Research Progress on the Joint Connection Mode of Steel Coupling Beam

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Abstract. Coupling beam is an important component of seismic structure, the damage of coupling beams can consume earthquake energy, thereby protecting the safety of the structure. In order to ensure that the advantages of steel coupling beams are fully utilized, the joint connection form of steel coupling beams and structures has become the focus of many scholars' research. This paper systematically summarizes the latest research progresses on the connection mode of joint with steel coupling beam, and their advantages and disadvantages are discussed, which provides a reference for engineering application.

1. Introduction

Due to functional needs, many buildings now need to open larger holes in the shear wall to form a coupled shear wall, and the coupling beams become an important component of coupled shear walls. The traditional reinforced concrete coupling beams often undergo brittle shear due to the relatively small span-depth ratio, which fails to realize the original design intention of ductility and energy dissipation. In addition, due to the setting of the edge steel members of the concrete shear wall, the construction difficulty is increased.

In order to fundamentally overcome the problems of poor ductility, limited energy dissipation, complex design and difficult construction of concrete coupling beams, researchers propose a new structure system that uses steel coupling beam instead of concrete coupling beam. Since the 1990s, scholars in the United States and Canada have proposed the steel coupling beam-concrete coupled shear wall structure. The structure dissipates energy through the shear deformation of the steel coupled beam and the plastic hinge deformation at the bottom of the wall columns, which can significantly improve the seismic performance of the reinforced concrete double limb shear wall[1-2]. Studies have shown that steel coupling beam has better ductility, good shear resistance and strong energy dissipation capacity than reinforced concrete coupling beam[3]. The advantages of steel coupling beams have been proved by many scholars in many countries, so the reinforced concrete coupling beams have been gradually replaced by steel coupling beams in the shear wall. In order to ensure that the advantages of steel coupling beams are fully utilized, the joint connection form of steel coupling beams and structures has become the focus of many scholars' research. In this paper, the connection mode of steel beam joints is reviewed to provide reference for theoretical research and engineering application.
2. The Joint Connection Mode of Steel Coupling Beam

2.1. Embedded Type

The first developed node connection method is the direct embedded joint of steel coupling beam and concrete wall. With the emergence of new connected nodes, the direct embedded joint is called the traditional connected mode as shown in the Fig 1. The steel coupling beam is directly embedded into the reinforced concrete wall to form the composite concrete coupled wall, which requires the steel coupling beam to have a certain depth of embedding in the concrete shear wall and interact with the longitudinal and transverse reinforcement in the wall. During the construction, it is necessary to determine the position of the steel coupling beam in the reinforced cage of the embedded steel column at the edge of the concrete shear wall before pouring concrete. So the connection is difficult and the period is long.

Many scholars have studied the connection mode of direct embedded. According to the results such as Shahrooz[4] in the United States, Canada's Harris[5], South Korea's Wan-Shin Park and Hyun-Do Yun[6] design for different forms of specimens. They studied ductility and energy dissipation capacity of directly embedded steel coupling beam joints when they were damaged by different reasons and put forward a series of suggestions on connection structure. The results show that the seismic performance of the specimens designed base on shear yield is better than that of bending yield, which is also consistent with the principle of "strong shear and weak bending" required by concrete design. The research shows that this kind of joint has a higher stiffness, which can effectively transfer the shear force from steel beam, but the ductility of the joint is lower and has obvious strength degradation.

Others scholars have conducted theoretical studies on the calculation model of embedded length of steel coupling beam, such as Minami[7], Wan-Shin Park[8] and others proposed formulas. According to previous research results, Su Mingzhou[9] summarized the results into five calculation models.

In addition, in order to improve the direct embedded joint of traditional steel beam and concrete shear wall, Li Guoqiang[10] proposed to embedded steel columns in the edge of concrete shear wall. As shown in figure 2, the shear studs and round holes in embedded steel columns can increase the combination of steel embedded column and concrete, which prevent relative sliding under force. It also acts as a restraint member in the edge of shear wall, increasing the ductility of shear walls. Welding the steel bracket on the embedded column, steel bracket and steel girder are connected by high strength bolts or welding seams through the end plate, which is easy to repair steel coupling beam after earthquake.

2.2. Post-tensioned Type

The prestressed rods pass through the steel coupling beam and the precast shear wall limbs by the post-tensioned. The steel coupling beam is fixed between the two shear wall limbs by unbonded post-tensioned prestressed technology, as shown in the Fig 3. Weldon[11] studied the nonlinear behavior of coupling beams under the action of monotone and low cyclic repeated load. The study showed that the kind of connecting has greater ductility, good resetting after the earthquake, smaller residual displacement, and less damage to the structure, which can be used for the repair and reinforcement of existing buildings. However, the joint stiffness is small, and the design and construction are relatively complex[12].

