

Two-stage Power System Transient Stability Assessment Based on Post-disturbance Measurement Response Information

Du Y., Hu Z., Wang F., Zhang Y.

Henan Polytechnic Institute, Nanyang, Henan 473000,
China

ABSTRACT

In order to minimize the loss of life and property in an earthquake, the beam-column joints of buildings need to have good seismic performance. This paper briefly introduced concrete beam-column joints and used a steel skeleton to strengthen the seismic performance of concrete beam-column joints. The concrete beam-column and reinforced concrete beam-column joints were prepared for experimental analysis. The skeleton curve and energy dissipation capacity of the joints were tested using quasi-static loading experiments. The relative displacement of the column at different heights in the beam-column joints was tested under an eight-degree earthquake simulated by a vibration table. The results showed that the reinforced concrete beam-column joint had higher peak loads and ultimate displacements when the quasi-static loading displacement exceeded the yield displacement; the reinforced concrete beam-column joint had stronger energy dissipation capacity in the face of cyclic loads; the reinforced concrete beam-column joint had smaller relative column displacements in the face of an eight-degree earthquake.

1. INTRODUCTION

The rapid economic development has led to the transformation of rural areas into cities, and this process has led to an increase in not only traffic and roads but also buildings of all kinds [1]. However, due to the movement of the earth's crust, earthquakes can occur on the surface, resulting in a large number of casualties. One reason for casualties is that the vibration from the earth's crust can drive the surface buildings to vibrate together, and breakage will occur when the limits of building materials are exceeded [2]; the other reason is that earthquakes are random and cannot be accurately predicted by current technical means, resulting in no room for timely evacuation. Therefore, the main way to reduce the damage caused by earthquakes is still to improve the seismic strength of buildings. Concrete is the building material used in most buildings, which has good plasticity before solidification and good mechanical properties after solidification [3]. However, concrete has limits in the face of earthquake vibrations. In order to improve the seismic performance of concrete beam-column joints in buildings, in addition to strengthening the concrete itself, skeletons [4] can be added to the building parts (e.g., beam-column joints, etc.) when they are made, and the material of the skeleton varies according to the requirements. In this study, the relatively common steel was used as the supporting structure.

Liang et al. [5] studied the seismic performance of fiber-reinforced concrete beam-column joints through experiments and numerical simulations and found that the application of fiber-reinforced concrete could effectively improve the seismic performance of beam-column joints. Kang et al. [6] proposed a simplified model of reinforced concrete beam-column joints under earthquake loads, calculated the yield displacement of beam-column joints, and performed verification based on test data. Nteel beams, numerically simulated the joint under monotonic and cyclic loads using a finite element program and verified that this type of joint had a good seismic performance. Mou et al. [8] conducted experiments on a new beam to reinforced concrete-filled steel tube column joint and found through experiments that the cross section of the transfer sleeve in the column node was the key factor affecting the strength of the beam-column node. Chen et al. [9] investigated the seismic performance of a circular concrete an et al. [7] proposed a joint type of concrete-filled square steel tubular columns and filled steel tubular column-reinforced concrete beam frame under low cyclic loading and found through tests that the design method of the recycled aggregate concrete filled circular steel tube frame met the seismic design requirements of a stronger joint followed by the stronger column and the weaker beam and the frame had has good collapse resistance and energy dissipation capacity. In this paper, concrete beam-column joints were briefly introduced, the seismic performance of concrete beam-column joints was strengthened by a steel skeleton, and concrete beam-column joints and reinforced concrete beam-column joints were prepared for experimental analysis.

2. CONCRETE BEAM-COLUMN JOINTS

The beam and column structures interlock to form the general structure of a building, and the intersection of the beam and column is the building joint [10]. For a building, the mechanical properties of its beam-column joints directly affect the stiffness, strength and stability of the building structure. It is because that the beam-column joints play a role in the building structure to connect the horizontal and vertical structures, which is equivalent to the joints of the human body. Once the joints have problems, even if the “bones” are of high quality, they cannot form a whole [11].

