars established a calculation model based on general linear regression. The analysis showed that the prediction ability of peak ground motion velocity on transverse seismic response was poor, and the analysis method was suitable for cable-stayed bridges and continuous girder bridges.

At present, bridge seismic vulnerability analysis has become an important part of bridge seismic theory research. From a large number of research results of the above scholars, most scholars study the vulnerability of cable-stayed bridge from the operation stage, mainly for the vulnerability analysis of key components, the acquisition of seismic parameters, the improvement of mathematical calculation model, the definition of time-varying damage state, and how to improve the calculation efficiency. However, few scholars have carried out research on the seismic vulnerability of cable-stayed bridges during the construction phase. Inspired by the research methods and ideas of the above scholars, this paper will take the large tonnage rotating cable-stayed bridge in northeast China as an example to analyze the seismic vulnerability of the cable-stayed bridge during the rotation process. The number of swivel cable-stayed bridge in our country is more and more, the span is more and more big, and the construction technology is more and more complex. Therefore, the safety performance of swivel cable-stayed bridge under seismic load including construction stage should be fully considered. By analyzing the seismic vulnerability of the rotating cable-stayed bridge in the construction stage, the exceeding probability of the earthquake to the various components of the bridge and the overall damage of the bridge in the construction process of the rotating cable-stayed bridge can be judged, which can play a guiding role in the design, prevention and maintenance of the cable-stayed bridge before construction.

RESEARCH OVERVIEW AND METHODS

Overview of bridges

The span of Haxi cable-stayed bridge is 118m+198m+118m, the span arrangement diagram of cable-stayed bridge is shown in Figure 1. The main beam adopts prestressed concrete π type main beam, concrete C60, according to A type prestressed system design. The stay cables are fan-shaped with double cable planes, and there are 112 stay cables in the whole bridge. The stay cable is anchored on the outer side of the π type rib plate of the main beam through the anchor block, and the longitudinal standard cable distance is 7 m. The standard strength of stay cable with steel strand is 1860 MPa.

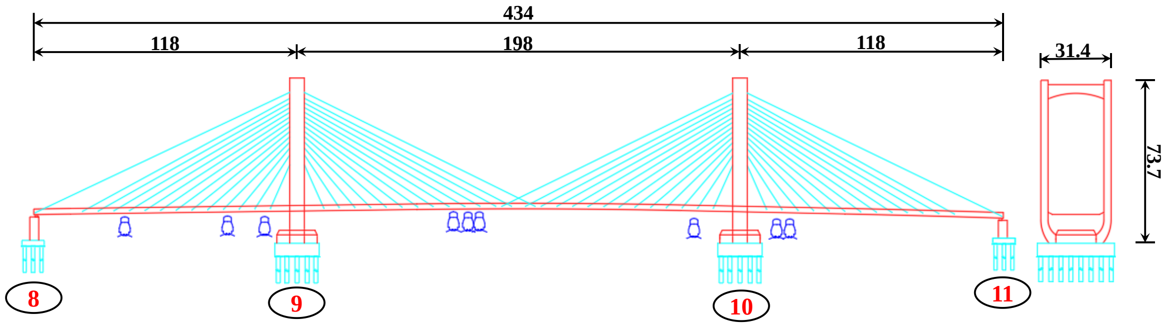


Fig. 1 – Layout diagram of span of cable-stayed bridge with rotation（m）

Cable-stayed bridge main tower height 73.7 m, H-shaped, C50 reinforced concrete structure. The main tower is set with one upper beam and one lower wall. The upper column is box section, the section size is 320cm (transverse)×650cm (longitudinal). The lower tower column is solid wall structure, the cross-sectional dimension is 2400cm~3140cm, the longitudinal dimension is 650cm, the main tower structure diagram is shown in Figure 2.

