Seismic Performance Study of Self-Centering Steel Reinforced Concrete Building Joints Under High-Intensity Earthquake

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ABSTRACT
The better the seismic performance of building joints, the more lives and property can be preserved in earthquake disasters. This paper briefly introduced the basic structure of self-centering reinforced concrete (RC) column-steel beam joints and then prepared three types of joint specimens. Specimen 1 was a self-centering RC column-steel beam joint, specimen 2 was obtained by removing the damping core plate based on specimen 1, and specimen 3 was obtained by removing both the damping core plate and prestressed reinforcement based on specimen 1. The quasi-static loading tests were carried out on the three types of joint specimens, followed by vibration tests with an eight-degree earthquake on a vibration table. The findings demonstrated that specimen 1 had a higher peak load and ultimate displacement when the quasi-static loading displacement was greater than the yield displacement; specimen 1 had higher energy dissipation capacity when facing periodic loading; when facing an eight-degree earthquake, specimen 1 had the best self-centering ability.

1. INTRODUCTION

As earthquakes are difficult to predict [1], it is more important to enhance the seismic performance of buildings. Concrete is a material that is commonly used in construction, which has favorable plasticity before solidification [2] and favorable mechanical properties after solidification [3]. However, concrete also has its limits when facing earthquake vibrations. To strengthen the seismic performance of buildings, besides strengthening the material of concrete itself, a "skeleton" can also be added to it, and the material of the "skeleton" can be varied according to the needs. In addition, after an earthquake, the structure of the building will be affected [4]. Even buildings that don't fall in a big earthquake will suffer serious loss of their basic structural functions and repairing them requires a lot of money and time costs. With the development of earthquake resistance concepts, the self-centering building structure has been proposed. This type of building structure has a certain automatic reset capability when facing displacement deformation, and although there is a limit to the reset capability [5], it can also make the building structure restore basic functions with only a small amount of repair after the earthquake, and even does not need to be repaired when the seismic intensity is small, which is conducive to the rapid and economical repair after the earthquake. Yang et al. [6] proposed a self-centering column-steel beam joint made of reinforced concrete (RC) with un-bonded post-tensioned strands and replaceable flexural restrained dampers. They found that the proposed node had the minimum residual drift and satisfactory performance.

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Huang [7] studied the hysteretic behavior of self-centering glulam beam-column joints and discovered that energy was dissipated by the friction dampers under low initial post-tension and clamping force. Bagheri et al. [8] carried out experimental analysis on a brand-new kind of energy-dissipating, self-centering steel pure tension support structure. The experiment showed that this system could offer reliable low-damage structural solutions for both new and existing structures. This article briefly introduced the basic structure of self-centering RC column-steel beam nodes, and then prepares three types of node specimens. The first specimen was a self-centering RC column-steel beam joint. The second specimen was obtained by removing the damping core plate on the basis of the first specimen. The third specimen was obtained by removing the damping core plate and prestressed reinforcement on the basis of the first specimen. Then, quasi-static loading experiments and vibration experiments with an eight-degree earthquake on the vibration table were carried out on the three types of specimens.

2. SELF-CENTERING REINFORCED CONCRETE COLUMN-STEEL BEAM JOINT

For a building, the frame it possesses is an important component, which can be compared to the skeletal system of a human body. The frame of a building plays a supportive role for the entire structure, especially the beam-column joint [9], whose mechanical performance directly affects the building's stability. This is because, like a joint in a human body, the beam-column joint connects the building's horizontal and vertical structures. Even if the "skeleton" has excellent quality, it cannot form a complete structure once a problem occurs at the "joint" [10]. If the load's contact surface abruptly shrinks as the force of the building load passes through the beam-column joint, the stress also changes significantly. Additionally, the beam and column are not a single entity, and their connection point is relatively small in comparison to the structure as a whole; as a result, the beam-column joint is regarded as the path's weakest link [11]. It can ensure safety when the state is stable, but once it is subjected to sudden loads caused by earthquakes or other factors, it is easy to cause deformation in the joint. If the deformation exceeds the range that the joint can bear, irreversible damage will occur [12].