For a building, the load due to gravity can be regarded as vertical load, the transmission path of the vertical load in the building structure from top to bottom is “floor - beam - column - foundation”. The upper load of the building must pass through the beam-column joint [9] when the vertical load is transmitted downward [12]. When the vertical load is transmitted to the beam-column joint, the contact surface of the load suddenly becomes smaller, and the stress will also change greatly. As the size of the joint between the beam and column is small compared to the overall structure and they are not a whole, the beam-column joint is considered as the weak point in the transmission path [13]. When an earthquake occurs, the beam-column joints in the building will be affected by the vibration from the ground, the internal stresses will change significantly, and this change is random and unstable, which will easily lead to joint deformation. In order to ensure that the upper load of the building can be transferred to the foundation smoothly, it is necessary to ensure that the joints do not undergo excessive deformation under the action of the earthquake.

Concrete is a common material in buildings, and its good plasticity before solidification makes it relatively easy to make different shapes of building structures. It has good mechanical properties after solidification [14], but building structures made of concrete are usually solid, which makes the stress inside the structure have a great impact on the structure, especially under the influence of earthquakes. A hollow structure can avoid the effect of internal stresses but will also cause a reduction in the strength of the structure [15].

Steel can also be used as a building material and has the advantages of being easily retrofitted and recyclable. Buildings with steel as the main material have poor fire resistance, i.e., they will soften under high temperatures, making it difficult to carry large loads, but in conventional environments, steel structures can effectively carry stress changes [16]. Therefore, in order to improve the seismic performance of concrete beam-column joints, steel structures are used. Mainly, the steel skeleton structure of the beam-column joint is produced based on the plasticity of steel, and then concrete is poured on the steel skeleton structure to produce a concrete beam-column joint containing a steel skeleton. Compared with the traditional concrete beam-column joints, the reinforced concrete beam-column joints is no longer completely solid inside, and the stress changes inside the concrete due to earthquakes will be borne by the internal steel skeleton with better toughness, thus reducing the impact of stress on the concrete structure.

3. EXPERIMENTAL ANALYSIS

3.1. Specimen Preparation

Figure 1 shows a schematic diagram of the reinforced concrete beam-column joint specimen fabricated in this study. The joint specimen was cross-shaped. The length of the beam in the transverse direction was 2100 mm. The cross-section of the beam was a 300 mm × 200 mm rectangle. The length of the column in the longitudinal direction was 1700 mm. The cross-section of the column was a 300 mm × 300 mm rectangle. In addition to C80 concrete [17], steel bars with a diameter of 16 mm were also used as the steel skeleton in the preparation of the reinforced concrete beam-column joint, and the architecture of the skeleton is shown in Figure 1.

C80 concrete was prepared with 375 kg of cement, 90 kg of fly ash, 50 kg of silica fume, 90 kg of slag powder, 750 kg of sand, 1100 kg of gravel, 8 kg of water reducing agent and 135 kg of water. The mechanical properties of the prepared solidified C80 concrete are as follows. The average cube compressive strength was 79.5 MPa, the standard cube compressive strength was 65.0 MPa, the standard compressive strength was 42.4 MPa, the standard tensile strength was 30.2 MPa, the Poisson's ratio was 0.2, and the modulus of elasticity was 380 GPa. The mechanical properties of steel bars used in this study are as follows: the yield strength was 670.3 MPa, the ultimate strength was 856.6 MPa, and the modulus of elasticity was 200 GPa.

In addition to the above reinforced concrete beam-column joint specimens, concrete beam-column joint specimens with the same specifications were prepared, and their shape and structure were the same as in Figure 1 except the steel skeleton.

