Research progress of replaceable steel coupling beam

Fengyuan Sun 1 *

1 Xiamen university of technology, School of Civil Engineering and Architecture, Xiamen, 361024, China
*Corresponding author’s e-mail: jwc@xmut.edu.cn

Abstract. Coupling beam is crucial to the seismic performance of the shear wall structure. When the coupling beam has enough ductility, there will be cracks on the section and plastic hinges will appear under earthquake, which will absorb a large amount of seismic energy. The coupling beam plays an important role in reducing the force inside the shear wall and delaying the yield of the shear wall. At the same time, the plastic hinge still transfers the bending moment and shear force, therefore, to act as a certain constraint on the shear wall to help the shear wall to maintain enough stiffness and strength. Among them, the replaceable coupling beam can help the recovery of structural performance, with great advantages and application prospects. This paper mainly summarizes the research progress of replaceable coupling beam, and analyzes its advantages and disadvantages.

1. Introduction
Shear wall is a common structural system of high-rise buildings. The so-called shear wall is the structure mainly bears the horizontal load caused by wind load or seismic action and vertical load (gravity). Coupling beam is a beam that connects the shear wall to the shear wall plane in the form of shear wall structure and frame-shear wall structure. Coupling beam generally has the characteristics of small span, large section, the wall stiffness connected with coupling beam and very large. Generally, under the action of wind load and earthquake, the internal force of the coupling beam is often very large. Under the action of the earthquake, the continuous beam consumes a lot of seismic energy, which plays an important role in reducing the internal force and delaying the yield of the shear wall.

Traditional coupling beam is generally reinforced concrete coupling beam, but it has an inevitable disadvantage. According to tests and observations, most of this type of components will appear shear damage, so that the degree of strength, stiffness degradation and energy consumption ability are not optimistic, and it is not easy to repair after the earthquake. In contrast, steel beam is superior to reinforced concrete beam in terms of energy consumption capacity and deformation. In recent years, steel beam gradually replaces reinforced concrete coupling beam due to its many advantages. Because the steel continuous beam usually produces entry plasticity to dissipate the seismic energy, serious damage often occurs, and the repair of the coupling beam is generally very difficult. Therefore, scholars have put forward the concept of replaceable coupling beam, that is, to change the force deformation characteristics of the steel coupling beam in the shear wall, so that the damage can occur in the replaceable coupling beam section, that is, the weakening section. The replaceable coupling beam is generally divided into section weakening type, integral disassembly type and bending type, and this paper discusses the research progress of the replaceable coupling beam.
2. Section weakened coupling beam

In 2007, Teng et al designed a coupling beam with long holes in steel plates at the lower yield point. The hysteresis curve obtained by the test results is full and has good ductility [1]. The researchers installed this beam in a flat shear wall and performed nonlinear analysis. It is found that the presence of the damper does not improve the frequency of the structure under frequent earthquakes. While under severe earthquake, the coupling beam damper increase the seismic performance of the structure. On this basis, the researchers designed the energy consumption module using a square coupling beam steel plate damper is conducted and proposed a horizontal and vertical layout. The seismic performance analysis of a super high-rise building using the damper, the research shows that the damping beam can form a number of seismic defense, the reinforced concrete beam damaged can still ensure the beam dissipation capacity and ductility performance, thus improve the overall energy consumption capacity, and reduce the damage degree of the shear wall.

In 2007, Fortney of the University of Cincinnati proposed to cut the traditional steel coupling beam in the left and right span, with the middle beam section as the energy consumption member to ensure the deformation concentration in the middle through the web thickness weakening,[2] which can effectively concentrate the deformation and energy consumption on the middle section to protect the non-energy consumption beam section. The energy consuming elements and the web and wing edges of both ends are bolted to facilitate replacement after the earthquake.

On the basis of this concept, Lv et al. also put forward a new coupling beam with diamond holes in the web of the ordinary steel coupling beam, as shown in Figure 1[3]. The test results show that the diamond opening beam is more suitable for coupling beam with small shear deformation.

