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Analysis of a Prefabricated Beam Column Joint Component with Energy Consuming Steel Plates

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Abstract: Prefabricated structures have the advantages of short construction period, fast construction speed, and low environmental pollution. Based on this, a new type of prefabricated beam column node with energy dissipating steel plates is proposed. The structure mainly consists of prefabricated beams, columns, prefabricated energy dissipating hinge structures, etc. A finite element model is established for analysis and comparison with cast-in-place structures. It is found that the seismic performance of prefabricated beam column nodes with energy dissipating steel plates is better, and their displacement ductility and energy dissipation capacity are much higher than cast-in-place structures. A prefabricated frame structure system with energy dissipating steel plates is established to study its structural failure sequence.

Key words: beam-column nodes; energy consuming steel plate; prefabricated structure; seismic performance

1. Introduction

Prefabricated nodes are the core of an prefabricated structure, and beam-column nodes serve as the main force transmitting structure, while also bearing the lateral resistance of the structure. The performance of nodes directly affects the safety and stability of the overall structure, and scholars have conducted extensive research on different prefabricated nodes.

Bruneau et al. proposed three possible scenarios and corresponding measures for energy dissipation and seismic reduction in prefabricated structures: (1) If the main body of the structure is less damaged or not damaged, its function can still be operated normally without taking measures; (2) Mild damage to the structure has a minor impact on its functionality, and the structure can continue to be used after simple repairs; (3) If the structure is damaged and its function is affected, immediate repair can restore normal function to the structure. Zhang et al. made a steel structure with restorable function and fabricated hole steel beam column joints, focusing on the performance effects of five parameter changes: cover plate thickness, bolt spacing, cover plate weakening width, and bolt quantity on the nodes. The research results indicate that the structure has excellent bearing capacity and recoverability. Weakening the cover plate can achieve plastic hinge area control of the beam-column node. The spacing between bolts is related to the maximum bearing capacity of the beam-column node, and the thickness of the cover plate in the beam column connection section is related to the yield load and maximum bearing capacity of the beam-column node.

Ghayeb et al. designed a prefabricated steel-concrete joint. Through loading tests, it is proved that the load-displacement curve of the joint is full, the energy dissipation capacity is strong, and the displacement ductility is good.

Li L et al. designed and fabricated a semi-dry steel-concrete beam column joint, and studied the effect of prestressed and axial compression ratio at the end of the column on the seismic performance of the joint. The conclusion showed that the seismic performance of prestressed precast reinforced concrete joints is similar to cast-in-place node. Ainthaneni et al. made a detachable precast concrete-beam column node, and after loading test, it was found that the damage of this kind of joint was mainly concentrated in the angle steel at the end of the precast beam and the concrete near the steel plate at the end of the beam. And the calculation formula of ultimate bearing capacity of joints was proposed.

It can be seen that current research on prefabricated beam column nodes mainly focuses on steel nodes and prestressed nodes, with less research on reinforced concrete nodes. This paper proposes a new type of prefabricated beam-column node component with energy dissipating steel plates.

2. Node Construction

The construction of prefabricated beam-column components containing energy consuming steel plates is shown in Figure 1. The prefabricated beam end is connected to the core area of the column end by a steel sleeve wrapped around the weakened steel plate and pin shaft. The node mainly consists of weakened energy consuming steel plates, shear transfer pin shafts and ear plates, prefabricated concrete beams and columns, and other components. The upper and lower connectors of the prefabricated energy dissipation hinge structure (Figure 2) are energy dissipation steel plates, with a pin structure in the middle that transfers shear force. After welding the precast beam end to the energy dissipation hinge structure, it is then welded to the steel sleeve in the core area of the precast concrete column. Figure 3 shows the dimensions and reinforcement diagram of a new type of prefabricated beam column node with energy consuming steel plates. The column section size is 400mm × 400mm, with a height of 2500mm. The precast concrete beam section size is 250mm × 550mm, with a length of 1000mm.

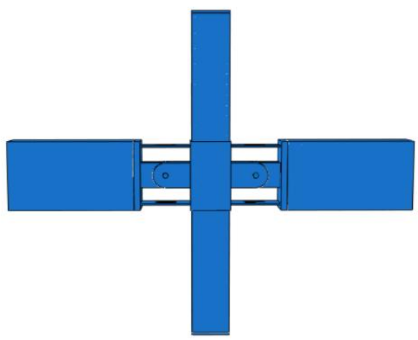


Figure 1. Prefabricated beam column components with energy consuming steel plates.

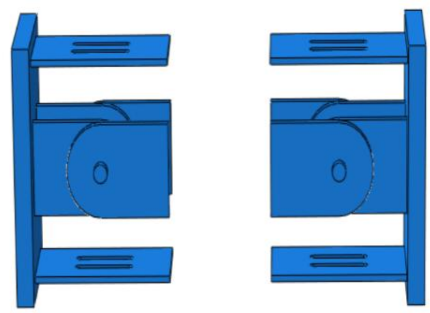


Figure 2. Prefabricated energy dissipation hinge structure.