Six specimens were prepared for every kind of beam-column joint. Three concrete beam-column joints and three reinforced concrete beam-column joints were used for the quasi-static loading experiments, and the remaining specimens were used for the seismic experiments under the eight-degree seismic waves. Average values were taken as the final experimental results.

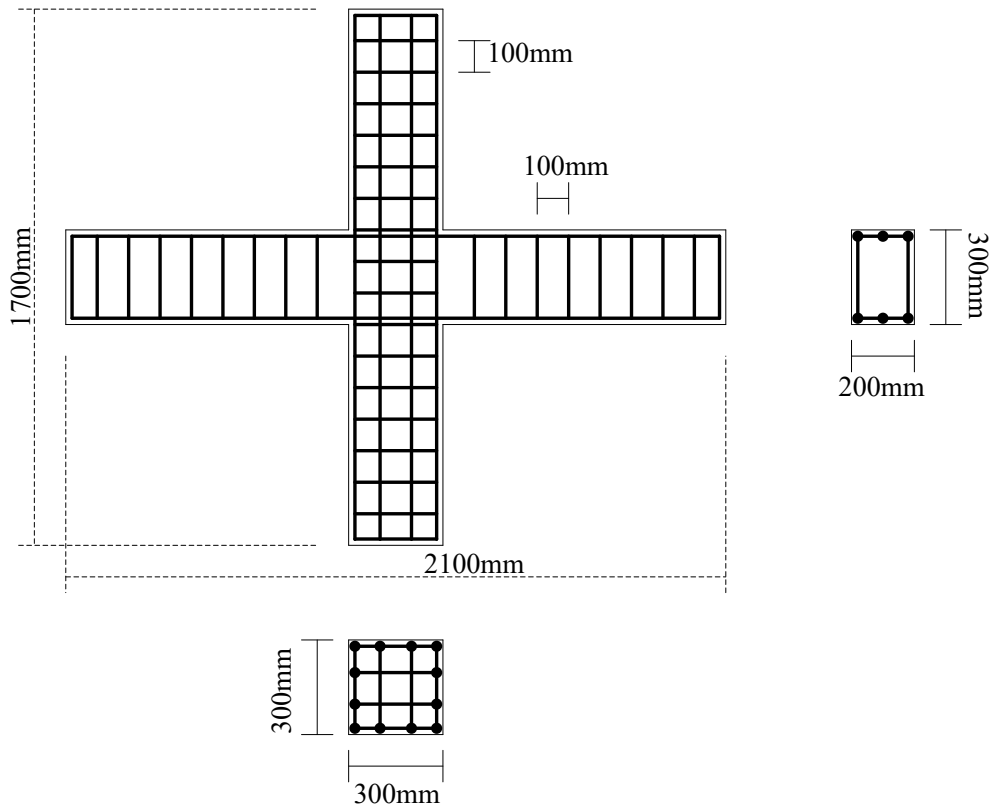


Figure 1. Schematic diagram of a reinforced concrete beam-column joint

3.2. Experimental Project

3.2.1. Seismic performance of beam-column joints under quasi-static loading

A gradually increasing repeated cyclic load was applied to the beam-column joints using a quasi-static loading device [18] under artificial control to measure the seismic performance of the beam-column joints in the controlled environment. Figure 2 shows the schematic diagram of the experimental setup for the quasi-static loading. The main structure included electro-hydraulic servo testing machine, dynamic signal acquisition system, displacement sensor, stress sensor, hydraulic jack, and push-pull jack [19]. The displacement sensor was installed outside the specimen, and the stress sensor was buried during the preparation of the beam-column joints.

