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Summary of Research Status on Seismic Performance of Multi-tower Cable-stayed Bridge

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Author's contribution

The sole author designed, analyzed, interpreted and prepared the manuscript.

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ABSTRACT

As one of the important forms of modern bridge structure, the research on the seismic performance of multi-tower cable-stayed bridge is of great significance to the safety and durability of bridge engineering. In this paper, the research status of seismic performance of multi-tower cable-stayed bridges is reviewed from three aspects: experimental research, numerical analysis and theoretical research. The methods of improving seismic performance through structural optimization and the technical means of improving seismic performance through constraint system are discussed. The purpose of this paper is to summarize the existing research results, identify the existing problems, and propose that future research should focus on the application of new damping equipment and the discussion of hybrid control system, so as to provide reference for the seismic design of multi-tower cable-stayed bridge.

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1. INTRODUCTION

Multi-tower cable-stayed bridge is widely used in modern long-span bridge engineering because of its excellent spanning ability and structural stability. However, the destructive effect of earthquake on bridge structure makes it particularly important to study its seismic performance. In recent years, scholars at home and abroad have done a lot of research on the seismic performance of multi-tower cable-stayed bridges and achieved rich results. This paper will summarize the existing research results from three aspects: experimental research, numerical analysis and theoretical research, and discuss the methods of improving the seismic performance of multi-tower cable-stayed bridges through structural optimization and constraint system.

2. STUDY ON SEISMIC PERFORMANCE OF MULTI-TOWER CABLE-STAYED BRIDGE

2.1 Present Situation of Experimental Research

At present, the research on the seismic performance of multi-tower cable-stayed bridges includes experimental research, numerical analysis, and theoretical research. Some scholars often combine numerical and experimental methods, numerical and theoretical methods. Experimental research is an important means to verify and supplement theoretical analysis and numerical simulation. Through shaking table test and model test, the actual response data of multi-tower cable-stayed bridge under earthquake action can be obtained. Existing research shows that the vibration modes of multi-tower cable-stayed bridges are complex, and the coupling between different towers has a significant impact on the seismic response of the overall structure. In addition, the experimental study also involves the performance test of the damping device. For example, shaking table tests using viscous dampers, friction dampers and other damping devices can evaluate their damping effects under actual earthquakes. These experimental results provide an important basis for the optimal design and practical application of the damping device.

(Zhou Lianxu et al. 2019) used the shaking table test method to study the damping effect of the transverse damping system of the long-span cable-stayed bridge under the action of near and far field earthquakes. Taking Sutong Bridge as the background, a full-bridge test model of cable-stayed bridge with 1 / 35 geometric similarity ratio was designed, and the shaking table tests of transverse damping system and traditional transverse fixed system were carried out respectively. Among them, the steel damper and the sliding ball steel bearing are arranged in parallel at the pier, and the steel damper is arranged at the bridge tower to form a lateral damping system. Based on the test results, the damping behavior of the damping system is analyzed. The results show that under the action of near-field and far-field earthquakes, the damping system can significantly reduce the seismic force transmitted from the main beam to the pier and the bridge tower. The lateral force transmission of the pier-beam and tower-beam connection is reduced by more than 50 %, and the displacement of the main beam is limited to an acceptable range. The damping system also significantly reduces the displacement, curvature of the tower body and the curvature demand of the pier bottom. Among them, the curvature of the tower bottom section is reduced by 34 % on average, and the curvature of the pier bottom of the auxiliary pier near the tower is reduced by 67 % on average. The steel damper has a full hysteresis curve, but its hysteresis characteristics are related to the seismic input. Compared with the friction energy dissipation of the bearing, the energy dissipation capacity of the steel damper is more significant. Under the action of near-field earthquake with velocity pulse, the displacement response of steel damper and bearing has obvious pulse characteristics.