2.3. Welded Type

Replacing traditional reinforced concrete coupling beam with steel coupling beam has been proved to be feasible by a large number of theoretical studies, experimental studies and numerical simulation studies in developed countries such as the United States, Canada, Japan and South Korea. Song Anliang et al[13] proposed the use of steel coupling beams and steel reinforced concrete edge members to connect nodes through concealed columns to form a hybrid coupled wall system. This structure is called the new HCW, which can better solve the problems of difficult reinforcement of
concrete coupling beam and insufficient ductility of small span-to-height ratio coupling beam while having a better seismic performance.

The transmission sequence of the stress of the joint is from the steel beam to the embedded steel column in the hybrid coupled wall, and then the force is dispersed to the concrete around the embedded steel column. The force of this joint is more uniform and reasonable than that of the direct embedded joint. Secondly, it is convenient to use welded joints of embedded steel columns for construction. The steel frame can be built first, the concrete wall can be formed later, and construction progress can be accelerated to form multiple construction surfaces. However, the literature[14] points out that this method of welded is difficult to guarantee the quality of on-site welding, and sudden crack of welding seam will occur in the later stage of loading, and the bearing capacity will drop suddenly, which is not conducive to earthquake resistance.

2.4. Welded-bolted hybrid Type
In the earthquake, the connection between the coupling beam and the composite shear wall body is a weak part, because the quality of welding joints on the construction site is difficult to guarantee, and many joints connected by welding method have structural defects, which is easy to damage, and will also slow down the construction progress and increase the construction cost. Based on the above reasons, Wu Yuntian et al.[14] of Chongqing University proposed that the steel connecting beam and end plate could be welded together in the factory to ensure the quality of welding seams, as shown in the Fig 4. In the construction site, the assembly process is mainly completed, and the coupling beam of welded end plate is assembled together with section steel members in the embedded concrete through the end plate by high-strength bolts. The structure is simple and easy to construct. The low-cycle reciprocating quasi-static loading test was carried out on five double limb composite shear wall specimens of end plate bolt connection and one traditional type of small scale double limb reinforced concrete shear wall specimen. Combined with the numerical simulation results, it is shown that this kind of joint has high ductility, strong energy dissipation ability, stiffness and strength degenerate gently, effectively reducing the damage of concrete in the connection area. However, the end plate bolt connection can solve the welding problem, when the connecting beam is damaged after an earthquake, it is not easy to repair because the connecting bolt is completely placed inside the concrete wall.
Shi Yun[15] proposed a modular prefabricated joint outside the wall, which can be quickly repaired after an earthquake, as shown in the Fig 5. Through the finite element software, it is found that although the overall bearing capacity of this joint structure is slightly reduced compared with that of the welded joint with embedded steel column, its deformation capacity is improved, which reduces the possibility of cracking failure caused by the weld suddenly being pulled apart after loading at the joint and increases the seismic performance of the structure.

2.5. Bolted Type
Bolted joints are common in steel structures and are especially suitable for modular prefabricated multi-storey steel structures, as shown in the Fig 6. The composition of beam and column joints of steel structure can be completed through assembly. Based on the experimental study of full-welded and welded-bolted hybrid joint connection of prefabricated multi-storey steel frame structure, some scholars proposed full-bolted joint connection of steel structure. The connecting method is to splice the flange column with the column seat by high-strength bolts and assemble the truss beam with the joint vertical connecting plate by the column seat through the joint sticking plate and high-strength bolts. Liu Xuechun et al.[16] designed three kinds of multi-storey prefabricated joints connected by bolts with different parameters, and conducted experiments and finite element analysis. The results show that the weld quality, plate thickness and bolt arrangement have great influences on failure mode and many mechanical properties of the connection. Reducing the thickness of the chord and web of truss girder will significantly reduce the bearing capacity of this connection, but it has little influence on ductility performance and energy dissipation capacity of the connection. Although bolt joints may have many problems such as large number of bolts, large number of nodes and high bolt price than welded joints, their comprehensive economic cost is lower.

3. Conclusion
From the above review, it can be seen that great progress has been made in the research on the connection mode of steel beam joints. Different scholars have proposed different forms, but there are
still many scientific issues that need to be further studied:

(1) There are a variety of steel beam joint connection methods, but to find a convenient construction, replaceable form is always the direction of civil engineers need to work hard.

(2) Prefabricated steel structure has a broad application prospect in China. How to propose a joint connection form suitable for prefabricated steel structure based on these joint connection modes is a new challenge faced by researchers.

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