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Seismic performance of castellated beam-to-column end-plate joints with dual hinge mechanism

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ABSTRACT

In this paper, a castellated beam-to-column end-plate (CBE) joint was proposed to address the problem of brittle fracture of welds caused by high stresses in solid web beam-to-column end-plate connections and the development of plastic deformations in frame beams. Cyclic loading tests of 12 CBE joints were conducted to investigate the effects of floor, end-plate and opening parameters on the failure mode and hysteresis performance of the joints. The development of plasticity and the dual hinge failure mechanism of CBE joints were clarified. It is shown that the dual hinge failure mechanism is superior to the plastic hinge failure mechanism of the end-plate. A larger opening rate allows the beam to form a plastic hinge earlier than the connection, thus protecting the joint zone. Compared with solid-web joints, CBE joints demonstrate larger plastic deformation capacities (improved by about 14%) and smoother stiffness degradations. The ductility coefficient and energy consumption of the joints are 42% and 30% higher than those of solid-web joints, respectively. In addition, a calculation method for the bending bearing capacity of CBE joints was proposed. The calculation results are in good accordance with the experimental results and finite element analysis results.

1. INTRODUCTION

The traditional steel frame is widely used in industrial and civil buildings due to its advantages of light weight, uniform material, high strength, good toughness, convenient production, and easy assembly, especially in earthquake-resistant fortified areas and high-rise buildings [1- 3]. In this kind of structural system, beam-column joints often play an important role and are crucial to their ultimate bearing capacity and normal service capacity and even become an extremely important line of defense against structural collapse. In the traditional steel frame structure, some or all of the beam-column joints are manually welded on-site, and high-altitude operations occur from time to time. Although monitoring is required in terms of technology and management, it is difficult to control one by one. It is inevitable and difficult to control the physical and psychological influence of operators, and the on-site environment is not transferred by human will, resulting in the insecurity of welding quality, and the final implementation effect of beam-column joints often deviates from the design. In the 1994 Northridge Earthquake in the United States and the 1995

Hyogoken–Nanbu Earthquake in Japan, through on-site inspection of buildings with steel frame structure system, the beam-column joints connected by welding showed various forms of damage or brittle fracture and some even collapsed due to their existence. It causes a lot of waste of resources and economic losses [4-6], and the restoration of buildings and urban functions are seriously affected. As a result, it has attracted the great attention of many scholars in the field of geotechnical engineering.

Based on the reduction or avoidance of on-site welding work, the use of fully assembled steel beam-column joints is a good choice, that is, through reasonable building structure design, the components are connected by high-strength bolts or rivets, etc. The strength, stiffness, and seismic performance meet the functional requirements of normal use, the quality of joints can be effectively controlled, and the on-site labor cost can be greatly reduced [7], [8]. When the joint is damaged by a large earthquake, it is difficult to maintain and replace after the earthquake, and the building function is difficult to restore. Cheng-Chih Chen and other scholars proposed a fully assembled beam-column joint in which the components are basically connected by bolts, the welding between the components is completed in the factory, and the welding is basically eliminated on-site. Through experimental research and finite element numerical simulation, the results show that the possibility of brittle fracture can be effectively reduced, but the recoverable function after the earthquake is difficult to achieve [9- 11]. Based on the recoverability after an earthquake, the joint researchers of the United States and Japan proposed a kind of “earthquake resilient structure”, that is, a structure that can be restored to its use function after a small number of repairs or no services after an earthquake [12- 14]. The earthquake-resilient structures are easy to construct and maintain and have high profitability in the whole life cycle. There are many ways to realize them, mainly including self-centering structures, rocking wall structures, and structures with replaceable elements [15- 17], each of which has its own advantage. The self-centering or rocking wall structure releases the restraint between the superstructure and the foundation or the restraint between some components so that their mutual contact surfaces can bear the pressure but not the ability to be pulled. When subjected to earthquake action, the superstructure will sway and reset under the action of its own weight or prestress, reducing the demand for structural ductility due to earthquake action. The structure with replaceable components is to install energy-dissipating elements in relatively weak parts of the structure. When subjected to frequent earthquakes and fortification earthquakes, the energy dissipation elements work together with the main structure to contribute strength and stiffness to the structure; When subjected to a rare earthquake, the energy dissipating element yields first and dissipates energy. This process is similar to the action of a fuse to avoid damage or destruction to the main structure. After an earthquake, the damaged energy-consuming components can be easily and quickly removed and replaced. The implementation process has little impact on the normal use of the structure, thus realizing the recoverable function of the structure. Scholars such as [18], [19] proposed a structure with replaceable components and conducted elastic and inelastic research and analysis on the collapse mechanism and ductility of the structure. The results show that the collapse mechanism and ductility of the structure are close to or better than traditional steel frames. However, the level of assembly and industrialization of the structure is relatively low. Scholars such as [20- 22] proposed a new structure with replaceable energy dissipation elements. Through experimental research and numerical simulation, the strength, yield mechanism, energy dissipation capacity, and hysteresis curve of the structure were analyzed. The results show that the failure mechanism of the structure is good and the seismic performance is excellent, but the connection between the steel beam and the steel column is rigid or semi-rigid with bolt connection, and the design still can be uncertain, which needs further in-depth research or enhanced. At the same time, for a new type of structure with replaceable dissipative elements, when it is repaired after an earthquake, the new BMUA method proposed by [23] can be used to update the structural stiffness by considering the coupled effect of mass and stiffness.