Ji et al. of Tsinghua University proposed a dissipation steel beam, as shown in Figure 2[4]. The traditional coupling beam was replaced with the whole steel energy dissipation beam, and the influence of different web steel types, beam length and stiff rib arrangement, the connection mode of the non-dissipation beam section and the floor type through the quasi-static test were studied. The results show that the seismic performance of this dissipation beam is good.

Fortney et al. proposed a replaceable "fuse" link beam shown in Figure 3[2]. This scheme reasonably reduces the shear resistance of the coupling beam to make its shear yield energy consumption. A low-frequency cyclic loading test was carried out on the diagonal cross-reinforcement of steel concrete beam, steel beam embedded in reinforced concrete shear wall, steel beam with fuse, and composite beam wrapped with shear steel plate. The results show that the ductility and energy dissipation ability of the "fuse" coupling beam are good.
3. Steel truss coupling beam
On the basis of the research of solid web steel coupling beam, Deng proposed a new structural concept of steel truss coupling beam as shown in Figure 4[6]. Steel truss coupling beam is composed of upper and lower string horizontal steel and inclined web bar at the intersection, and the steel truss is buried at both ends of the shear wall concrete of steel truss. Under the seismic action, it mainly relies on the repeated pulling and pressure deformation, dissipating the seismic energy through the plastic deformation. In the design, the string to maintain the elastic state or enter the plastic degree is light, which is to let the string always effectively connect the shear wall, so that it can deform together and common deformation.

![Steel truss coupling beam](image)

Curved steel truss coupling beam of friction device is designed to concentrates deformation and energy consumption at the lower string bar, so that not relatively sliding under small vibration, friction energy consumption under medium shock, and ensure the elasticity of the steel truss under small and medium shock. The seismic performance of traditional steel truss coupling beam with 2.0 and 3.0 and friction steel truss coupling beam was compared by cyclic reciprocating static test of 6 scale specimens.

4. Energy-dissipation coupling beam with damper
The results show that the strong and stable energy consumption capacity of the dampers can greatly improve the seismic performance of the coupling beam. Dampers being widely used are friction dampers, metal dampers, viscoelastic dampers etc. The core idea of energy dissipation beam with damper is that the damper does not function under the small shock, and the coupling beam remains elastic to provide sufficient stiffness, and the damper enters the yield energy consumption before the coupling beam, so as to protect the non-energy dissipation beam section.

4.1. Energy dissipation coupling beam with friction damper
Han studied the equal-hole friction damper [7]. The influence of different parameters on the performance was studied by replacing different friction materials and applying different pretension forces. The test results show that the friction damper material should be hard and strong, to improve the damper energy consumption as shown in Figure 5. On this basis, Guo [7] also gave suggestions on the slot width and pretension force loss control of the sliding main board. The test results show that on the basis of meeting the rotating space, narrow slot dampers should be selected and use disc friction material at the pre-stressed bolts to reduce the loss of pre-stressed force.

![Coupling beam with friction damper](image)
4.2. Viscoelastic damper coupling beam

The viscoelastic damper is composed of viscoelastic materials and binding materials. Under the action of external force, it consumes energy through the shear deformation of viscoelastic materials. The viscoelastic damper is a velocity-related product, once started will consume energy, so it can provide energy consumption capacity also under the action of small shock. Well-performing viscoelastic materials may be too costly.

In 2010, Lyons at the University of Toronto proposed a replacement coupling beam with an additional viscoelastic damper, constructed as shown in the Figure 6[8]. The replaceable coupling beam of additional viscoelastic dampers has two main parts: a viscoelastic damper and a ductility fuse that reduces the beam section. The main idea is that under the load action, the viscoelastic damping device has a large shear deformation. After it reaches its design deformation, the ductile fuse device begins to deform and consume energy, thus protecting the viscoelastic damper from damage. Through experiment and numerical simulation of the optimization design examples, it shows that the viscoelastic damper in the middle position of the coupling beam.

