Earthquake-induced Collapse Simulation of a Super Long Span Cable-Stayed Bridge Based on an Open Source FE Program

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Abstract

Currently, the seismic performance assessments of long span bridges are generally conducted using commercial finite element (FE) software packages, which to some extent limit the in-depth investigation of associated topics. A numerical model system is proposed to simulate a super long span cable-stayed bridge with a maximum span of 1500 m based on an open source FE software package (i.e., OpenSees). The seismic performance of this bridge is investigated. The simulation results of OpenSees and the commercial software MSC.Marc are compared with a good agreement. Furthermore, a collapse simulation of the bridge is also successfully performed and the corresponding collapse mechanism is revealed. The research outcome could provide a reference for further studies on the seismic performance of super long span cable-stayed bridges based on open source FE programs.

Keywords: super long span cable-stayed bridge; seismic performance; collapse simulation; OpenSees; multi-layered shell element

1 Introduction

The recent rapid development of transportation networks has promoted the construction demand of long span bridges. This makes investigations on the seismic performance of long span bridges a critical issue in civil engineering. Numerous investigations have indicated that the FE method has gradually become an effective method to investigate the seismic performance of large-scale complicated structures due to the limitation of experimental facilities for such structures [1-6]; however, most seismic analyses of large span bridges were conducted using commercial FE software packages [3-6], which to some extent restrict the further investigation of this research field.

OpenSees (Open System for Earthquake Engineering Simulation), as an open source FE program, has become one of the most influential platforms for earthquake engineering research. In comparison with conventional commercial FE software packages, there are two notable advantages for using OpenSees. First, the source code of OpenSees is available for free, which enables further research and discussion on its internal mechanisms and functionalities. Second, researchers worldwide are permitted and encouraged to share their latest research outcomes using this software, thus facilitating the reuse of previous achievements and further in-depth research.

Despite the abovementioned advantages, OpenSees is mostly used to investigate the seismic performances of small or mid span bridges [7-9]. Research on the seismic performance of large span bridges using OpenSees has rarely been reported. The primary reason for the lack of such work is that OpenSees lacks an appropriate and versatile model for bridge towers, piers and decks, which are the most important components in large span bridges. The existing fiber model is incapable of simulating complex mechanical behaviours of such components, and the solid elements may lead to an unacceptable calculation workload. In addition, as the span of a bridge increases, the numerical model of the bridge will become large-scale and complicated, but OpenSees has rarely been used to investigate the seismic performance of large-scale and complicated bridges.

An important achievement in the numerical simulation of large-scale structures using OpenSees was recently accomplished by Lu et al. [2]. Specifically, a multi-layered shell element and associated material constitutive models were proposed and implemented in OpenSees. Furthermore, the analysis method, including modelling techniques, solution algorithms and memory management of OpenSees to perform seismic analyses of complicated large-scale super-tall buildings, was investigated. The rationality and reliability of this new element and analysis method were comprehensively validated. Despite this effort, this shell element has only been used for super-tall buildings. For structures such as long span bridges, the modelling techniques and the structural behaviours differ substantially from tall buildings. Furthermore, some essential issues, such as travelling wave effects, should be taken into account. Although the multi-layered shell element has the capacity to conveniently replicate the complex mechanical behaviour of towers, piers and decks, the validation for the rationality and reliability of such an element in simulating large span bridges is still required.

Based on the above requirements, the FE model of a cable-stayed bridge design scheme for the Qiongzhou Strait Bridge is established, and the correspondingly nonlinear seismic performance is investigated. Note that the commercial FE codes of MSC.Marc have been widely used in nonlinear analyses of large-scale complicated structures and well validated in terms of rationality and accuracy [1, 10]. Hence, the reliability of the simulation results of OpenSees is validated through comparison with those of MSC.Marc.

As part of lifeline engineering, the collapse of bridges, especially large-span bridges, may lead to severe casualties, immeasurably negative social impact and great economic loss. Hence, it is necessary to conduct collapse simulations of bridges induced by various hazards (e.g., earthquakes, explosions, windstorms [3-4, 11-13]). However, the research on the collapse simulation of bridges, especially large span bridges, using OpenSees has rarely been reported. In this study, by considering the flexural and shear failures of the shell element, the earthquake-induced collapse simulation of the abovementioned cable-stayed bridge is successfully performed.