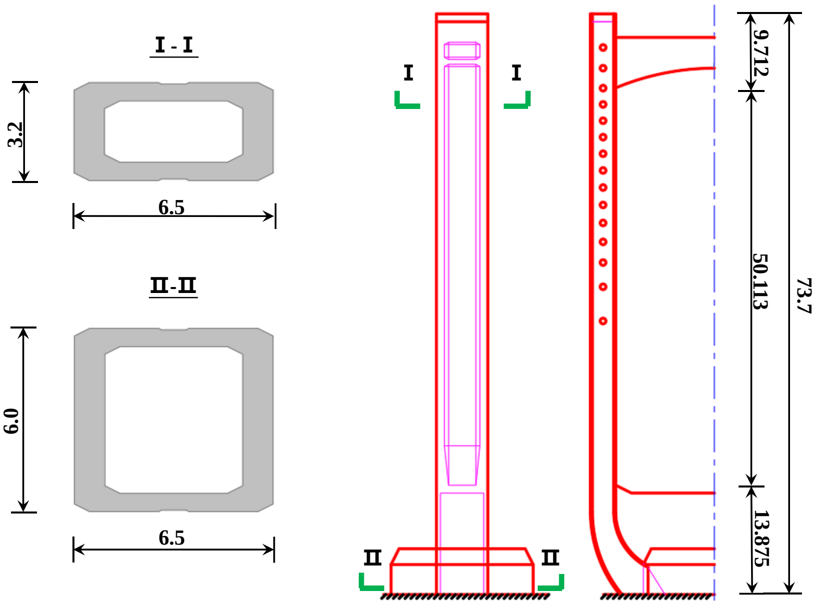


Fig. 2 – Structure diagram of main tower of rotary cable-stayed bridge（m）

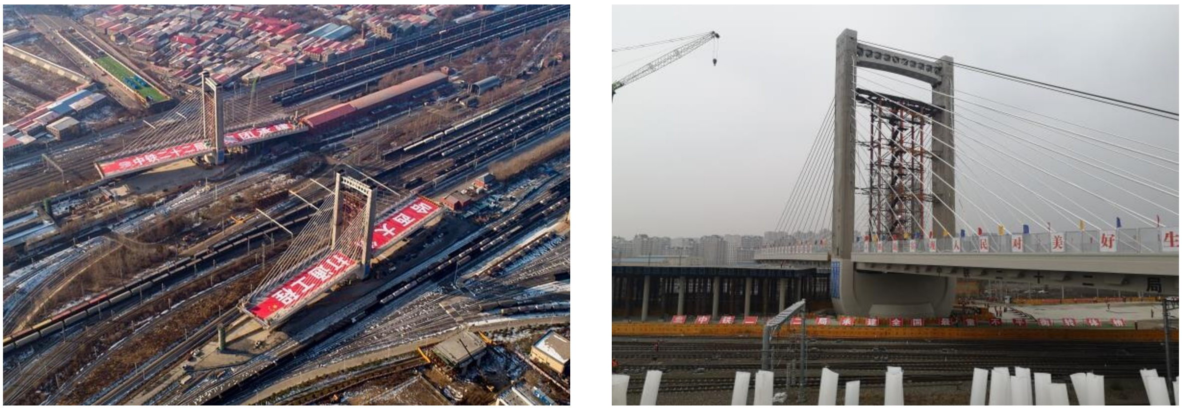


Fig. 3 – Structure diagram of main tower of rotary cable-stayed bridge（m）

Research method of seismic vulnerability of rotary cable-stayed bridge during construction

In the seismic vulnerability analysis, based on the incremental dynamic analysis method, Hwang [19] and Wang Xuewei [20] gave the calculation cases of seismic vulnerability of reinforced concrete girder bridges and long-span cable-stayed bridges in the area lacking ground motion records, and proposed the related research steps of vulnerability analysis. It is summarized into three main parts, namely, the establishment of finite element model, the input of ground motion, the calibration of structural damage index under seismic action, the calculation of structural seismic response and the drawing of vulnerability curve. In this paper, the vulnerability curve is established based on the incremental dynamic analysis method to analyze the seismic vulnerability of the cable-stayed bridge during the rotation construction stage.

Division of Construction Phases of Swivel Cable Stayed Bridge

The construction process of the rotating cable-stayed bridge can be divided into the foundation construction stage, the main pier cap construction stage, the support stage, the maximum cantilever stage, the rotating unsealed hinge stage, and the closing stage. However, due to the great influence of seismic action on the high-rise structure, the construction of the first two stages is below the ground. The embedded effect of structure and soil makes the seismic response of the structure relatively small. In the closure stage, the structure is mainly close to the bridge completion stage. Compared with the support and cantilever stage, the structural redundancy in the rotation stage is the lowest and the mobility is the highest. So, this paper mainly analyzes the seismic vulnerability of the cable-stayed bridge in the rotation stage.

The main components of the cable-stayed bridge in the rotation stage are the main tower, main beam and stay cable. Professor Ye Aijun draws a guiding conclusion in his research results. Under the action of seismic force, the material performance of the main beam is always maintained in the elastic stage and is not easy to damage [21,22]. Therefore, in the seismic vulnerability analysis of rotating cable-stayed bridge in this paper, the target component is the main tower and stay cable.

Seismic vulnerability analysis method of rotating cable-stayed bridge based on incremental dynamic analysis

The incremental dynamic analysis process is: (1) Establish a finite element model of the target structure; (2) Select the appropriate ground motion and amplitude modulation input; (3) Definition of damage indicators; (4) Time history analysis of the structure under various levels of earthquakes.

In this paper, the direct regression method is used to establish the vulnerability curve. Firstly, it is assumed that the logarithm of the seismic capacity of the structure and the logarithm of the seismic demand obey the normal distribution [23]. The probability density function see Equation (1).

$$f(x) = \frac{1}{\sqrt{2\pi}\,\sigma_{\ln x}} e^{\frac{(x-\mu_{\ln x})^2}{2\sigma_{\ln x}^2}} \tag{1}$$

See equation (2) for probability distribution function.

$$F(x) = \int_0^x \frac{1}{\sqrt{2\pi}\,\sigma_{\ln x} x} e^{\frac{(x-\mu_{\ln x})^2}{2\sigma_{\ln x}^2}} dx = \Phi\left(\frac{\ln x - \mu_{\ln x}}{\sigma_{\ln x}}\right) \tag{2}$$

Among them: *x* is the damage variable; $\mu_{\ln x}$ is the logarithmic mean of the random variable *x*; $\sigma_{\ln x}$ is the logarithmic standard deviation of random variable *x*; Φ is the standard form of normal distribution function.

The calculation result of seismic vulnerability is the probability that the structural response exceeds the damage degree at all levels under different seismic intensities. Here, *R* is used to represent the resistance of structural components, and *S* is used to represent the seismic demand. Then, the functional function of components based on the reliability theory is shown in Equation (3).

$$Z = R - S \tag{3}$$

The failure probability (exceedance probability) of structural components is shown in Equation (4).

$$P_f = P(Z < 0) = P\,(R - S) \tag{4}$$

Since the logarithm of *R* and *S* obeys the overall distribution, we can get:

$$\begin{gathered}\ln R \sim N\left(\overline{\ln R}, \sigma_{\ln R}^2\right) \\ \ln S \sim N\left(\overline{\ln S}, \sigma_{\ln S}^2\right)\end{gathered} \tag{5}$$

According to the statistical theory, $\ln R - \ln S$ also obeys the normal distribution, and we can get :

$$(\ln R - \ln S) \sim N\left(\overline{\ln R} - \overline{\ln S}, \sigma_{\ln R}^2 + \sigma_{\ln S}^2\right) \tag{6}$$

Then the failure probability is shown in Equation (7) and Equation (8).

$$P[(\ln R - \ln S) < 0] = P\left[\frac{(\ln R - \ln S) - \left(\overline{\ln R} - \overline{\ln S}\right)}{\sqrt{\sigma_{\ln R}^2 + \sigma_{\ln S}^2}} < \frac{0 - \left(\overline{\ln R} - \overline{\ln S}\right)}{\sqrt{\sigma_{\ln R}^2 + \sigma_{\ln S}^2}}\right] \tag{7}$$

$$P[(\ln R - \ln S) < 0] = \Phi\left(\frac{\overline{\ln S} - \overline{\ln R}}{\sqrt{\sigma_{\ln R}^2 + \sigma_{\ln S}^2}}\right) \tag{8}$$

Among them: $\overline{\ln R}$ is the logarithmic mean of the structural capacity value; $\overline{\ln S}$ is the logarithmic mean of the seismic demand value; $\sigma_{\ln R}$ is the logarithmic standard deviation of the structural capacity; $\sigma_{\ln S}$ is the logarithmic standard deviation of the seismic demand.