This paper presents a fully fabricated, beam-column hinged joint with replaceable dissipative elements. In the joint domain, the connection between the components is mainly as follows: the steel beam and the steel column are hinged with pins, and the energy dissipation element attached to the corner of the beam column is rigidly connected with the steel column by a section of H-beam and high-strength bolts and hinged with the steel beam with high-strength bolts. All components are made of Q345B [24], high-strength bolts are made of M12.9, and pins are made of 40Cr. There is no on-site welding in the node installation process, and the whole assembly is basically realized. The seismic energy dissipation mainly depends on the energy dissipation components, and it is easy to replace after the earthquake. The main research contents are as follows:

(1) Investigate the failure mechanism and the strength, stiffness, ductility, hysteresis curve, and energy dissipation capacity under external loads for the joints with replaceable energy-dissipating elements, fully fabricated, beam-column hinged.
(2) Investigate the stress distribution of the energy-dissipating elements for the joints with replaceable energy-dissipating elements, fully fabricated, beam-column hinged when part or all of the section of the energy dissipation element enters the yield state.
(3) Investigate the influence of the linear stiffness ratio of the energy dissipation element to the steel beam on the strength, stiffness, ductility, hysteresis curve, and energy dissipation capacity for the joints with replaceable energy-dissipating elements, fully fabricated, beam-column hinged when the position of the energy dissipation element is constant.
(4) Investigate the influence of the vertical position of the replaceable energy-dissipating element on the strength, stiffness, ductility, hysteresis curve, and energy dissipation capacity for the joints with replaceable energy-dissipating elements, fully fabricated, beam-column hinged when the vertical position of the replaceable energy dissipation element remains unchanged.
(5) Investigate the seismic performance differences between the joints with replaceable energy-dissipating elements, fully fabricated and traditional all-welded steel frame beam-column joints, and find out reasonable design principles or methods.

In the next investigation, when this new type of fabricated beam-column connection with replaceable energy dissipation elements is applied to actual projects, the PPSD method [25] will be used to evaluate the long-term behavior of the structure, using the TF method [26] to examine the effects of seismic or civil engineering equipment on the structure.

2. Conclusion

The research was focused on the main seismic performance evaluation factors such as failure mode, strength, stiffness, ductility, hysteresis curves, and energy dissipation capacity through the experimental study and finite element numerical simulation of 6 groups of steel frames with replaceable energy dissipation elements, and compared with the finite element numerical simulation of the traditional welded steel frame. The conclusions are as follows:

(1) For the assembled and beam-column hinged joints with replaceable energy-dissipating elements, the seismic performance evaluation factors of the test and finite element numerical simulation such as the strength, stiffness, ductility, hysteresis curve energy dissipation coefficient, and equivalent damping coefficient are approximately consistent, which verifies that the test results are basically reliable.
(2) For the assembled and beam-column hinged joints with replaceable energy-dissipating elements, as the failure process obtained by the test is consistent with the finite element numerical simulation in general, their destruction mode can realize the new seismic design concept of “energy consumption destruction first, and replacement after earthquake”. Subjected to the action of frequent earthquakes, the energy dissipating elements cooperate with the rest of the structure in elastic

behavior and provide sufficient strength and stiffness; Subjected to the action of moderate earthquakes and rare earthquakes, the energy-dissipating elements enter the plastic stage, providing sufficient energy-dissipating capacity, while the remaining components and accessories still maintain elastic behavior.

(3) For the assembled and beam-column hinged joints with replaceable energy-dissipating elements, when the horizontal length is constant, and the ratio of the linear stiffness of the energy dissipation element to the steel beam is approximately 0.7, their seismic performance is in a relatively good state. From the analysis of the 6 groups of tests, it can be concluded that the seismic performance of JD-2 and JD-4 is better than the other groups.

(4) For the assembled and beam-column hinged joints with replaceable energy-dissipating elements, under the condition of constant vertical position and the material properties of energy dissipation elements and steel beams, when the ratio of horizontal length to span is 0.225, their seismic performances are superior. From the analysis of 6 groups of tests, it can be concluded that the seismic performance of JD-4 is better than that of JD-2.

(5) For the assembled and beam-column hinged joints with replaceable energy-dissipating elements, compared with the traditional welded beam-column joints in the steel frame, when the ratio of linear stiffness of energy dissipation element to steel beam is about 0.7, and the ratio of horizontal length to span is about 0.225, they are considered to be a good alternative of it, because the seismic performance is basically close to or beyond that of traditional welded steel frame beam-column joints. From the 6 groups of test analysis, it can be concluded that the seismic performance of JD-4 is better than any other group, and it is closer to the beam-column joint of the traditional welded steel frame.

(6) For the assembled and beam-column hinged joints with replaceable energy-dissipating elements, their welding works can be completed in the factory, and there is basically no welding on site, which is conducive to environmental protection; Their beam-column connection nodes are hinged, which is completely controllable in practical applications compared to rigid or semi-rigid connection nodes connected by bolts; after the earthquake damage, the damaged energy-consuming components can be removed to restore normal use, which is convenient and fast and is conducive to improving the resilience of the city.

3. References

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