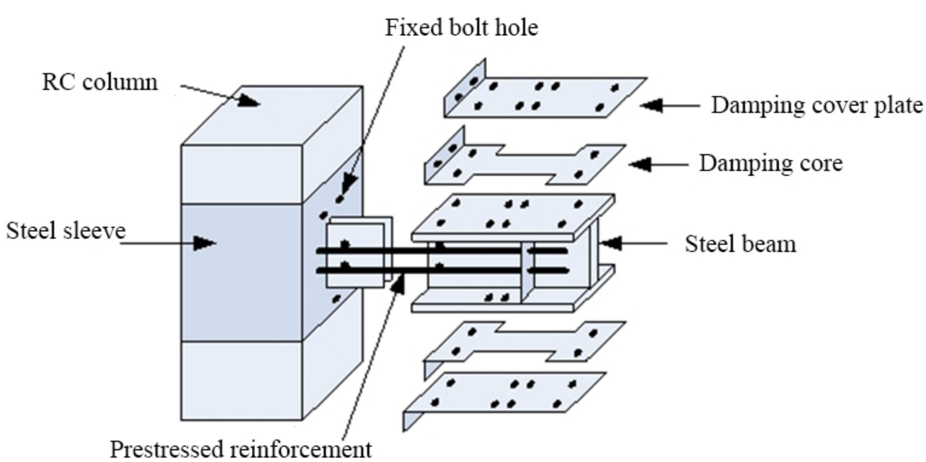

Figure 1. The basic disassembled structure of a self-centering RC column-steel beam joint

In order to reduce the damage to beam-column joints under external forces such as earthquakes, the seismic performance can be improved by enhancing the mechanical properties of the materials used for the beam and column, or the damping structures can be increased in the joint to utilize the high energy dissipation characteristic of damping structures [13]. Figure 1 shows the basic structure of a self-centering RC column-steel beam joint. The column part of the joint is made of RC, while the beam part is made of an I-shaped steel beam. The column and beam are fixed together using bolts. Thus, the components can be prefabricated and assembled on site. The advantage of the RC column-steel beam joint is that the steel beam can span a large distance while reducing the economic cost of the column structure by using RC [14].

As shown in Figure 1, the RC column is wrapped with a steel sleeve at the connection with the steel beam. The steel sleeve not only is welded with a connecting plate but also has corresponding fixed bolt holes. The beam in the joint is I-shaped, and the web plate near the end of the column has fixed bolt holes to connect with the connecting plate of the column. The upper and lower sides of the steel beam are the damping core and damping cover plate of the damper, respectively, from inside to outside. In addition to using a connecting plate to fix the RC column and steel beam together, prestressed reinforcement is used to pull them together [15].

For a self-centering RC column-steel beam joint, the prestressed reinforcement used for column-beam connection is an important structural element for achieving self-centering of the joint. When the joint is subjected to earthquake, the end of the beam will bend; when the bending moment exceeds a certain value, the contact surface between the beam and column will detach, causing an opening at the joint. As a result, the beam and column will rotate relative to each other, and the stiffness of the joint will be greatly reduced. Without special treatment, the opening will continue to enlarge until the beam and column completely detach [16]. In a self-centering beam-column joint, when the beam and column rotate relative to each other due to excessive bending moment at the beam end, the prestressed reinforcement at the end of the beam will be tightened, increasing the prestressing force. After the earthquake ends, the tensile force generated by the prestressed reinforcement will pull the beam back to its original position, thus reducing the post-earthquake deformation of the joint. However, the prestressed reinforcement only plays a tensile role and do not have a significant energy dissipation effect. Moreover, in order to achieve self-centering, the constraints at the joint are relatively relaxed, making the contact surface between the beam and column more susceptible to damage from seismic energy. Therefore, damping elements need to be added to the joint to dissipate the energy from the earthquake, reduce the damage to the contact surface, and facilitate post-earthquake repairs [17].