When the maximum value $P_{\max}$ under the short-term combination of accidental loads acts on the section when calculating the bending moment-curvature curve, the mean value of the logarithm lnR of the structural capacity value is itself after conservatively considering the randomness of the structure. We only need to consider the randomness of the earthquake, namely:

$$\begin{gathered}\overline{\ln R} = \ln R \\ \sigma_{\ln R} = 0\end{gathered} \tag{9}$$

In this way, the calculation formula for the probability of failure (exceeding probability) is:

$$\begin{aligned}P[(\ln R - \ln S) < 0] &= P\left[\frac{(\ln R - \ln S) - \left(\overline{\ln R} - \overline{\ln S}\right)}{\sigma_{\ln S}} < \frac{0 - \left(\overline{\ln R} - \overline{\ln S}\right)}{\sigma_{\ln S}}\right] \\ &= \Phi\left(\frac{\overline{\ln S} - \ln R}{\sigma_{\ln S}}\right)\end{aligned} \tag{10}$$

The first-order boundary method [24] is used to study the system vulnerability of cable-stayed bridge in swivel stage. Regarding the shape of the cable-stayed bridge at each stage as a series system, according to the reliability theory and ignoring the correlation of various components, the upper and lower bounds of the damage probability of the system at all levels are calculated by Equation (11).

$$\max_{i=1}^{m}[P_{fi}] \leqslant P \leqslant 1 - \prod_{i=1}^{m}[1 - P_{fi}] \tag{11}$$

Among them, P represents the system damage probability; P_{fi} represents the component damage probability, which is the maximum value of the damage exceeding probability of each damage unit (cross section, stay cable) under the same earthquake level.

Damage calibration

The research on damage degree of bridge structural members is one of the main contents of performance-based seismic research. At present, in order to evaluate the damage state of the structure, the damage of concrete members is usually divided into four grades: slight, medium, serious and complete damage.

At present, most scholars use the sectional curvature corresponding to the change of material strain as the damage index of bridge tower structure in the seismic vulnerability analysis of cable-stayed bridges. Various damage situations and corresponding sectional curvature levels are shown in Table 1 [25].

Tab. 1: Curvature damage index

Damage status	Damage feature	Corresponding parameters of curvature level
Slight damage	The first yielding of longitudinal steel bars	$\varepsilon_y < \varepsilon_s \leqslant \varepsilon_{sh}, \varepsilon_c \leqslant 2\varepsilon_{cd}$
Moderate damage	Non-linear deformation appears	$\varepsilon_{sh} < \varepsilon_s \leqslant 0.55\varepsilon_{su},\ 2\varepsilon_{co} < \varepsilon_c \leqslant 0.75\varepsilon_{ccu}$
Severe damage	The protective layer concrete is peeling off	$0.55\varepsilon_{su} < \varepsilon_s \leqslant \varepsilon_{su},\ 0.75\varepsilon_{ccu} < \varepsilon_c \leqslant \varepsilon_{ccu}$
Eventual failure	Confined concrete core is crushed	$\varepsilon_s > \varepsilon_{su},\ \varepsilon_{ccu} \leqslant \varepsilon_c$

Note: ε_s is the tensile strain of longitudinal reinforcement outside the section, ε_c is compressive strain of concrete with outer protective layer, ε_y is tensile yield strain of longitudinal reinforcement, ε_{cd} is the outermost compressive strain of cross-section core concrete, ε_{co} is the ultimate compressive strain of concrete cover with a value of 0.002, ε_{sh} is the initial hardening tensile strain of longitudinal reinforcement, taking 0.015, ε_{su} is the fracture strain of longitudinal reinforcement, and the value is 0.09. ε_{ccu} is the ultimate compressive strain at the outermost edge of the core concrete of the section, which depends on the stirrup structure.

The cable stayed in the cantilevered state in the rotating phase is more likely to have stress exceeding the limit under the action of strong earthquakes. In this paper, the damage calibration method based on the strength and deformation criterion of Wu Shaofeng[9] is adopted, and the stress ratio Equation (12).

$$\alpha_c = \frac{f_{y1}}{R_y^b} \tag{12}$$

Among them, f_{y1} and R_y^b are the cable stress and the ultimate tensile strength of the stay cable under the earthquake. And using the classification method of Professor Wang Jingquan[26] to calibrate the damage index : α_c=0.45 for mild damage, α_c=0.60 for moderate damage, α_c=0.75 for severe damage, α_c=0.90 for complete damage.

Establishment of finite element model

In References [21,22], the seismic plasticity analysis of the main girder of cable-stayed bridge structure is not carried out. At the same time, according to the principle of capacity protection, it is generally expected that the pier, main tower and other components will first enter the plastic stage in bridge design to ensure the safety of the main girder. Therefore, the plastic stage of the main girder is not considered in the seismic response analysis in this paper, the π-type main girder is simulated by elastic beam element. The stay cable component is simulated by nonlinear truss element, and the elastic modulus is corrected by Ernst formula.

In this stage, the main beam and the main tower are temporarily anchoraged by vertical prestress, and the connection between the main beam and the main tower is simulated by rigid connection; The beam end anchorage of stay cable is simulated by rigid master-slave connection, and the main node is the midline node of single beam. The tower end anchorage of stay cable is connected by common nodes; The inertia moment of the modified section of the tower root section is consistent with that of the upper cap; The connection between the upper and lower caps (rotating system) uses the relevant data of the weighing test to convert the rotational stiffness simulation of the elastic connection; There is a 5cm gap between the supporting foot and the slideway in the rotating system, Midas is used to simulate the general connection. The specific operation is as follows: select the spring element in the general connection characteristic value dialog box, define the inelastic characteristic value (clearance element), select the general link, the hysteresis model is "slip double polyline/compression only", and define the yield strength (The yield strength of the support foot is selected here), and the initial gap is 5cm, which simulates the mechanical characteristics of the gap between the support foot and the slide; at the same time, the pile-soil interaction is considered.

