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Seismic performance study on prefabricated self-centering rocking steel frame

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ABSTRACT

To reduce the damage of the traditional steel frames under strong earthquakes, a type of prefabricated steel frame structure with self-centering rocking column footings was proposed. The construction details and working mechanism of the frame were introduced. A rocking steel frame with a scale ratio of 1/4 was designed and manufactured. The low-cycle reversed loading tests and finite element simulation were carried out on the specimen to investigate its seismic performance. The research results show that the rocking steel frame realizes the controllable rocking of the column footings under strong earthquakes based on composite combination disc spring, whereas the cumulative damage and residual deformation of the frame are effectively controlled by the energy dissipation device of the beam-to-column connections. The frame exhibits relatively plump flag-shaped hysteretic loops, confirming that it possesses relatively good self-centering and energy dissipation capability. As the inter-story drift of the frame reaches the extremely rare inter-story drift ratio of 1/30, the beam-to-column connections and column bases do not show notable yielding or buckling, the main structure remains elastic and the damage is concentrated at the energy dissipation device. Moreover, the second-phase loading curves are consistent with the original loading curves after the energy dissipation device is removed and replaced by a new one, which effectively achieves the design goal that the energy dissipation device can be replaced and the structural functions can be restored after strong earthquakes. The results of finite element simulation agree well with test results, validating the established finite element model can reasonably predict the hysteretic behaviors of the rocking steel frame under cyclic loading.

1. INTRODUCTION

The bridge piers serve as lateral resistance and energy dissipation components in girder bridges [1]. Traditional ductile seismic design concepts may lead to significant residual displacements in bridge piers after an earthquake, causing difficulties in post-earthquake repairs [2], [3]. [4] were the first to apply unbonded-prestressing technology to rocking bridge piers, proposing the design concept of prestressed self-centering rocking bridge piers. Subsequently, [5], [6] proposed the monolithic beam analogy and the modified monolithic beam analogy, enabling the theoretical calculation of the load-displacement envelope curve for rocking bridge piers. To enhance the energy dissipation capacity of bridge piers, [7] proposed the addition of embedded energy-dissipating steel reinforcement in rocking bridge piers, which significantly enhanced the load-bearing capacity and energy dissipation capability of the piers. However, it also increases residual displacement, and at the same time, replacing the internal energy-absorbing steel bars becomes challenging after an earthquake. [8] proposed the use of externally replaceable steel rods as a means of energy dissipation for bridge piers. Subsequently, other scholars have also put forward externally placed energy-dissipating steel bars [9], externally placed energy-dissipating aluminum bars [10], and shape memory alloy of energy-absorbing bars [11], all of which greatly improved the post-earthquake repair ability performance of prestressed rocking bridge piers. [12] found through experimental studies that externally installed buckling-resistant energy-dissipating steel plates significantly enhance the energy dissipation capability of bridge piers compared to externally installed energy-dissipating steel rods.

However, the pier bodies of existing reinforced concrete rocking bridge piers have relatively weak energy dissipation and an anti-toppling capacity. Some scholars have conducted research on concrete-filled rocking bridge piers with better ductility performance. For example, [13] conducted pseudo-static comparative tests on prestressed rocking concrete-filled steel bridge piers, prestressed rocking reinforced concrete piers, and socket prestressed concrete-filled steel bridge piers. It was found that the prestressed rocking concrete-filled steel bridge pier exhibited the best seismic performance. [14] performed numerical simulation analysis on prestressed concrete-filled steel bridge piers under three different boundary conditions, which are hinged connection, semi-rigid connection and rigid connection. In addition, other scholars have conducted seismic performance tests on segmentally assembled prestressed rocking concrete-filled steel bridge piers [15], [16].

Compared to reinforced concrete and concrete-filled steel bridge piers, hollow steel structure piers can not only avoid local crushing of concrete, but also have advantages such as lightweight, high strength, and environmental sustainability. In recent years, [17- 22] proposed ductile design methods for steel bridge piers, filling the gap in seismic research on steel bridge piers in China. [23- 25] studied the seismic performance of self-centering rocking steel bridge piers by conducting pseudo-static tests and finite element (FE) calculations for the first time. They found that properly designed piers exhibit excellent ductility and resilience. However, elliptical deformation at the bottom surface and local buckling deformation at the plastic damaged zone may occur, which affect the seismic performance and post-earthquake repair ability of the piers. Currently, this new type of pier structures is both seismic resilient and cost-effective, which makes it promising for application in high-intensity seismic areas. However, further research is needed to explore the seismic performance and design calculation methods.

This study focuses on circular-section prestressed self-centering rocking steel bridge piers. Two bottom reinforcement methods were proposed, which are thickening the steel plate at the bottom and adding longitudinal stiffeners. Numerical simulations were conducted to analyze the influence of overall design parameters and bottom reinforcement parameters on the bridge pier. The research findings provide important insights for the development, design and application of self-centering rocking steel bridge piers.

2. Conclusion

To study the seismic performance of rocking steel bridge piers, a high-precision FE computational model suitable for such structures was established for numerical simulation analysis. Based on the calculation results and theoretical analysis, the following conclusions can be drawn:

(1) A comparison with the existing pseudo-static test results shows that the FE model used in this study achieves a high level of accuracy in simulating the horizontal load-displacement curve of rocking

steel bridge piers;

(2) Since the pier body is only used for energy dissipation peripherally and exhibits low plastic deformation, the hysteresis curves of concrete-filled rocking steel bridge piers and hollow rocking steel bridge piers are quite similar. Directly using hollow steel pier bodies improves the economic efficiency of the design;

(3) Increasing the self-recovery index λ significantly enhances the energy dissipation capacity of the bridge pier, but care should be taken to prevent excessive residual displacement. With an increase in prestress ratio, both the bearing capacity and residual displacement of the pier increase. Significantly thicker base plate compared to the wall plate can significantly improve the pier's resistance to local instability. Making the radius of the base plate slightly larger than the cross-sectional radius of the pier avoids concave deformation of the base plate and increases the pier's bearing capacity by approximately 5%. An increase in axial compression ratio increases the additional moment, leading to early degradation of the bearing capacity;

(4) Thickening base plates and adding longitudinal stiffeners can enhance the seismic performance of rocking steel bridge piers. Regardless of reinforcement within the range of 0.15 m or 0.3 m, reinforcing the thickness of the wall plate yields better results compared to additional longitudinal stiffeners.

(5) When the wall plate is thickened as the diameter-to-thickness ratio reaches 0.048 within a range of 0.3 m, the maximum load-carrying capacity of the rock piers increases by 11.5%, energy dissipation decreases by 0.1%, initial stiffness increases by 18.9%, and the residual displacement decreases by 54.7%. Reinforcement at the bottom of the pier has little influence on energy dissipation capacity but can slow down the growth of residual displacement, increase the lateral stiffness of the pier, and have a positive effect on the seismic performance of the bridge. A greater reinforcement height is more effective in reducing residual displacement compared to thickening the wall plate.

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