The damper shown in Figure 1 is the necessary damping element, and the damping core is the core of the energy dissipation element. The damping cover plate holds the folded energy dissipation core plate to the steel beam. The core plate is between the steel beam and the cover plate. The damping core plate will undergo plastic deformation to dissipate the seismic energy when the end of the beam bends due to forces. The damping element is connected to the joint with high-strength bolts, which facilitates replacement [18].

3. EXPERIMENTAL ANALYSIS

3.1. Specimen Parameters

The basic three-view drawings of the self-centering RC column-steel beam joint specimen to be experimentally validated in this article are shown in Figure 2. The dimensions of the column have been indicated in the three-view drawings. The material of the column is RC, and the section diameter of the reinforcement used as the column skeleton is 16 mm. The filling material of the column is C80 concrete. The steel sleeve in the middle of the column, the connecting plate, and the steel beam are all made of Q345 steel [19]. The energy-absorbing core plate in the damper is made of Q235 steel. Their basic mechanical properties are shown in Tables 1 and 2.

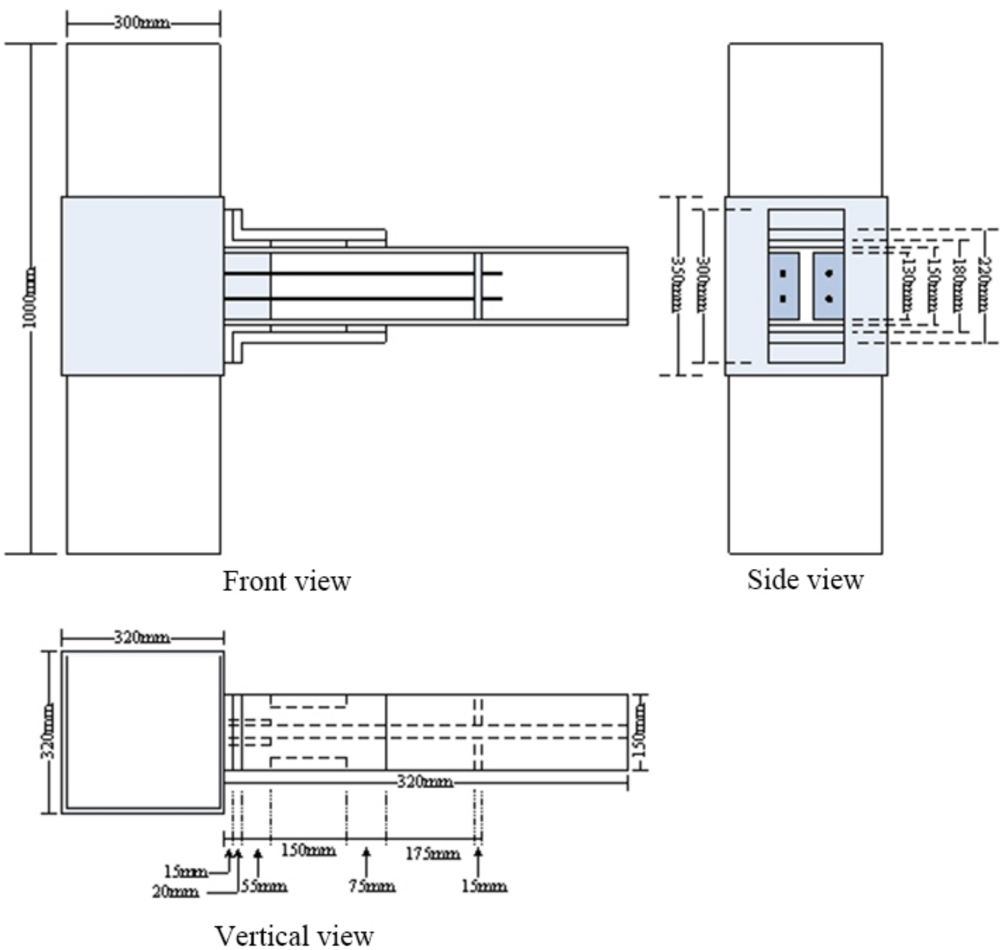

Figure 2. The three-view drawings of the self-centering RC column-steel beam joint specimen

In this study, in order to further verify the seismic performance of the node specimen in Figure 2, two other joint specimens were also fabricated. Specimen 1 is the proposed joint specimen, and its detailed material and structural parameters were described above. Specimen 2 was obtained by removing the damping core plate from specimen 1, and specimen 3 was obtained by removing both the damping core plate and prestressed reinforcement from specimen 1.