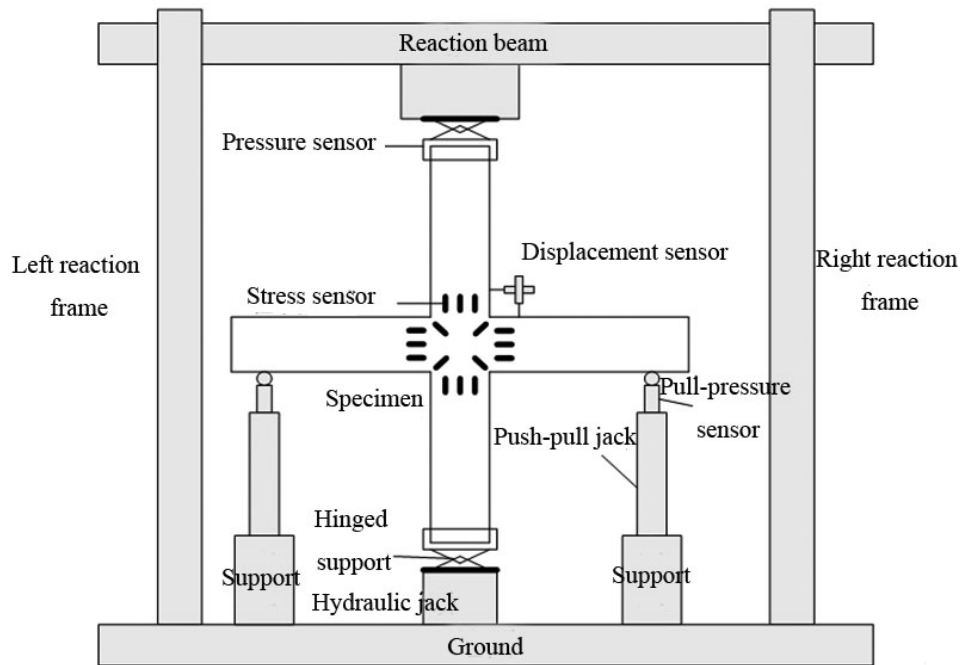


Figure 2. Schematic diagram of the experimental setup for quasi-static loading

After setting up the device and the specimen, the specimen was loaded. The quasi-static loading mode was displacement loading [20]. Firstly, axial pressure was applied to the column using a hydraulic jack to the target size. Then, repeated cycle loads were applied to the beam using a push-pull jack at both ends of the beam. Initially, every level of load was applied for one cycle, and the increment between every level of load was 5 mm. Then, the load was improved step by step until the specimen yielded (when the longitudinal tensile strain in the plastic hinge region of the beam reached 3300, the joint yielded, and the displacement at the beam end was the yield displacement at that moment). After that, the increment of every level of load became half of the yield displacement. The test ended when the load value at the beam end dropped to 85% of the peak value during the test, when the specimen was severely damaged locally or when the structural deformation of the joint increased sharply.