Conclusively, this study proposed a numerical modelling method for the super long span cable-stayed bridge based on an open source FE program (i.e., OpenSees). Nonlinear dynamic analyses and particularly collapse simulations of a real-world engineering practice are successfully performed using the proposed method. The research outcomes could provide a reference for further research on the seismic performance of super long span bridges based on open source FE programs.

2 Qiongzhou Strait Bridge

Qiongzhou Strait lies between the Leizhou Peninsula in Guangdong, southern China, and Hainan Island. The length of Qiongzhou Strait is approximately 80 km from east to west and 30 km from south to north. The average water depth is 44 m, with a maximum value of approximately 120 m.

The bridge studied in this research is one of the proposed cable-stayed bridge design schemes for the Qiongzhou Strait Bridge. The length of the entire bridge is 4304 m, and the heights of the main and side towers are 460 m and 386 m above sea level. The channel clearance is 1270 m × 81 m. Figure 1 illustrates the general layout of the cable-stayed bridge design scheme.

3 Modeling details

The absence of a graphical user interface (GUI) in OpenSees makes it difficult to establish large-scale complicated models of super long span cable-stayed bridges. In consequence, Lu et al. developed a conversion program to convert the model from MSC.Marc to OpenSees [2]. This program is also adopted here to establish the FE model of OpenSees. The model of the cable-stayed bridge consists of five main parts: bridge towers/piers, decks, cables, anchorage region in the towers, and links between the girder and bridge towers/piers. A numerical model system, integrating multi-layered shell elements for decks/piers and truss elements for prestressed cables, is herein proposed to simulate this bridge. The conversion program is expanded to convert this model from MSC.Marc to OpenSees, and the corresponding conversion relationship is illustrated in Figure 2.

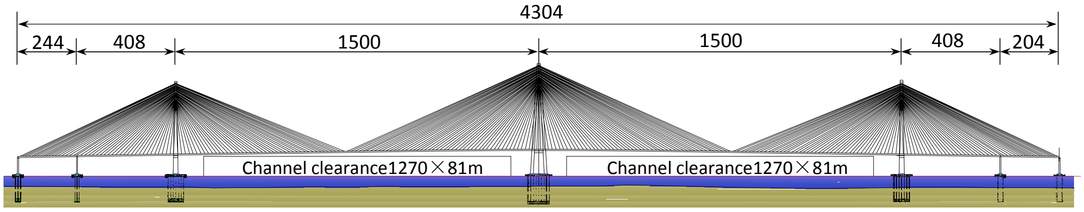


Figure 1. Overall layout of the cable-stayed bridge

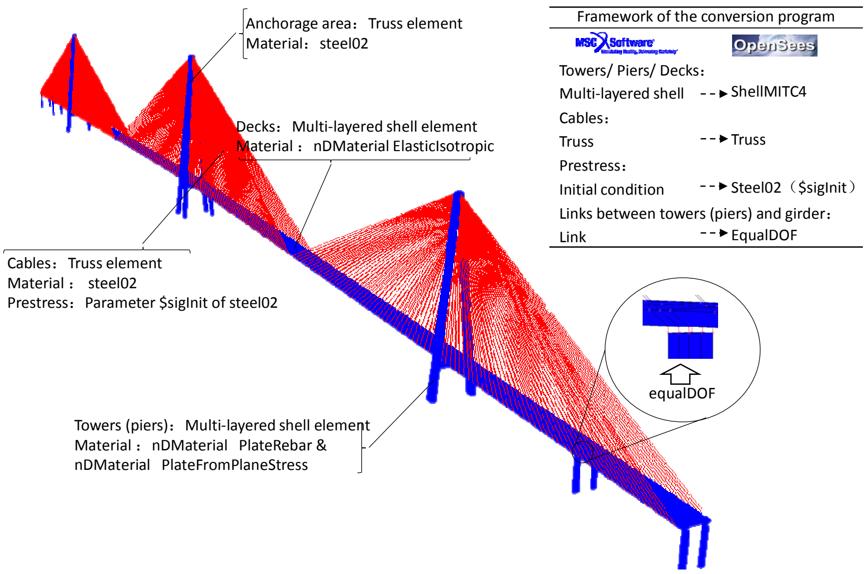


Figure 2. Finite element model in OpenSees

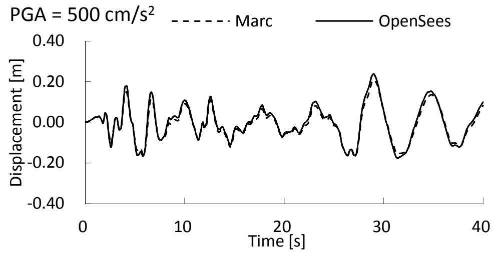
4 Elasto-plastic analysis of the Qiongzhou Strait Bridge