Table 1. Mechanical properties of C80 concrete column

Material	Compressive strength	Tensile strength	Poisson's ratio	Modulus of elasticity
C80 concrete column	$80MPa$	$42MPa$	0.2	$380GPa$

Table 2. Mechanical properties of column frame reinforcement, prestressed reinforcement, and damping core plate

Material	Yield strength	Ultimate strength	Modulus of elasticity
Column frame reinforcement	$670MPa$	$857MPa$	$200GPa$
Prestressed reinforcement	$1787MPa$	$1931MPa$	$195GPa$
Damping core plate	$305MPa$	$442MPa$	$179GPa$

3.2. Experimental Items

Figure 3 shows the basic structure of the loading device used for the quasi-static experiment of the joint specimen [20]. An electro-hydraulic servo testing machine, a dynamic signal acquisition system, a hydraulic jack, a horizontal jack, a stress sensor, and a displacement sensor were the main parts of the device. During the preparation of the joint, the stress sensors were embedded in the beam-column joint, and the displacement sensors were installed outside the specimen.

After setting up the device and specimens, the quasi-static loading was performed by displacement loading. The loading procedure was as follows. 1) The axial load was exerted on the column using the hydraulic jack until the target value was reached. 2) The column end was subjected to cyclic loads that were applied by means of a horizontal jack, every level of load was applied for one cycle initially, and the increment between every level of load was $5mm$. 3) The load was gradually increased until the specimen yielded, i.e., when the longitudinal tensile strain in the plastic hinge of the beam was up to 3,300 (the displacement at the beam end was the yield displacement), and the subsequent increment of the load was changed to half of the yield displacement. 4) The test was over when the beam end load fell to 85% of its peak value, severe local damage to the specimen occurred, or the deformation of the joint structure increased rapidly.

Although the above quasi-static loading experiment involves gradually increasing cyclic loads, which is closer to earthquake vibration, it is still a controllable vibration. Earthquakes are sudden vibrations with randomness and short duration. Although the horizontal jack in the loading device of Figure 3 can gradually adjust the amplitude of the cycle, it is difficult to simulate the random seismic vibration. Therefore, this study also used a vibration table to simulate high-intensity earthquakes and detected the seismic performance of the joint under this earthquake. The steps were as follows.