3.2.2. Seismic performance of beam-column joints under high-intensity seismic signals simulated by vibration table

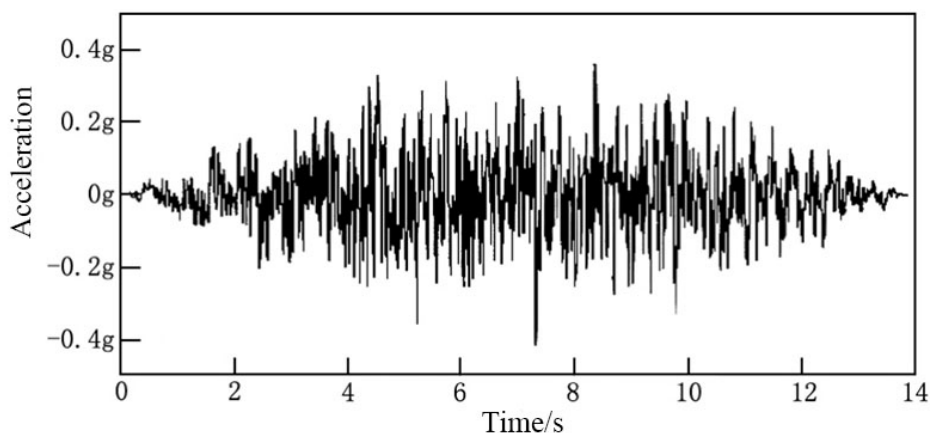


Figure 3. Artificially fitted eight-degree seismic wave

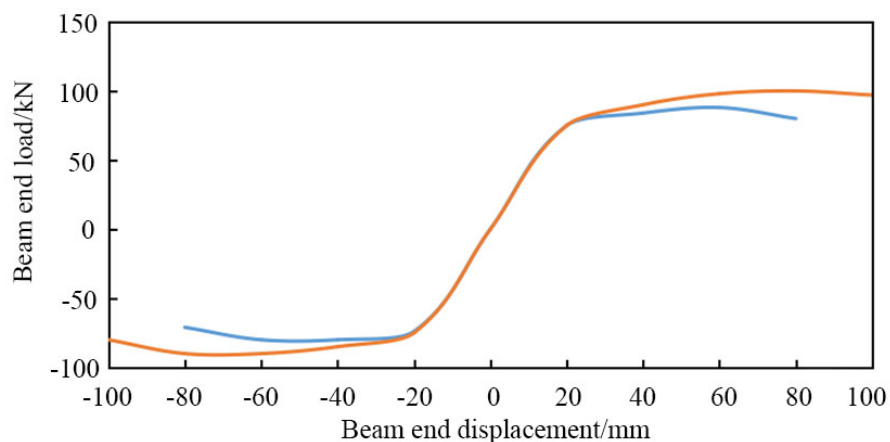
The quasi-static loading test detected the seismic performance of beam-column joints when the cyclic load was gradually increased in a controlled environment, but realistic earthquakes are random and short-lived. Thus, the seismic performance of the joints under high-intensity earthquakes simulated by the vibration table was detected. The experimental steps are as follows.

1. The beam-column joint specimen was prepared as described above, and then the bottom end of the column was connected to the vibration table using an L-shaped steel plate, and a displacement sensor was set up every 100 mm in the column area from bottom to top along the axial direction.
2. The vibration table was turned on to vibrate the specimen with the eight-degree seismic signal. The seismic signal is shown in Figure 3.
3. When the vibration was over, the interlayer displacement of the column was recorded using the installed displacement sensors.

3.3. Experimental Results

During the quasi-static loading, the peak of the load-displacement curve of the first cycle of every loading level was connected into an envelope curve, i.e., the skeleton curve. The skeleton curve reflected the bearing capacity of the specimen under different loading levels, which could judge the resistance of the specimen in the face of earthquake vibration. Figure 4 shows the skeleton curves of the two specimens under the same loading system. It was seen from Figure 4 that under the same loading system, when the displacement of the beam end was between -20 mm and 20 mm, the skeleton curves of the two specimens nearly overlapped and were approximately linear, and the two specimens were in the elastic change stage. After the displacement of the beam end exceeded the range of -20 mm and 20 mm, the slope of the skeleton curves of both specimens decreased significantly, and the beam end in both specimens gradually reached the peak load; at that moment, the beam end displacement corresponding to the peak beam end load at the reinforced concrete beam-column joint was larger than that at the concrete beam-column joint, and the peak beam end load that can be reached was also larger than that at the concrete beam-column joint.

After reaching the peak beam end load, the load-displacement continued to increase, and the beam end load started to decrease; in this stage, the structure of the beam-column joint has been destroyed, the load of the reinforced concrete beam-column joint decreased slowly, and the ultimate load and the beam end displacement corresponding to the ultimate load were larger in the reinforced concrete beam-column joint than the concrete beam-column joint.



— The concrete beam-column joint — The reinforced concrete beam-column joint

Figure 4. Skeleton curves of two specimens

The comparison results of the skeleton curves showed that the reinforced concrete beam-column joint withstood not only greater loads in the face of the gradually increasing repeated cyclic loads (i.e., vibrations) but also greater loads and ultimate displacements in the damage phase, guaranteeing the structural integrity.