Based on the engineering background of a three-tower composite girder cable-stayed bridge with a main span of 616 m, (Zhang Chao et al. 2013) made a dynamic scale model and carried out three array shaking table tests. On the basis of one-way uniform excitation shaking table test, multi-dimensional excitation and multi-point excitation shaking table test are carried out, and the results are compared with the numerical analysis results. The test results show that the basic vibration mode of this structure is the coupling vibration of the longitudinal bending of the middle tower and the vertical bending of the main beam. Under the action of longitudinal consistent earthquake, the main tower and the main beam will have larger seismic response.

Under the transverse uniform seismic excitation, the seismic response of the middle tower is more unfavorable than that of the side tower. The shaking table test under multi-point excitation shows that the traveling wave effect increases the seismic response of each component to varying degrees. Finally, the accuracy of the direction combination calculation method in the specification is verified by the test results under multi-dimensional seismic excitation.

Taking Wuhan Erqi Yangtze River Bridge as the engineering background, (Fang Zhenzheng et al. 2012) designed a shaking table test model and carried out three array shaking table tests to explore the seismic response law of three-tower long-span composite girder cable-stayed bridge under uniform excitation and multi-point excitation. The analysis of dynamic characteristics shows that the first-order longitudinal bending vibration of the middle tower occurs earlier than the first-order longitudinal bending vibration of the side tower. The results of multi-point excitation test show that the influence of traveling wave effect on seismic response can not be ignored.

(Pang Yutao et al.) established a 1 / 20 scale three-dimensional model of a 22.5 m cable-stayed bridge in China by using the shaking table equipment of Tongji University and carried out dynamic tests. The cable-stayed bridge includes three towers and one side pier. The results of the comprehensive shaking table test carried out on the cable-stayed bridge have been used to derive the fragility curves according to the system approach.

2.2 Numerical Analysis and Theoretical Research Status

Numerical analysis is an important method to study the seismic performance of multi-tower cable-stayed bridges. By establishing a finite element model to simulate the dynamic response of the bridge structure under seismic action, detailed stress, displacement and vibration modal information can be obtained. The existing research mainly adopts two methods: time history analysis and response spectrum analysis. The time history analysis method can simulate the dynamic response of the bridge structure under the actual ground motion input, and has high accuracy. The response spectrum analysis method is suitable for the preliminary design stage, and the seismic performance of the structure is evaluated by calculating the response of the structure under different frequency ground motions.

Theoretical research mainly includes seismic design theory and seismic analysis method. Performance-based seismic design (PBSD) is a new seismic design concept developed in recent years. By setting performance objectives under different seismic intensities, it ensures that the structure has sufficient safety and functionality under earthquake action. The application of PBSD theory can significantly improve the seismic performance of multi-tower cable-stayed bridges. In addition, the development of ground motion input simulation technology also provides a new means for the seismic research of multi-tower cable-stayed bridges. The progress of these theoretical studies provides a solid theoretical basis for the seismic design of multi-tower cable-stayed bridges.

Based on theoretical calculation and numerical analysis, (Zhu et al. 2011) used power spectral density function to simulate bridge deck roughness. In this paper, the single-degree-of-freedom spring-mass system is used to simulate the vehicle vibration model. The cable-stayed bridge structure is idealized as the elastic support at the anchor point, and the motion equation is established to analyze the dynamic analysis of the Yellow River Shengli Bridge. The analysis shows that the dynamic response of the bridge is sensitive to factors such as vehicle speed and static weight.

Based on the engineering background of Chishi Bridge, (Su Xiaoyang, Kang Houjun et al. 2017) studied the simulation effect of four-tower cable-stayed bridge model established by different cable elements based on Ansys finite element software. It is found that the Link1 (Link1 element can simulate truss, chain rod and spring. The degree of freedom of each node of the two-dimensional bar element only considers the linear displacement in x and y directions, and it is an element that can withstand uniaxial tension and compression.) element simulation can accurately simulate the overall stiffness of the cable-stayed bridge, but the local vibration data of the cable cannot be obtained. The overall stiffness error of the bridge model simulated by the Beam3 element to simulate the cable element can decrease with the increase of the modal order, and the local vibration related data of the cable can be obtained to a certain extent.