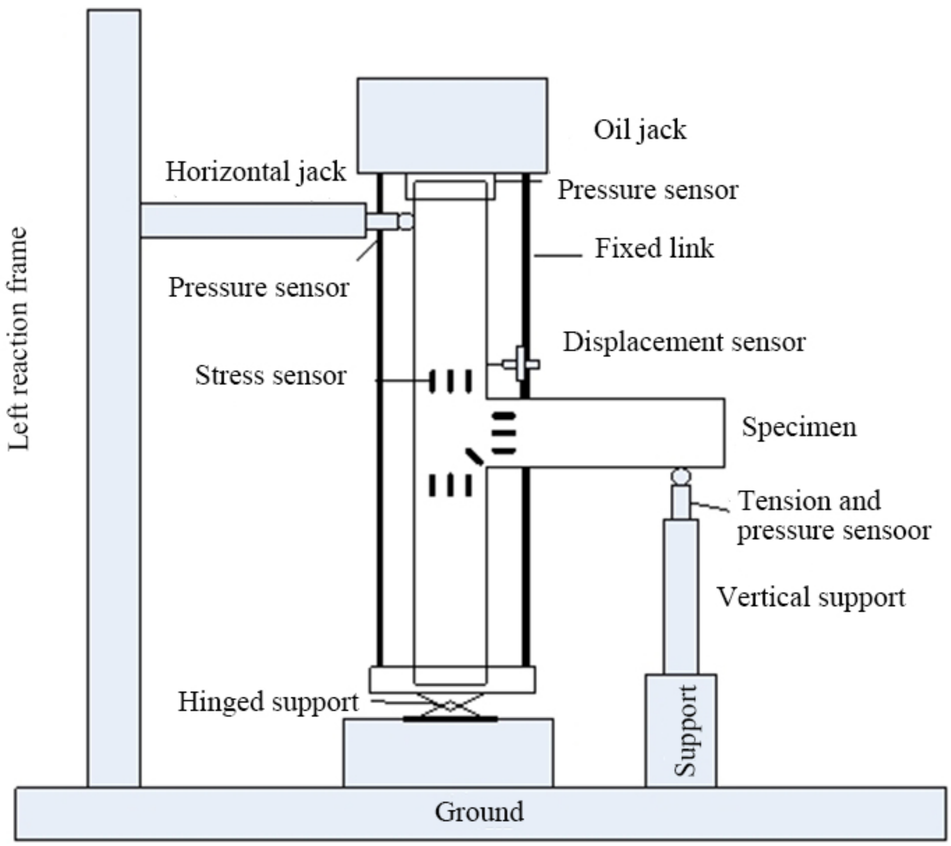

Figure 3. The basic structure of the loading device used for experiments.

1) A specimen of the beam-column joint was made as previously described, and an L-shaped steel plate was used to connect the bottom of the specimen column to the surface of the vibration table. In the column area, a displacement sensor was installed every $100mm$ in the axial direction from bottom to top.
2) The vibration table was started, and an eight-degree seismic signal was applied to the specimen.
3) The change of the displacement angle of the node beam end was recorded using the installed displacement sensor.

3.3. Experimental Results

In the quasi-static loading process of the two types of specimens, the peak points of the load-displacement curve of each loading level in the first cycle were connected to create the skeleton curve. The skeleton curve could reflect the bearing capacity of the specimens under different loading levels and was used to judge the resistance ability of the specimens to earthquake vibration. The three specimens' skeleton curves under the same loading system are depicted in Figure 4. According to Figure 4, the skeleton curves of the three specimens were almost identical and nearly linear when the displacement of the beam end was $-20mm{\sim}20mm$ under the same loading system, indicating that all three specimens were in the stage of elastic deformation. The slope of the skeleton curves of the three specimens all dramatically decreased after the beam end displacement went above the range of $-20mm{\sim}20mm$, and the three specimens gradually reached their respective beam end load peaks. Among them, when specimen 1 reached the peak, not only did it have the largest beam end load peak, but it also had the highest displacement. As the loading displacement continued to rise after reaching the beam end load peak, the beam end load gradually decreased, and the contact surface between the beam and column developed an opening. During this stage, specimen 1 experienced a gradual decrease in load and a greater ultimate load and beam end displacement than specimens 2 and 3; specimen 2 was better than specimen 3.