RESEARCH RESULTS AND ANALYSIS

Identification of vulnerable parts of rotary cable-stayed bridge

In this paper, the swivel structure of No.9 tower of swivel cable-stayed bridge is selected for vulnerability analysis. Due to the uncertainty of the vulnerable section, the vulnerable section is first identified, which can not only reduce the complexity of the analysis process, but also accurately locate the vulnerable section. At this stage, the main tower and stay cable are selected for vulnerability analysis. According to the site characteristics of the target cable-stayed bridge, 10 seismic waves are selected in the Pacific seismic center, as shown in Table 2, and the finite element model is input in longitudinal and transverse directions.

Tab. 2: Seismic wave name

Earthquake number	Earthquake name	Time	PGA（g）
1# seismic wave	Cape Mendocino	1992	0.1191
2# seismic wave	Chi-Chi Taiwan	1999	0.1777
3# seismic wave	Chuetsu-Koi	2007	0.1920
4# seismic wave	Imperial Valley-06	1979	0.1717
5# seismic wave	Irpinia Italy-01	1980	0.1097
6# seismic wave	Iwate	2008	0.3613
7# seismic wave	Landers	1992	0.2792
8# seismic wave	Loma Prieta	1989	0.1513
9# seismic wave	San Simeon Ca	2003	0.0906
10# seismic wave	Taft Lincoln School	1952	0.1048

When identifying the vulnerable section of the main tower, it mainly analyzes the changes in the section curvature of the main tower components along the height of the main tower under different earthquakes, and the analysis shows that the section with the largest curvature under the earthquake action is the earthquake vulnerable part of the main tower; The stress ratio is selected as the quantitative index for the vulnerability identification of stay cables, that is, the ratio of the stress of stay cables to the ultimate strength of stay cables under ground motion. The analysis shows that the stay cables with the largest stress ratio under seismic action are regarded as vulnerable stay cables.

The amplitude of the ground motion is modulated to 1.0g, under the action of the longitudinal and transverse bridge directions, the curvature envelope diagram of the main tower section of the cable-stayed bridge at the turning stage is shown in Figure 4~5; The stress ratio envelope diagrams of stay cables are shown in Figure 6~7.