(Wu Fangwen et al. 2010) focused on the dynamic characteristics and response of the traveling wave effect on the super-long-span cable-stayed bridge, and compared it with the uniform excitation. The results show that for the super-long-span cable-stayed bridge, the traveling wave effect has a more significant effect on the internal force of the cable-stayed bridge structure.

Taking Jiashao Bridge as the engineering background, (Geng Fangfang and Ding Youliang et al. 2014) analyzed the seismic influence of longitudinal restraint system and full floating system on six-tower cable-stayed bridge. The results show that only the fully floating system has a longitudinal floating mode, and the stronger the longitudinal constraint of the tower beam, the higher the vertical bending mode frequency of the main beam. The longitudinal restraint system of tower beam has little effect on the torsional vibration mode of the main beam and the lateral bending vibration mode of the main tower.

(Ye Aijun, Hu Shide et al. 2002) analyzed and compared a variety of seismic systems, and found that the elastic restraint system of the tower beam can improve the strength and deformation ability of the bridge for the long-span cable-stayed bridge. The elastic stiffness of the constraint system should be selected according to different engineering practices.

(Lou 2015) studied the influence of different parameters of linear viscous damper on the seismic performance of long-span cable-stayed bridge. The results show that after setting the longitudinal viscous damper of the bridge, the relative displacement of the key parts of the structure under earthquake can be effectively reduced by adjusting the parameters of the viscous damper, and the longitudinal displacement of the long-span cable-stayed bridge can be effectively controlled.

Based on the spectral solution method to simulate the fluctuating wind field, (You Xinpeng and Peng Chengming et al. 2011) carried out the time domain analysis of buffeting considering geometric nonlinearity, and studied the seismic performance of Jiashao Bridge under different wind attack angles and wind speeds. It is found that the wind speed has little effect on the vertical buffeting displacement of the main beam during construction, and has a great influence on the lateral and torsional vibration displacement and buffeting internal force.

(Li Zhongxian et al. 2006) numerically simulated the seismic response of long-span cable-stayed bridges by using deterministic seismic wave uniform excitation, traveling wave excitation and random seismic wave multi-point excitation. The results show that the spatial effect is considered.

3. SEISMIC PERFORMANCE OF CABLE-STAYED BRIDGES WITH DIFFERENT SYSTEMS UNDER EARTHQUAKE

The overall seismic performance of cable-stayed bridges is usually evaluated from two aspects: internal force and displacement. Under the action of earthquake, the goal of seismic design is to reduce the internal force and displacement of cable-stayed bridge as much as possible. However, these two aspects are often contradictory. To reduce the internal force response, it is usually necessary to bear a large displacement, and vice versa. Cable-stayed bridges with different structural systems have different stiffness due to different combinations of beams, towers and cables, so the displacement performance of the bridge is also different.

According to the different connection modes of tower beam, it is divided into full floating system (tower beam separation), semi floating system (tower beam sliding) and tower beam pier consolidation system. The seismic performance of cable-stayed bridges with different systems is also different. In the fully floating system, the main girder and the bridge tower are relatively free in the bridge. This kind of system makes the overall displacement response under earthquake action very large, but the internal force response such as bending moment and axial force of bridge towers and other components is small. However, the fully consolidated system of tower-beam-pier is completely opposite. The main girder and the bridge tower are completely consolidated, resulting in the disappearance of the longitudinal drift mode of the main girder. This makes the overall displacement response under the action of earthquake is small, but the internal force response of bridge tower and other components is very large. Due to the vertical support at the tower beam, the semi-floating system will produce a large negative bending moment at the tower and the main beam. In addition, the setting of auxiliary piers will also have an impact on the seismic resistance of multi-tower cable-stayed bridges. The setting of auxiliary piers can improve the stiffness of multi-tower cable-stayed bridge system. However, under the action of earthquake, with the increase of the number of auxiliary piers, the displacement of the main beam of the auxiliary pier span decreases obviously, while the displacement of other beam sections increases slightly. At the same time, the relative displacement of the pier beam junction remains basically unchanged. This shows that the effect of adding auxiliary piers on improving the seismic performance of multi-tower cable-stayed bridges is not significant. On the contrary, the increase in the number of auxiliary piers may enhance the seismic response of the main girder in all directions, thus weakening its overall seismic performance.