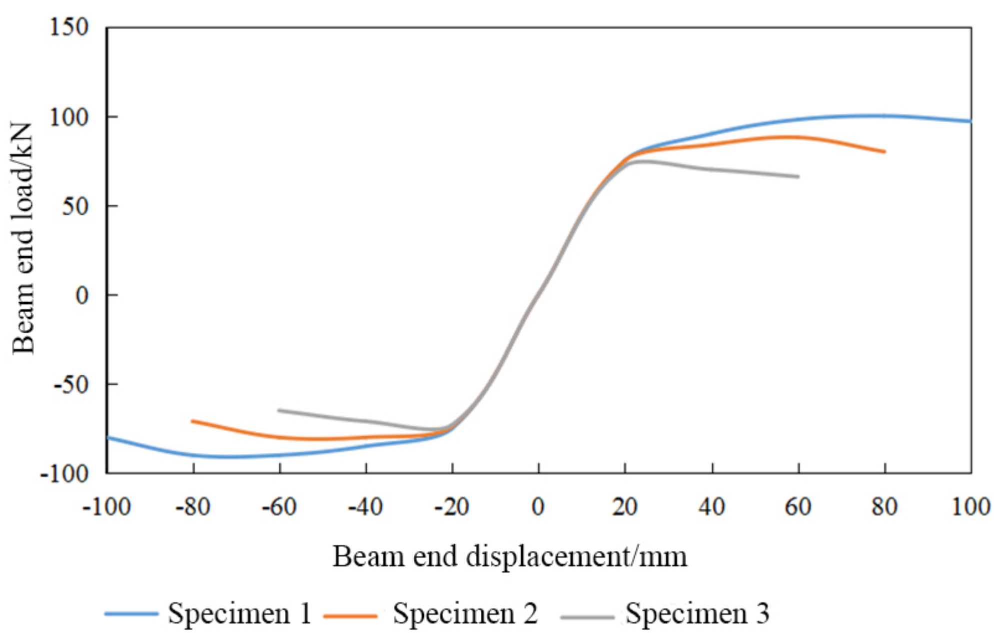

Figure 4. Skeleton curves of three types of joint specimens during quasi-static loading experiment

The comparison results of the skeleton curves showed that when facing the same gradually increasing cyclic load, i.e., earthquake vibration, specimen 1, which was a self-resetting RC column-steel beam joint carrying with the prestressed reinforcement and damping core plate, only withstood larger loads but also borne larger loads and ultimate displacements in the failure stage, ensuring the integrity of the structure.

Figure 5 shows the energy dissipation values of three types of joint specimens during quasi-static loading experiments. The specific data of energy dissipation values in the forward and reverse displacement of the beam and the total energy dissipation values of the joint specimens were also marked in Figure 5 and will not be repeated here. It was seen from Figure 5 that the energy dissipation values achieved by each type of joint specimen during the forward and reverse displacement of the beam were generally similar, but the energy dissipation value was relatively higher in the process of forward displacement due to the fact that the beam end underwent a certain degree of deformation in the forward direction after forward loading displacement, which led to a decrease in the energy dissipation capacity during reverse loading. The reason is as follows. Specimen 1 not only had prestressed reinforcement with self-centering structural function but also had a damping core plate for energy dissipation. When there was relative rotation between the beam and column in the joint, i.e., when an opening appeared at the connection, the damping core plate underwent tensile deformation to consume energy. Specimen 2 had no damping core plate, so when there was relative rotation in the joint, the stiffness was completely provided by the prestressed reinforcement, and the prestressed reinforcement underwent deformation due to tension, but its stiffness was larger than that of the damping core plate, resulting in less deformation and lower energy dissipation effect. Specimen 3 had neither a damping core plate nor prestressed reinforcement, and when the beam end was loaded, the stiffness was provided by the connecting plate between the beam and column, which also underwent deformation. However, the degree of deformation was small, and the energy dissipation capacity was poor. Moreover, when an opening appeared between the beam and column, there was no stiffness provided by prestressed reinforcement, so the unstable structure could not achieve energy dissipation.

Table 3 The centering capacity of the three types of joint specimens under an eight-degree earthquake simulation on a vibration table

	Maximum positive displacement /mm	**Maximum negative displacement /mm**	**Residual positive displacement /mm**	**Residual negative displacement /mm**	**Centering capacity coefficient**
Specimen 1	69.08	-69.35	12.41	-17.05	0.7869
Specimen 2	69.11	-69.06	17.76	-20.54	0.7226
Specimen 3	69.03	-69.16	25.82	-29.78	0.5967