As shown in the previous skeleton curve, in the early stage of loading, both specimens were in the elastic stage, and the loading displacement had a linear relationship with the beam end load. When every level of loading displacement reached and then withdrew, its beam end load also reduced, and the reduction coincided with the amount of change at loading. After the loading displacement reached the yield displacement of the specimen, it was no longer the elastic deformation. After every level of loading displacement was unloaded, the structure of the specimen failed to fully restore to its original shape, and the deformation residual prevented the curve at unloading from coinciding with the curve at loading. As the increasing load was loaded and unloaded cyclically, the load-displacement curve finally became annular, and the area surrounded by the annular curve was the energy absorbed by the specimen from cyclic loads. . Figure 5 shows the energy dissipation capacity of the two specimens during loading. The left beam was the beam end in the direction of the left reaction frame, and the right beam was the beam end in the direction of the right reaction frame. The displacement load applied upward was the forward direction, and the displacement load applied downward was the reverse direction. For the concrete beam-column joint, the cumulative energy consumption of the left beam was 1.8618×10^4 kN·mm under loading in the forward direction and 1.6229×10^4 kN·mm under loading in the reverse direction; the cumulative energy consumption of the right beam was 3.2220×10^4 kN·mm under loading in the forward direction and 2.9309×10^4 kN·mm under loading in the reverse direction.

The total energy consumption of the concrete beam-column joint was 9.6376×10^4 kN·mm. For the reinforced concrete beam-column joint, the cumulative energy consumption of the left beam was 2.5705×10^4 kN·mm under loading in the forward direction and 2.9344×10^4 kN·mm under loading in the reverse direction; the cumulative energy consumption of the right beam was 4.4021×10^4 kN·mm under loading in the forward direction and 4.9751×10^4 kN·mm under loading in the reverse direction. The total energy consumption of the reinforced concrete beam-column joint was 14.8821×10^4 kN·mm. It was seen from the comparison in Figure 5 that the reinforced concrete beam-column joint had a greater energy dissipation capacity in the face of cyclic loading and was more capable of withstanding the load from vibration.