4.1 Selection of analysis domain

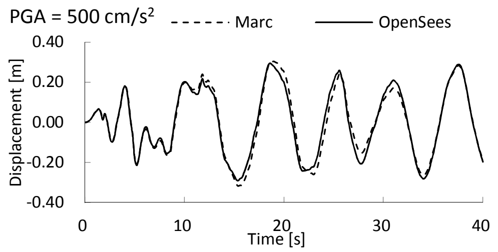
For the FE model of large-scale structures, the number of elements and nodes will be extremely large. The analysis domains recommended by Lu et al. are adopted here [2]. Through a series of analyses, the components of the analysis domain proposed by Lu et al. are also proven to be stable and efficient for super long span cable-stayed bridges.

4.2 Nonlinear dynamic analysis

The proposed design scheme of the Qiongzhou Strait Bridge considers the seismic design intensity of VII (peak ground acceleration (PGA) with a 2% probability of being exceeded in 50 years equals 500 cm/s^2) according to the Chinese Guidelines for Seismic Design of Highway Bridges [14]. The El-Centro ground motion, which is scaled to a PGA value of 500 cm/s^2, is used as the seismic input to the structure both in longitudinal and transverse directions. Note that the synchronous earthquake motions are considered here. The comparisons of the time-history curves, including the displacements of the top of the main tower and the middle of the girder, are illustrated in Figures 3 and 4.

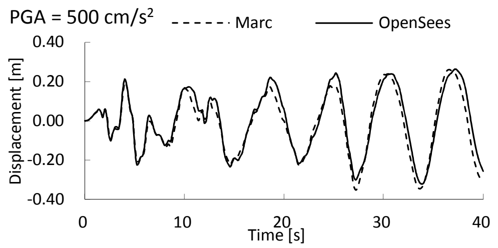


(a) Displacement at the top of the main tower

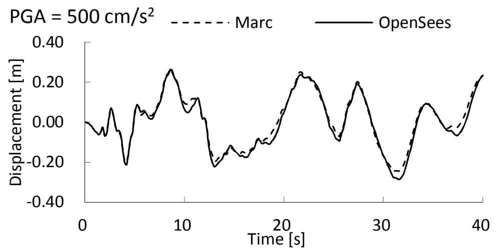


(b) Displacement in the middle of the girder

Figure 3. Time-history analysis results of El-Centro 1940 ground motion in the transverse direction (PGA = 500 cm/s^2).



(a) Displacement at the top of the main tower

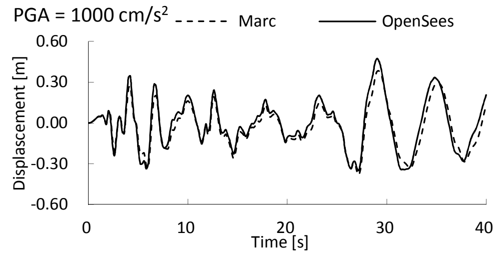


(b) Displacement in the middle of the girder

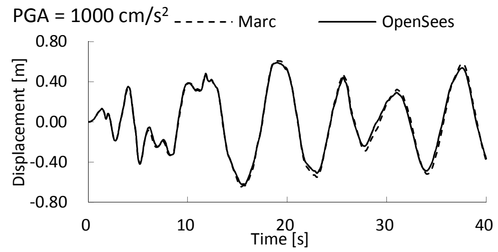
Figure 4. Time-history analysis results of El-Centro 1940 ground motion in the longitudinal direction (PGA = 500 cm/s^2)

The results indicate that the overall response of the entire bridge under two ground motions are basically identical, which validate the feasibility and reliability of seismic analyses of super long span cable-stayed bridges using OpenSees.