The experimental results mentioned above were obtained using a quasi-static loading device. In the experiment, the load was gradually increased until the ultimate seismic resistance capacity of the joint specimen was obtained. However, in actual earthquakes, earthquakes occur randomly and have a short duration, unlike the quasi-static loading experiments where the load is gradually increased. Therefore, this study used a vibration table to simulate an eight-degree earthquake, recorded the maximum positive and negative displacement of the joint beam end and residual displacement during the process, and calculated the centering capacity coefficient of the joint specimen. The larger the capacity coefficient, the easier it was for the joint to recover after the earthquake. The centering capacities of the three joint specimens under an eight-degree earthquake on the vibration table are shown in Table 3. According to Table 3, the maximum positive and negative displacement changes that the beam end of the three types of node specimens could reach during the shaking process were almost the same. This was because the displacement changes produced at the beam end were caused by the vibration table, and all three types of specimens were subjected to the same vibration conditions. In terms of residual displacement, the residual displacement of specimen 1 was the smallest, that of specimen 2 was larger, and that of specimen 3 was the largest. Finally, the centering capacity coefficient of the 1st specimen was the largest, followed by specimen 2, and specimen 3 had the smallest coefficient.

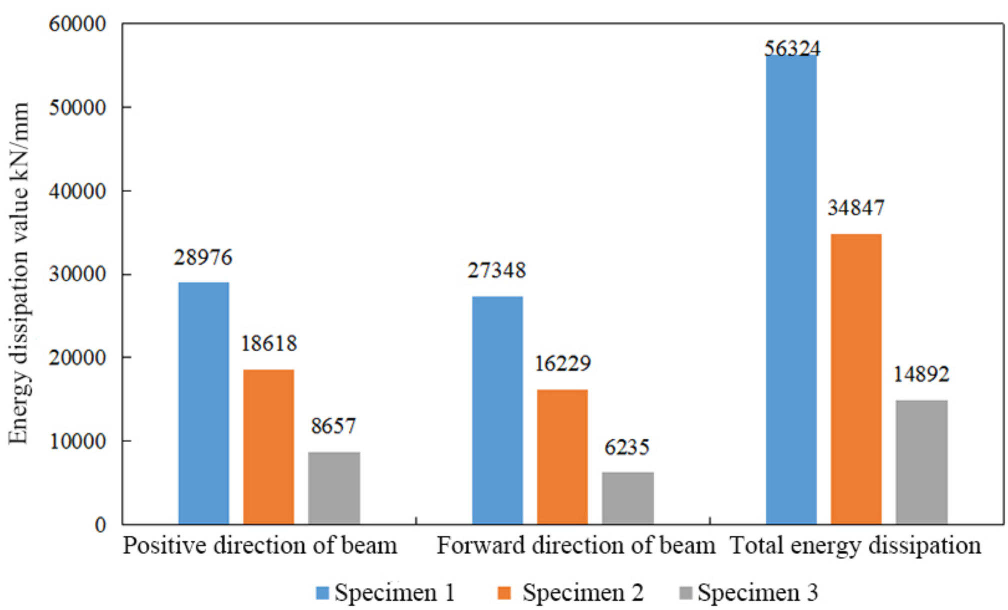

Figure 5 The energy dissipation values of three types of joint specimens during quasi-static loading experiments

4. CONCLUSION

This article briefly introduced the basic structure of self-centering RC column-steel beam joints. Three types of joint specimens were prepared. Specimen 1 was the self-centering RC column-steel beam joint, specimen 2 was obtained by removing the damping core plate from specimen 1, and specimen 3 was obtained by removing both the damping core plate and prestressed reinforcement from specimen 1. The three joint specimens were tested using quasi-static loading tests and vibration tests with an eight-degree earthquake. The resulting outcomes are as follows. The skeleton curves indicated that all three specimens were in the elastic stage when the loading displacement was . The specimens began to yield and fail when the loading displacement exceeded this range, and during this process, specimen 1 had a higher peak load and ultimate displacement. When facing cyclic loads, specimen 1 had greater energy dissipation capacity and withstood loads from vibration better. In the eight-degree earthquake vibration, the maximum positive and negative displacements of the three joint specimens were not significantly different; the residual displacement of specimen 1 was the smallest, followed by specimen 2, and specimen 3 had the largest residual displacement. Finally, the centering capacity coefficient of specimen 1 was the largest, followed by specimen 2, and specimen 3 had the smallest coefficient.

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