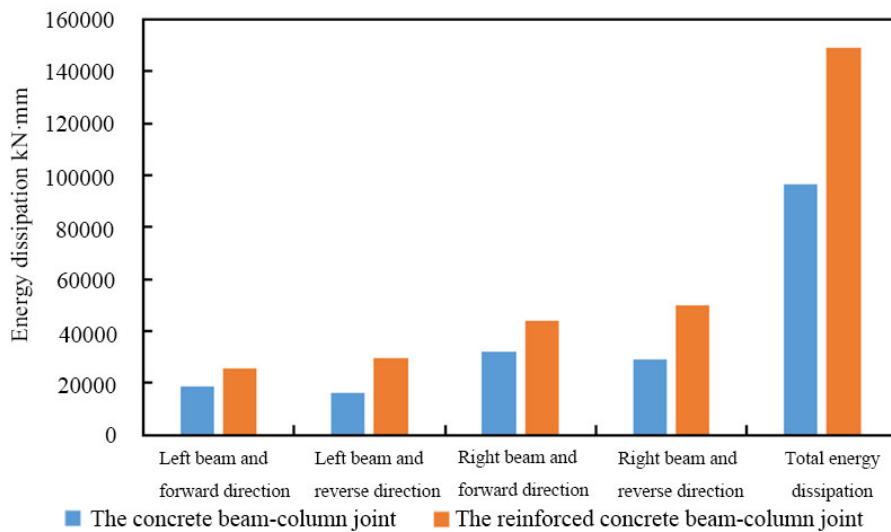


Figure 5. Energy dissipation capacity of two specimens during loading

The results of the above two experiments were the test results obtained under the quasi-static loading system. The cyclic loads on the beam-column joints were progressively increasing controllable loads for testing the ultimate seismic performance of the beam-column joints. However, in reality, earthquakes are random in nature and usually short in duration and do not increase the load gradually as in the quasi-static loading experiments. Therefore, this paper used a vibration table to simulate an eight-degree earthquake and tested the relative displacements of columns at different heights in the beam-column joints under this seismicity, as shown in Figure 6. It was seen from Figure 6 that the relative column displacements of both specimens tended to increase with the increase of column height under eight-degree earthquake, but the higher it was, the less the increase was the relative column displacements of the reinforced concrete beam-column joint were smaller under the same column height.

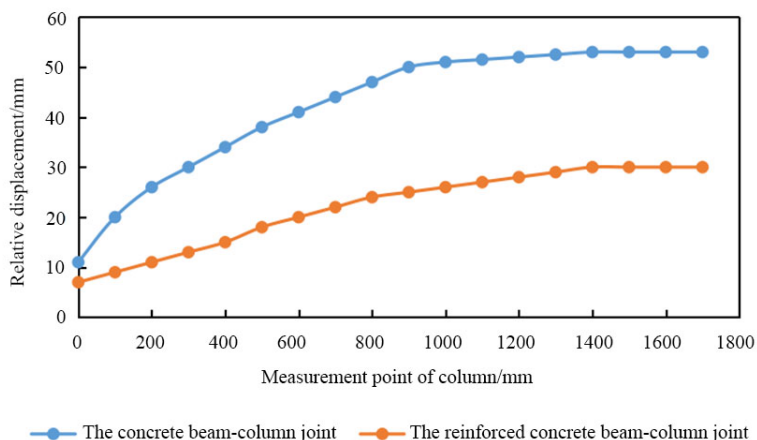


Figure 6. Relative displacement of the column at different heights in two specimens under eight-degree earthquake

4. CONCLUSION

This paper briefly introduced concrete beam-column joints and used a steel skeleton to strengthen the seismic performance of concrete beam-column joints. The concrete beam-column joint and reinforced concrete beam-column joint were prepared for experimental analysis. The skeleton curve and energy dissipation capacity of the joints were tested using quasi-static loading experiments. The relative displacement of the column at different heights in the beam-column joints was tested under an eight-degree earthquake simulated by a vibration table. The results are as follows. The skeleton curves showed that when the loading displacement at the beam end was between -20 mm and 20 mm, both specimens were in the elastic stage; when the loading displacement exceeded the range, the specimens yielded and was damaged, and the reinforced concrete beam-column joint had higher peak load and ultimate displacement in this process. The reinforced concrete beam-column joint had greater energy dissipation capacity in the face of cyclic loads and was more capable of withstanding the loads from vibrations. Under the eight-degree earthquake, the relative column displacement increased with the increase of the column height, but the higher it was, the smaller the increase was the relative column displacement of the reinforced concrete beam-column joint was smaller for the same column height.

REFERENCES

- [1] Melo, J., D.A. Pohoryles, T. Rossetto, and H. Varum, Full-scale cyclic testing of realistic reinforced-concrete beam-column joints. *MethodsX*, 2021. 8: p. 101409.
- [2] Jia, S., W. Cao, and Z. Liu, Experimental study on seismic performance of a low-energy consumption composite wall structure of a pre-fabricated lightweight steel frame. *Royal Society Open Science*, 2019. 6(4).
- [3] Lu, X., B. Zhao, and D. Wang, Experimental Study on Seismic Performance of Precast Concrete Shear Wall with Joint Connecting Beam Under Cyclic Loadings. *Journal of Building Structures*, 2015. 35(10): p. 373-386.