In addition, to investigate the response of critical structures under the ground motions beyond the seismic design intensity, the El-Centro ground motion, which is scaled to a PGA value of 1000 cm/s^2, is also adopted to conduct a dynamic analysis. The simulation results of OpenSees and MSC.Marc are compared in Figures 5 and 6, showing high consistency, which validates OpenSees as being capable of accurately investigating the seismic performance of super long span cable-stayed bridges, even under strong earthquakes.

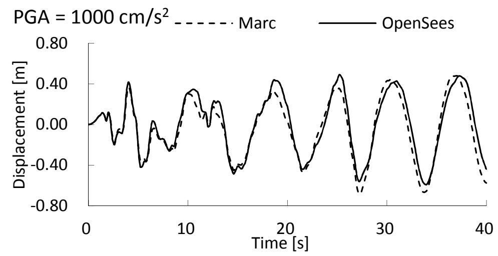


(a) Displacement at the top of the main tower

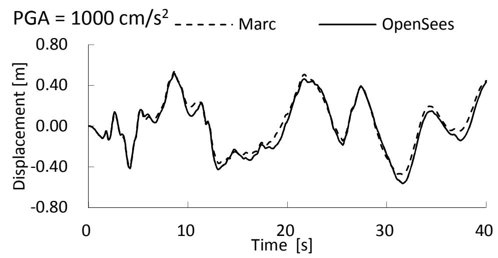


(b) Displacement in the middle of the girder

Figure 5. Time-history analysis results of El-Centro 1940 ground motion in the transverse direction (PGA = 1000 cm/s^2).