![Figure 6. Viscoelastic Damper Energy Link beam](image)

Lyons proposes a coupling beam damper made in series of the viscoelastic material and the shear yield type fuse, as shown in Figure 7[8]. When the viscoelastic damper reaches a certain deformation, the fuse can assist the adhesive metal damper through deformation. (El-plastic) In 2010, Teng and others proposed a low yield steel metal damper, which opened long bar holes in the plane of the low yield steel plate to ensure that deformation is concentrated on the metal dampers, connected to the shear wall to form a coupling beam [9]. The results show that the delay curve of the beam is full and has good energy consumption. However, this kind of coupling beam replaces the overall coupling beam with the damper, so the span of the coupling beam is relatively large, which is easy to lead to the off-surface buckling of the damper, which needs further research.

![Figure 7. Viscoelastic connecting beam damper for series shear fuse](image)

In 2014, Lv proposed two kinds of energy dissipation beams, double web I-steel filled in a section composed of webs and wings, and parallel double steel pipe filled in steel pipe, with cyclic reciprocating loading tests for two energy dissipation beams[10]. The test results show that the two replaceable coupling beams will not reduce the bearing capacity and reduce the strength degradation, which can effectively increase the equivalent viscosity damping coefficient.

4.3. Composite damper coupling beam

In 2012, Kim et al. proposed a damper consisting of U steel and high damping rubber and arranged in coupling beams as shown in Figure 8[11]. The composite damper has two-stage working ability, its design concept is as follows. The first stage is under the influence of high damping rubber, U steel to ensure the overall stiffness. The second stage is that the U steel itself yields under the large shock, but then the overall stiffness will be reduced. A vibration bench test on the coupling beam installed with
this damper showed a reduced structural acceleration response and damage. The coupling beam structure with composite damper is generally complex and has high cost, which is not conducive to the extensive application.

Chuang first arranged the friction damper in the middle position of the coupling beam span to form the energy dissipation coupling beam as shown in Figure 9[12]. The external members and the I-section beam are bolted to facilitate the repair after the earthquake, and the friction materials are added to the middle to improve the seismic performance of the coupling beam. The nonlinear time-range analysis of joint shear wall structure shows that the friction damper can be effectively reduced in the beam span.

Qu proposed the steel coupling beam with the friction damper as shown in Figure 10, and conducted the experimental study [13]. The study shows that the performance of friction damper is good and stable, without excessive load capacity and good energy consumption. Based on this, in 2019, Qu also studied the influence of the floor on the steel coupling beam of the mid span friction damper. The results showed that the floor suffered serious damage and produced a concentrated bending crack of 6 mm when the angle of coupling beam reached 4%. At this time, the shear force in the plate exceeds 10% of the strength of the friction damper, which is considered a potential source of super strength for the design of the type steel beam section and the surrounding components. The friction damper coupling beam is proposed by Qu [14].

In 2019, on the basis of the study of friction damping components, Yang also proposed a friction steel beam shown in Figure 11, and investigated the influence of ordinary concrete floor, fiber floor and prefabricated floor on friction steel beam [15]. The test data show that the mixed coupling beams using friction dampers have more energy consumption ability and better damage control ability compared with the traditional reinforced concrete beams. The stiffness of the floor slab is very weak compared with the beam body, and the floor slab of different materials and structures basically make no contribution to the bearing capacity of the coupling beam. Furthermore, three embedded end plate connection structures for steel coupling beams are proposed. The stress characteristics of the nodes and the overall damage development process are analyzed. The results show that the delay curve of the anchor bar and shear plate is full and the rotation and vertical sliding of the embedded beam are small.
5. Conclusion
This paper summarizes the research progress of replaceable beam in the past 15 years, and compares the advantages of replaceable coupling beam over the previous reinforced concrete coupling beam. It is hoped that in the future development, the research of replaceable coupling beam can be further advanced.

(1) It can be replaced or repaired after an earthquake.
(2) It is easy to install.

It is hoped that in future development, the research of replaceable coupling beam can be further advanced.

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