- [4] Xiao, J., Z. Chen, T. Ding, and B. Xia, Effect of recycled aggregate concrete on the seismic behavior of DfD beam-column joints under cyclic loading. *Advances in Structural Engineering*, 2020. 24(8): p. 136943322098272.
- [5] Liang, X.W., Y.J. Wang, Y. Tao, and M.K. Deng, Seismic performance of fiber-reinforced concrete interior beam-column joints. *Engineering Structures*, 2016. 126: p. 432-445.
- [6] Kang, S.B. and K.H. Tan, A simplified model for reinforced concrete beam-column joints under seismic loads. *Magazine of Concrete Research*, 2018. 70(3-4): p. 138-153.
- [7] Nan, L. and N.Z. Dong, Numerical Simulation of Joint between Concrete-Filled Square Steel Tubular Column and Steel Beam on Seismic Behavior. *Applied Mechanics and Materials*, 2015. 744-746: p. 207-210.
- [8] Mou, B., X. Liu and Z. Sun, Seismic behavior of a novel beam to reinforced concrete-filled steel tube column joint. *Journal of Constructional Steel Research*, 2021. 187(2): p. p. 106931.
- [9] Chen, Z., J. Zhou, Z. Li, X. Wang and X. Zhou, Seismic Behavior of Concrete-Filled Circular Steel Tubular Column - Reinforced Concrete Beam Frames with Recycled Aggregate Concrete. *Applied Sciences*, 2020. 10(7): p. 2609.
- [10] Zhang, Z.Y., R. Ding, X. Nie, and J.S. Fan, Seismic performance of a novel interior precast concrete beam-column joint using ultra-high performance concrete. *Engineering Structures*, 2020. 222(3): p. 111145.
- [11] Nahar, M., A. Billah, H.R. Kamal, and K. Islam, Numerical seismic performance evaluation of concrete beam-column joint reinforced with different super elastic shape memory alloy rebars. *Engineering Structures*, 2019. 194: p. 161-172.
- [12] Attari, N., Y.S. Youcef, and S. Amziane, Seismic performance of reinforced concrete beam-column joint strengthening by frp sheets. *Structures*, 2019. 20: p. 353-364.
- [13] Zhou, J., T. Kang, F. Wang, and Y. Shu, Experimental study on the seismic behaviors of wasted fiber recycled concrete frame joints. *World Information on Earthquake Engineering*, 2017. 36(2): p. 235-242.
- [14] Feng, S., D. Guan, Z. Guo, Z. Liu, G. Li and C. Gong, Seismic performance of assembly joints between HSPC beams and concrete-encased CFST columns. *Journal of Constructional Steel Research*, 2021. 180(8-9): p. 106572.s
- [15] Ugale, A.B. and S.N. Khante, Study of energy dissipation of reinforced concrete beam-column joint confined using varying types of lateral reinforcements. *Materials Today: Proceedings*, 2020. 27(7).
- [16] Sivapriya, J. and S. Sruth, Seismic Vibration Reduction of Beam Column Joint in Buildings with Step-Backs. *Materials Today: Proceedings*, 2020. 24(4): p. 1100-1111.
- [17] Deng, M., F. Ma, S. Song, H. Lü, and H. Sun, Seismic performance of interior precast concrete beam-column connections with highly ductile fiber-reinforced concrete in the critical cast-in-place regions. *Engineering Structures*, 2020. 210: p. 110360.
- [18] Aavi-Dehkordi, S., D. Mostofinejad, and P. Alaei, Effects of high-strength reinforcing bars and concrete on seismic behavior of RC beam-column joints. *Engineering Structures*, 2019. 183(MAR.15): p. 702-719.

- [19] Cheng, G., X. Zhou, J. Liu, and Y. Chen, Seismic behavior of circular tubed steel-reinforced concrete column to steel beam connections. *Thin-Walled Structures*, 2019. 138(MAY): p. 485-495.
- [20] Shi, Q., Y. Ying, B. Wang, Experimental investigation on the seismic performance of concrete-filled steel tubular joints in diagrid structures. *Structures*, 2021. 31: p. 230-247.