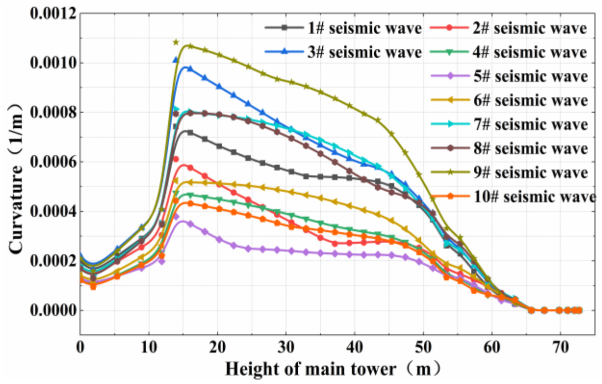


Fig. 4 – Curvature envelope diagram of longitudinal seismic main tower

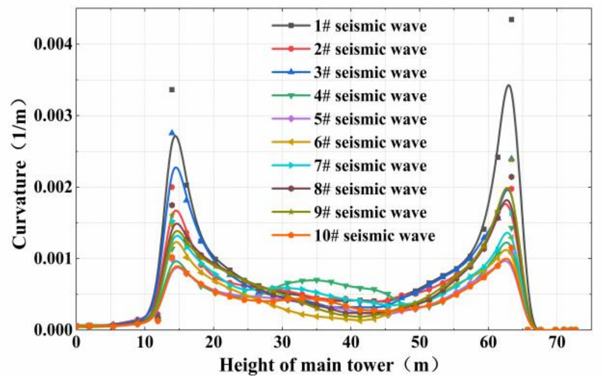


Fig. 5 – Curvature envelope diagram of transverse seismic main tower

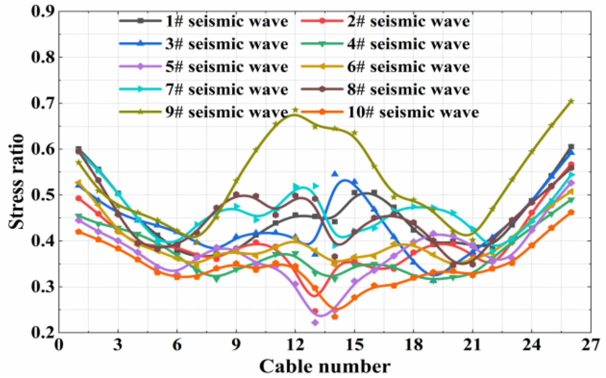


Fig. 6 – Envelope diagram of longitudinal seismic cable stress ratio

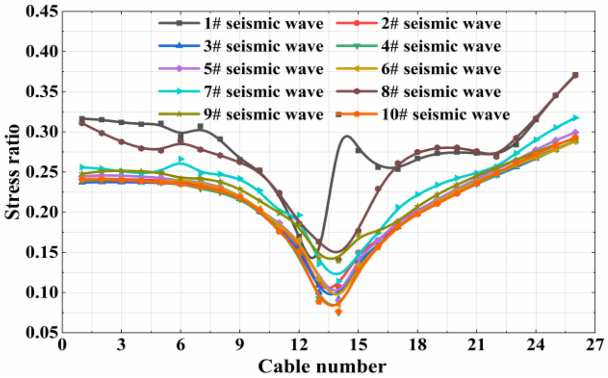
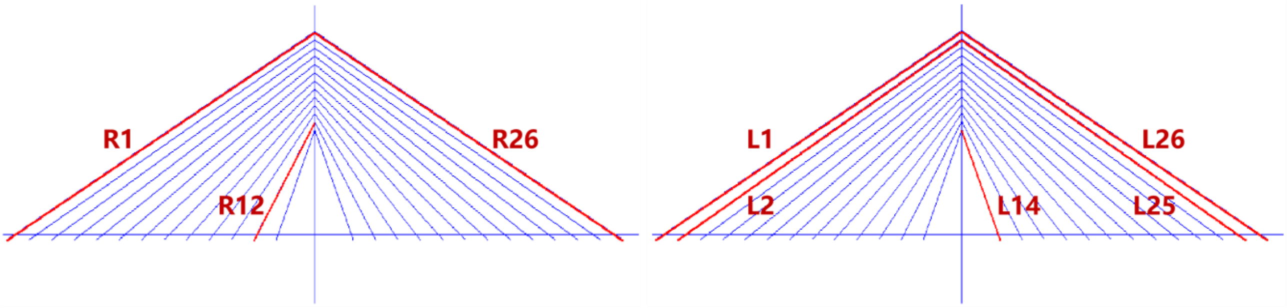


Fig. 7 – Envelope diagram of transverse seismic cable stress ratio

Under the action of 10 longitudinal bridge-directed ground motions with an intensity of 1.0g, the curvature of the main tower changes as follows: The section curvature of the pier from the tower root to the lower beam section decreases first and then increases gradually, and the peak section curvature of the lower column is obtained near the lower beam section; From the lower beam section to the upper beam section, the curvature of the tower column section decreases slowly from the maximum value and then drops sharply to 0. Select the lower tower column curvature peak section, the upper tower column curvature peak section, and the upper tower column curvature reduction rate change section as the longitudinal bridge seismic vulnerability analysis section. The change trend of the cable stress ratio is: At first, the cable stayed at the beam ends on both sides is the peak of the stress ratio, and then the stress ratio gradually decreases from the beam ends to the main tower and then gradually increases to the maximum. The third peak value of stress ratio was obtained in 12# cable. The 1#, 12#, 26# stay cables are selected as the longitudinal bridge seismic vulnerability analysis cables.

Under the action of 10 cross-bridge ground motions with intensity of 1.0 g, the variation trend of the main tower curvature is: The lower tower column gradually increases from the tower root to the lower beam, the section curvature appears two peak positions, namely the section near the lower beam and the section near the upper beam. The two peak curvature sections are set to the cross bridge seismic vulnerability analysis section; The change trend of the cable stress ratio is: From the beam end to the main tower direction, the peak stress ratio of stay cables is obtained at the beam end. The peak stress ratio of 14# cable is obtained under the action of 1# seismic wave. The 1#, 2#, 14#, 25# and 26# stay cables are selected as the horizontal bridge seismic vulnerability analysis stay cables.

In summary, the specific vulnerable stay cables and the vulnerable main tower section are shown in Figure 8~Figure 9. Analysis object : L1 cable, L2 cable, L14 cable, L25 cable and L26 cable on the left cable plane in the forward direction of the bridge are selected for the transverse seismic vulnerability cable, and R1 cable, R12 cable and R26 cable on the right cable plane are selected for the longitudinal seismic vulnerability cable; The cross section of the seismic vulnerable main tower is α section and β section, and the cross section of the seismic vulnerable main tower is γ section, δ section and η section.



Vulnerable cable in longitudinal earthquake *Vulnerable cable in transverse earthquake*

Fig. 8 – Summary map of vulnerable stay cables

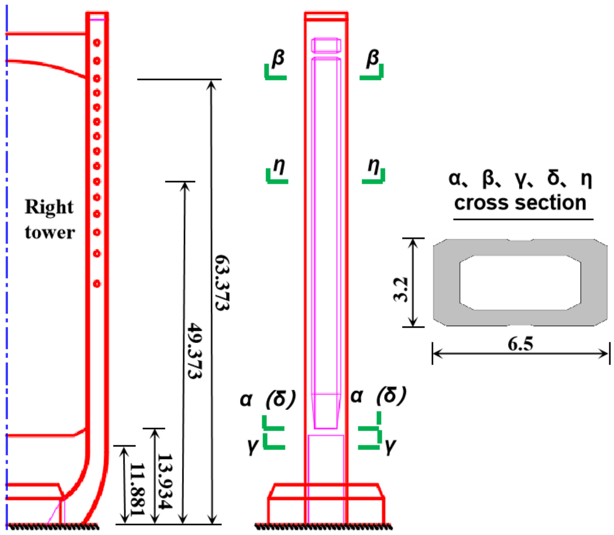


Fig. 9 – Summary of vulnerable section of main tower（m）

Vulnerability analysis of rotation

Vulnerability analysis of the main tower

The calculation of bending moment-curvature curve is to obtain the curvature of compression-bending members under different loads, and then establish the corresponding relationship between the curvature change and the ultimate strain of non-confined concrete, confined concrete and longitudinal reinforcement. Combined with the above damage calibration, the sectional curvature corresponding to each damage level can be calculated to classify the damage level. The section curvature of the main tower section is shown in Table 3 under the seismic action of the longitudinal bridge direction and the transverse bridge direction.