(a) Displacement at the top of the main tower

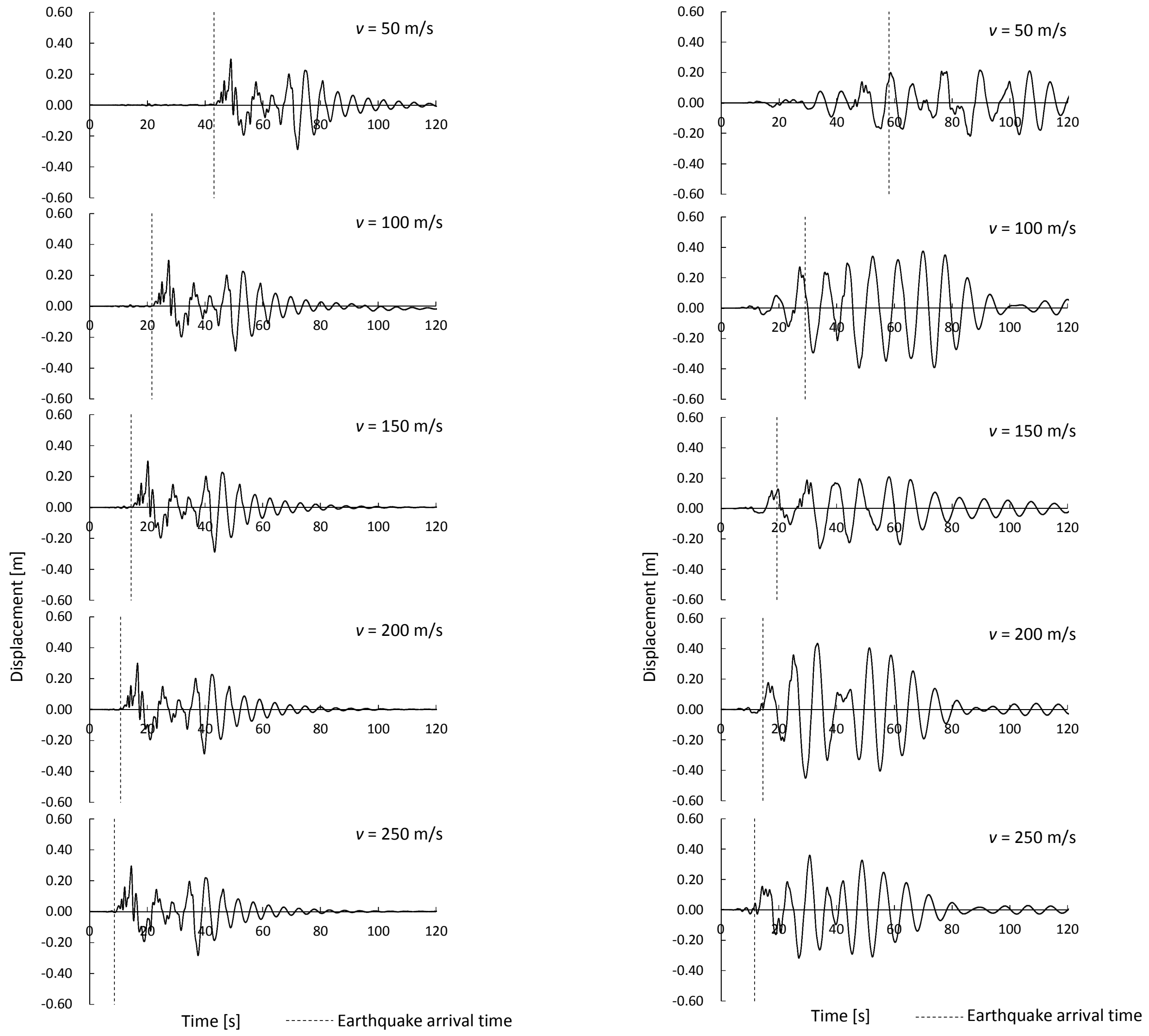


(b) Displacement in the middle of the girder

Figure 6. Time-history analysis results of El-Centro 1940 ground motion in the longitudinal direction (PGA = 1000 cm/s^2)

4.3 Asynchronous ground motion input

For large span structures, such as the Qiongzhou Strait Bridge, the travelling wave effect should be considered during seismic analyses [15-17]. The site condition mainly consists of medium-soft soil and soft soil, such as grit and sludge. According to the Chinese Code for seismic design of buildings [18], the wave velocity is considered between 50 m/s and 250 m/s. The El-Centro ground motion (PGA = 500 cm/s^2) in the transverse direction is also selected during the asynchronous ground motion analyses. The comparison of the time-history curves under different wave velocities, including the displacement of the top of the main tower and the middle of the girder, are presented in Figure 7.



(a) Displacement at the top of the main tower (b) Displacement in the middle of the girder

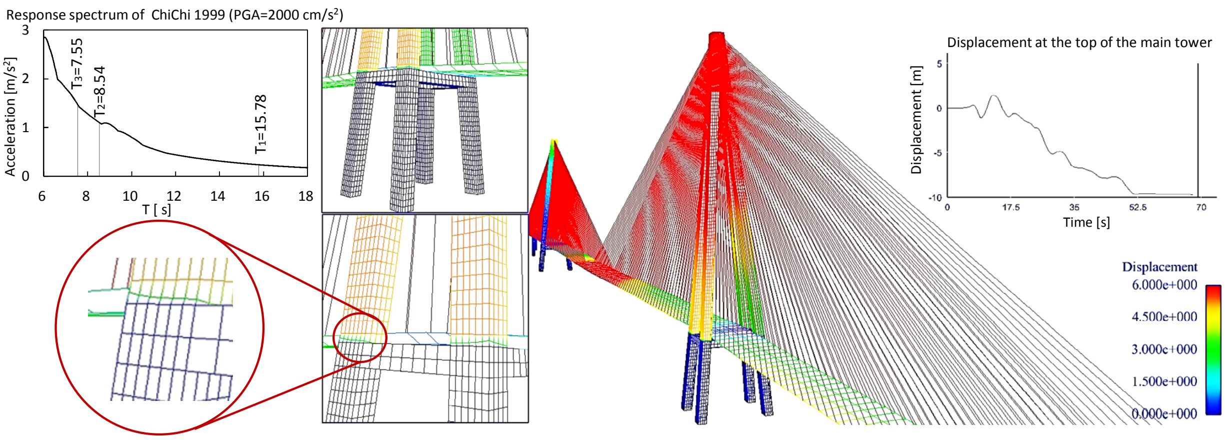
Figure 7. Time-history analysis results of asynchronous El-Centro 1940 (PGA = 500 cm/s^2)

The results indicate that the influence of the traveling wave effect on the displacement of bridge towers is negligible. In contrast, the response of the girder differs to a certain extent under different velocities. The maximum displacement of the girder reaches 0.44 m when *v* = 200 m/s, and the girder experiences a maximum displacement of 0.21 m when *v* = 150 m/s, which is less than half of the maximum displacement when v = 200 m/s.