4. RESEARCH STATUS OF SEISMIC CONTROL OF MULTI-TOWER CABLE-STAYED BRIDGE

At present, the bridge damping control methods mainly include four categories: passive control, active control, semi-active control and hybrid control. Among them, passive control has been widely used in practical engineering practice due to its outstanding damping effect, durability, safety and economy. Commonly used seismic isolation devices include elastic restraint devices and damping energy dissipation devices. The elastic restraint device has elastic cable, rubber bearing and other isolation bearings. The rubber bearing is divided into plate rubber bearing and lead rubber bearing. The elastic restraint device mainly changes the stiffness of the structure, and some devices can also increase the structural damping to achieve the purpose of shock absorption, and its elastic stiffness is the main influencing factor. Under the action of earthquake, the internal force and deformation of the structure can be controlled to a large extent by reasonable parameter design. On the contrary, if the elastic stiffness is not properly selected, it may be detrimental to the seismic resistance of the structure. For the floating system without constraint between tower and beam, the stiffness is small and the displacement is large. For the system with elastic constraint between tower and beam, the overall stiffness of the system increases with the increase of elastic constraint stiffness, the period will decrease, and the displacement of the bridge will also decrease. However, the horizontal inertia force of the bridge deck system increases with the increase of elastic constraint stiffness, so that the inertia force transmitted to the tower column also increases. Therefore, the stress of the tower bottom section will increase, and the damping energy dissipation device has viscous damper, friction damper and metal damper. The improvement of seismic performance of multi-tower cable-stayed bridge is mainly achieved by installing damping devices on the bridge. Among them, the viscous damper is a more commonly used damping device for this bridge type. Viscous dampers reduce the seismic response by providing additional ability to dissipate seismic input energy to the structure. The damping force mainly depends on the speed and plays a role in energy dissipation and shock absorption under earthquake action. Therefore, viscous dampers are often used as longitudinal restraint devices in multi-tower cable-stayed bridges, which improve the seismic performance of the structure and have obvious energy dissipation and shock absorption effects. And the full floating system using viscous damper damping effect is better; viscous dampers used in the partially consolidated system can more effectively control the internal force and node displacement of the section, so as to achieve the damping effect; however, when the viscous damper is used to reduce the vibration, the relative displacement of the pier beam will be amplified in the actual project, and its distribution position should be reasonably controlled. In this kind of damping method, the reasonable installation of damping and energy dissipation devices at the connection between the main beam and the bridge tower of the cable-stayed bridge and the top of the pier can not only ensure that the cable-stayed bridge dissipates the seismic energy through these devices under the action of earthquake, but also change the dynamic characteristics of the structure to reduce the seismic response of the structure.

5. CONCLUSION

This paper reviews the seismic performance of multi-tower cable-stayed bridges, covering experimental, numerical, and theoretical studies. Experimental research indicates that the use of damping devices such as viscous dampers and friction dampers can significantly reduce the seismic response of the structure, thereby enhancing the seismic resilience of the bridge. Numerical simulations, including time-history analysis and response spectrum analysis, have accurately predicted the dynamic behavior of multi-tower cable-stayed bridges under different seismic loads, providing important references for structural design.From a theoretical perspective, advancements in performance-based seismic design (PBSD) theory and earthquake wave input simulation techniques have deepened our understanding and application of seismic resilience for multi-tower cable-stayed bridges. Structural optimization, particularly improvements in damping and constraint systems, can effectively enhance the seismic performance of bridges.

In summary, significant progress has been made in improving the seismic performance of multi-tower cable-stayed bridges. However, further research is needed to innovate damping technologies and optimize seismic control strategies. Future studies should focus on the application of new damping devices, the exploration of hybrid control systems, and enhancing the accuracy and practical applicability of seismic design models.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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