Tab. 3: Calibration table of damage limits of main tower section

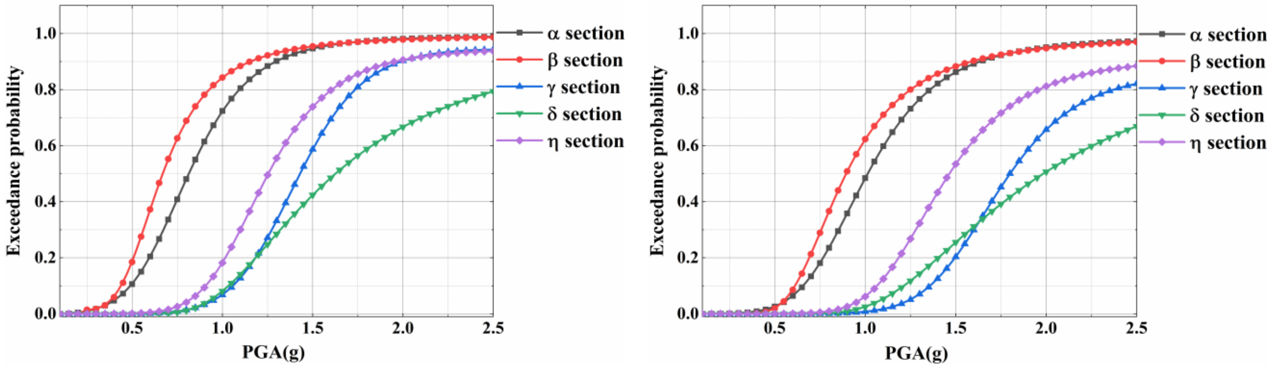
Seismic direction	Vulnerable section	Damage grade (1/m)			
		Slight damage	Moderate damage	Severe damage	Complete damage
Transverse direction	α	9.912E-4	1.249E-3	6.943E-3	8.186E-3
	β	8.705E-4	1.169E-3	9.937E-3	12.000E-3
Longitudinal direction	γ	4.248E-4	5.380E-4	6.027E-3	11.21E-3
	δ	4.840E-4	5.936E-4	3.780E-3	4.094E-3
	η	4.554E-4	5.671E-4	4.397E-3	5.013E-3

Figure 10 shows the comparison of the fragility curves of the main tower section of the rotating cable-stayed bridge during the rotating phase.

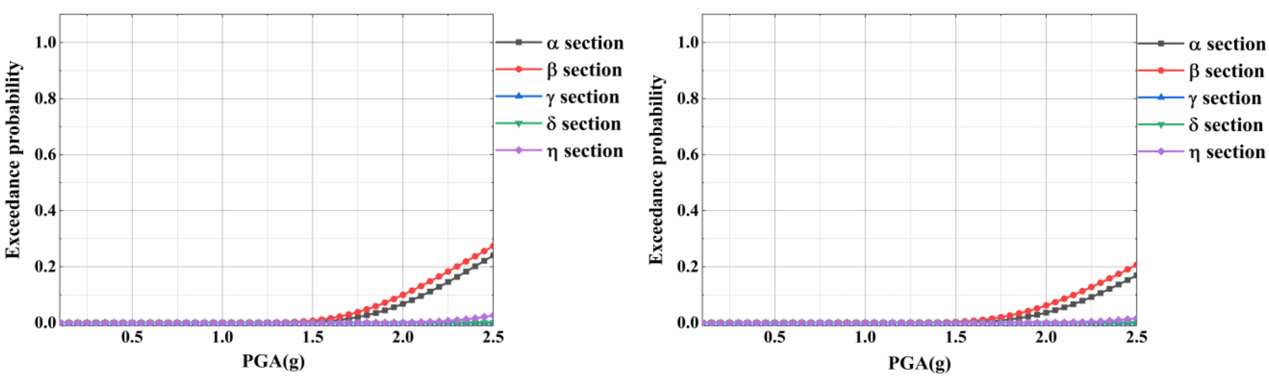
（1） It can be seen from Figure 10 that under the same of the same seismic level, the damage exceeding probabilities at all levels of the vulnerable section of the cable-stayed bridge in the swivel stage under the action of earthquake are greater than those under the action of the longitudinal earthquake; It can also be found that the damage probabilities of β section at all levels are greater than those of α section under cross-bridge seismic action, within the range of PGA less than 2.5 g, both of them can certainly exceed slight damage, and the possibility of exceeding moderate damage is great, both of them have a small possibility of exceeding severe and complete damage states; It can also be found that the analysis section is more likely to exceed slight damage and medium damage under longitudinal and bridge seismic action, but there is almost no possibility of exceeding serious and complete damage. The exceeding probability of damage at all levels of η section is greater than that of the other two sections during the continuous increase of seismic intensity, and only the probability of exceeding slight damage of PGA in the range of 2.0g~2.5g is slightly less than that of γ section.

（2） According to the slope of the curve in the graph, in the analysis of minor damage and moderate damage, the slope of δ section is small, which indicates that the probability of cross-section damage increases slowly. The slopes of the other four sections are basically the same, and the probability of cross-section damage increases faster; The probability growth rates of α-section and β-section are roughly the same and relatively slow when they exceed severe and complete damage; The η section is less likely to exceed serious damage. In the severe and complete damage analysis of the γ section and the δ section, the slope of the curve indicates that the probability growth rate is the slowest, and the ultimate probability of exceeding is very low, so the two sections almost do not suffer from serious and complete damage.

On the whole, the most vulnerable section of the main tower in the rotation stage is the β section under the cross-bridge seismic action.



(a) Slight damage *(b) Moderate damage*



(c) Severe damage　　*(d) Complete damage*

Fig. 10 – Comparison of section vulnerability curves of main tower in rotation stage

Vulnerability analysis of stay cables

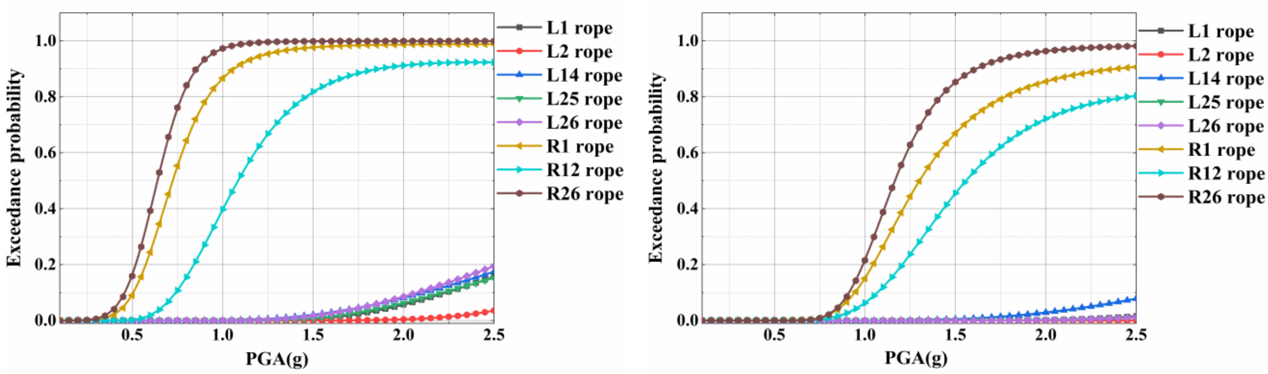
Vulnerability curves of stay cables in swivel stage of swivel cable-stayed bridge are shown in Figure 11.