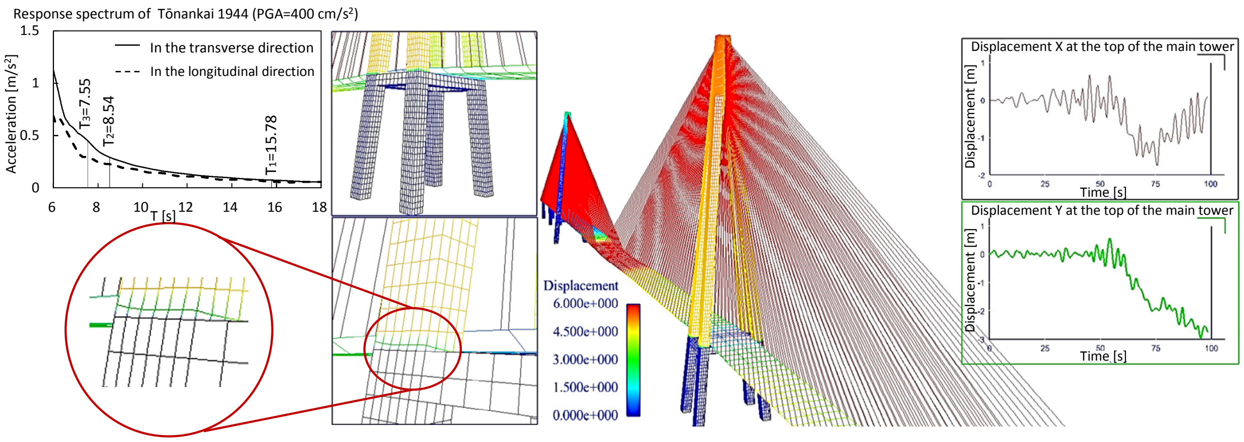
5 Seismic collapse simulation

To realize a collapse simulation, both the flexural and shear failure of the shell element are required to be considered in OpenSees. Those are achieved by assigning threshold values for the tensile, compressive and shear failure strains of the corresponding materials. The failure strains of concrete under compression and shear are both equal to 0.004, whereas the tensile fracture strain for rebar is 0.15 [19]. Because the fundamental period of this bridge is over 15 s, such long period structures will have a larger response under a long-period ground motion action. Hence, the ChiChi and Tonankai ground motions, which are two typical long-period ground motions, are adopted to conduct the collapse simulation. Note that the bi-directional earthquake excitation is considered in the case study of Tonankai ground motion input.

The ground motion is scaled up step by step and the bridge starts to collapse when the PGA reaches 2000 cm/s^2 and 400 cm/s^2 under ChiChi and Tonankai ground motions, respectively. The overall and detailed collapse processes are presented in Figure 8. The simulation results under both ground motions indicate that the most vulnerable parts of the bridge are the junction between the beams and columns of the bridge tower. Concrete crushes in these regions, leading to the collapse of the entire bridge. It can also be observed from the time-history curves that the top of the main tower lean to one direction under both ground motions. Based on the above discussions, it can be concluded that it is feasible to conduct the collapse simulation of large-scale bridges using OpenSees.



(a) ChiChi 1999 earthquake excitation (PGA = 2000 gal)



(b) Bi-directional Tōnankai 1944 earthquake excitation (PGA = 400 gal)

Figure 8. Collapse simulation of Qiongzhou Strait Bridge

6 Conclusion

The research of the seismic performance of long span bridges has become a popular issue in civil engineering. The study proposed a numerical modelling method for a super long span cable-stayed bridge based on an open source FE software (i.e., OpenSees). Subsequently, nonlinear dynamic analyses of a real-world engineering practice is successfully performed using the proposed method, and the simulation results of OpenSees and a well-validated commercial FE software MSC.Marc are compared with a good agreement, which validates the feasibility and reliability of the proposed FE model. Furthermore, the collapse simulation of the bridge is also successfully performed and the corresponding collapse mechanism is revealed. The research outcome could provide a reference for further studies on the seismic performance of super long span cable-stayed bridges based on open source FE programs.

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7 References

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