（1） It can be seen from Figure 11 that the probability of the target stay cable exceeding the damage at all levels under the action of transverse bridge is smaller than that under the action of seismic longitudinal bridge. Under longitudinal bridge seismic action, except that the exceedance probability of R12 cable is slightly larger than that of R1 cable in complete damage analysis, the exceedance probability of other three-level damage is in the order of R26 cable > R1 cable > R12 cable, indicating that the damage probability of long cable at all levels under longitudinal bridge seismic action is large. Under the action of cross-bridge earthquake, the probability of each stay cable exceeding slight damage is large, followed by the probability of exceeding moderate damage, and the damage in turn to almost no exceeding complete damage.

（2） By analyzing the slope of cable vulnerability curve in longitudinal bridge direction, it can be seen that the slope of R26 cable is larger in all levels of damage. The slope of R1 cable and R12 cable vulnerability curve is slightly different in slight damage, and the slope of other levels of damage is roughly the same. It shows that the growth rate of exceedance probability of R26 cable at all levels of damage is the fastest, and the other two cables are followed. It can be seen that in the turning stage of the construction process of the rotating cable-stayed bridge, the stay cable also has the possibility to exceed the damage at all levels, which cannot be ignored.

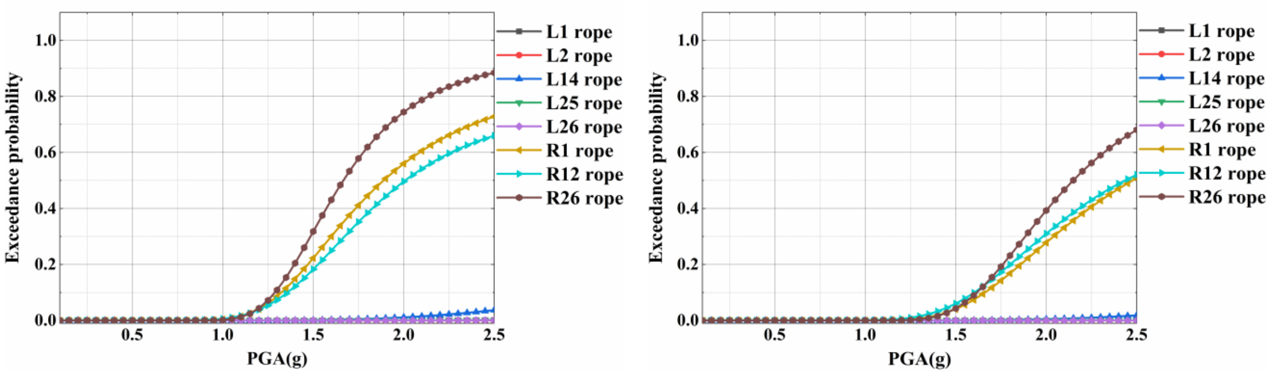
（3） It can be seen from the analysis of the distribution of cable vulnerability curve in the cross-bridge direction in the figure that the probability of L14 cable exceeding slight damage is slightly smaller than that of L26 cable, and the probability of damage at all levels is the maximum at all levels of seismic level. The analysis shows that the short cable near the main tower in the rotation stage is most likely to be damaged under the cross-bridge seismic action.

Overall, the most vulnerable cable in the rotation stage is R26 cable under longitudinal earthquake.



(a) Slight damage

(b) Moderate damage



(c) Severe damage

(d) Complete damage

Fig. 11 – Comparison of section vulnerability curves of main tower in rotation stage

System vulnerability analysis of rotary cable-stayed bridge

The seismic vulnerability analysis of swivel cable-stayed bridge includes two types of components: main tower and stay cable. The vulnerability curve of cable-stayed bridge system in rotation stage is calculated by Equation (11), as shown in Figures 12–15.

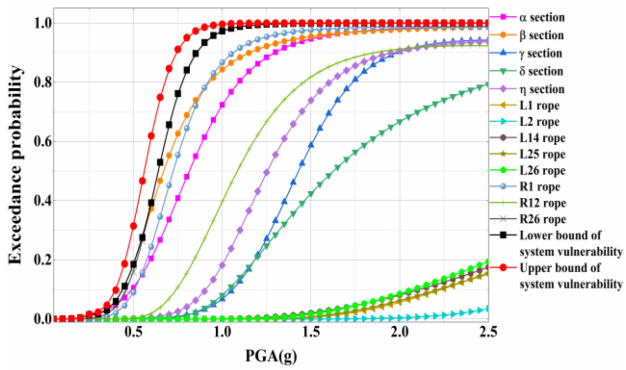


Fig. 12 – Limits of slight damage

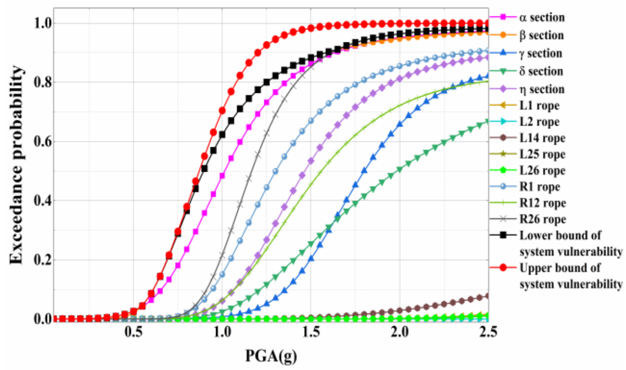


Fig. 13 – Limits of moderate damage

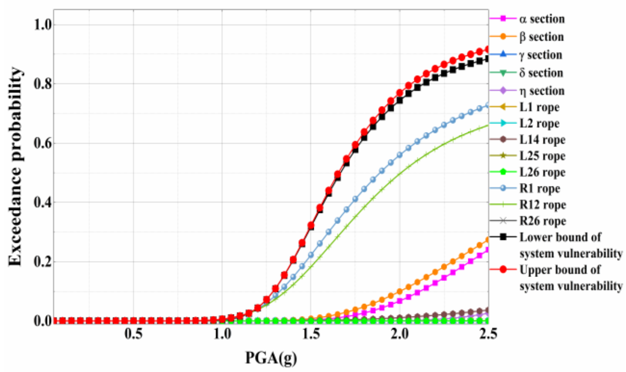


Fig. 14 – Limits of Severe damage

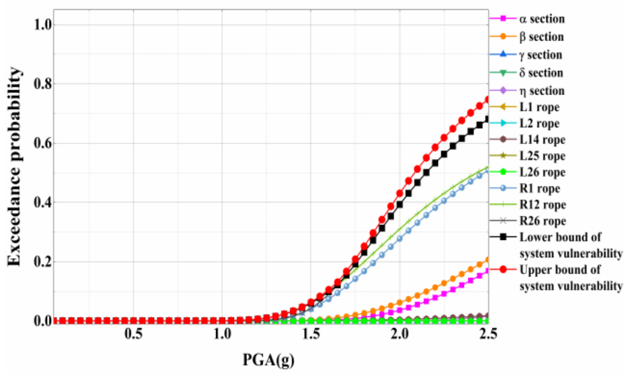


Fig. 15 – Limits of Complete damage

（1）It can be seen from Figs. 12–15 that the upper and lower bounds of the damage probability in the system vulnerability are greater than the damage exceeding probability at all levels of a single component. According to the slope of vulnerability curve, the upper bound probability growth rate of system damage at all levels is the largest.

（2）When the PGA reaches 0.95 g, the exceedance probability of the upper bound of the system slight damage reaches 99.22 %, and the lower bound reaches 99.19 % when the PGA reaches 1.15 g. It is considered that the slight damage must occur at this time. Compared with the vulnerability of the analysis unit in the system, the PGA required earthquake is reduced by at least 0.2 g. When PGA reaches 1.65 g, the upper bound exceeding probability of moderate damage in the system reaches 99.21 %, and the lower bound reaches 97.21 % when PGA reaches 2.15 g. The increase of the lower bound exceeding probability is very low. It is considered that moderate damage must occur at this time. Compared with the vulnerability of the analysis unit in the system, the PGA required for the earthquake is at least 0.35 g. When the PGA reaches 2.5 g, the upper bound exceeding probability of the system serious damage reaches 91.64 %, and the lower bound exceeding probability reaches 88.48 %. It is considered that the possibility of serious damage in the system is very large, and the exceeding probability is increased by 3.16 % compared with the maximum probability of the analysis unit in the system. When PGA reaches 2.5 g, the exceedance probability of the upper bound of the complete damage of the system reaches 74.71 %, and the exceedance probability of the lower bound reaches 68.11 %. It is considered that the possibility of the complete damage of the system is large at this time. Compared with the maximum probability of the analysis unit in the system, the exceedance probability increases by 6.60 % at most.

CONCLUSION

（1）In the rotation stage of cable-stayed bridge, under the action of earthquake, the vulnerable part of the main tower is the section mutation of the main tower near the upper and lower beams, and the vulnerable cable is the long cable at the end of the beam and the short cable near the main tower.

（2）Based on the incremental dynamic analysis method, the seismic fragility curve of vulnerable main tower section is established. When the vulnerable section of the cable-stayed bridge at the turning stage is under the same seismic level, the probability of damage at all levels when the transverse bridge is applied to the earthquake is greater than that of the longitudinal vulnerable section; When PGA does not change within 2.5 g, under the action of cross-bridge earthquake, the probability level of the vulnerable section of the main tower exceeding slight and medium damage is large, and there is little possibility of serious and complete damage; Under the action of the longitudinal bridge earthquake, the vulnerable section of the main tower has a greater probability of exceeding minor and moderate damage, but severe and complete damage will hardly occur; The most vulnerable section of the main tower in the rotation stage is the section near the cross beam of the main tower under the transverse earthquake.

（3）Based on the incremental dynamic analysis method, the seismic vulnerability curve of vulnerable cable is established. The probability that the vulnerable stay cables exceed the damage at all levels in the transverse direction of earthquake is smaller than that in the longitudinal direction of earthquake. The damage probability of cables at all levels under longitudinal bridge earthquake is large. Under the action of cross-bridge earthquake, the probability of each stay cable exceeding slight damage and medium damage is large, and the probability of serious and complete damage is very low, and the possibility of short cable damage near the main tower in the rotation stage is the largest. Therefore, the cable has a high possibility of damage in the construction process, which cannot be ignored. The most vulnerable cable stayed in the rotation phase is the R26 cable under the action of the longitudinal bridge earthquake.

（4）According to the vulnerability curve of the cable-stayed bridge system in the rotation stage, the upper and lower bounds of the damage probability are greater than the damage exceeding probability at all levels of a single component unit, and the growth rate of the upper bound probability of the damage at all levels of the system is the fastest. Under the same damage probability, the required ground motion intensity of the system can be reduced by up to 0.35 g compared with the component. Under the same seismic intensity, the system damage probability is 6.60 % higher than the component damage probability at most. When the PGA does not change within 2.5 g, slight and moderate damage of the system must occur, and the possibility of serious damage and complete damage is large.

To sum up, the seismic vulnerability of the cable-stayed bridge in the rotation stage should not be underestimated. This article has reference significance for the construction of the rotation cable-stayed bridge in areas lacking ground motion records.

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