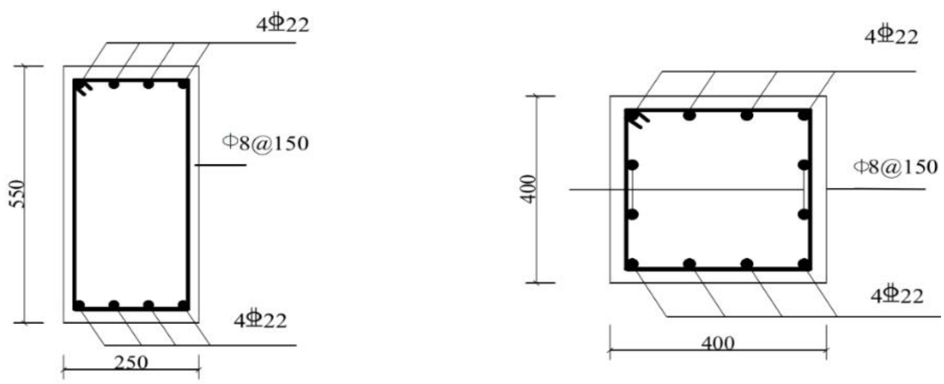
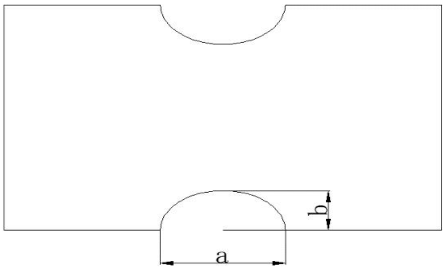
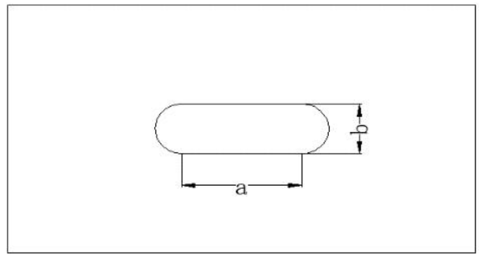


Figure 3. Reinforcement diagram for beams and columns.

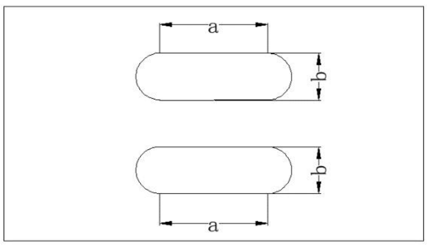
This article proposes four different weakening shapes of energy consuming steel plates based on the failure modes of the plates and engineering experience (as shown in Figure 4), and establishes and calculates a large number of finite element numerical models. By analyzing the stress of the four different weakening shapes of energy consuming steel plates under different aspect ratios, weakening lengths, and opening ratios, the mechanical properties such as failure modes, skeleton curves, stiffness degradation, and energy dissipation capacity are studied. Based on the steel utilization rate and energy dissipation capacity, suitable energy consuming steel plates are selected as the energy consuming components in the new node proposed in this article. Finally, the vertical seam double opening weakening steel plate is selected as the energy consuming steel plate component in the new component in this article.



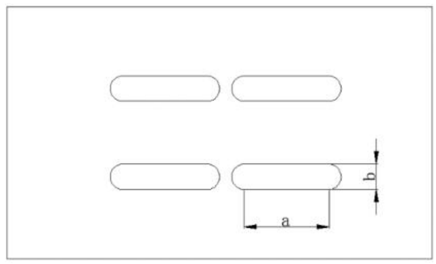
(a) Dog-bone style weakened



(b) Vertical seam single hole weakened



(c) Vertical seam double opening weakened



(d) Continuous weakening of vertical seam with double openings

Figure 4. Schematic diagram of weakened steel plates with different shapes.

3. Structural Seismic Performance Analysis

3.1 Finite element element selection and mesh partitioning

The plastic damage model of concrete is used as the constitutive model of concrete material in this paper, and the steel adopts the double line model. The selection of appropriate element types in ABAQUS finite element software can ensure the accuracy of the calculation results. In this article, solid three-dimensional single element (C3D8R) is used for concrete, energy consuming steel plates, and loading end plates, and truss elements (T3D2) that only bear uniaxial tensile and compressive loads are used for steel reinforcement simulation. The node connection is located in the stress concentration area, which should use more refined grid elements. For areas with lower stress and areas far from the node, the grid size can be appropriately increased. The selection and size division of grid elements not only affect the accuracy of the calculation results, but also affect the speed of finite element iteration. A grid that is too fine can seriously affect the calculation speed, so an appropriate grid size should be selected for calculation.

3.2 Contact relationships and boundary conditions

Embed steel bars into concrete elements of prefabricated beams and columns using the embedding constraints in ABAQUS finite element software. The loading pad and concrete unit are constrained by binding, and the contact between the outer surface of the pin shaft and the ear plate is made using the universal contact in ABAQUS software. The steel sleeve at the end of the column is in hard contact with the concrete in the normal direction; Use Coulomb friction model contact in the tangent direction. This experiment is designed with an axial compression ratio of 0.3, and a constant 750kN concentrated force is applied at the top of the upper column. Simulated fixed hinge support constraints at the bottom of the column allow it to only rotate freely in the plane, i.e. only opening UR1 degrees of freedom. The two ends of the beam are allowed to move horizontally, with U1 degrees of freedom open. After the top pressure of the column is loaded, displacement load at the end of the beam is applied. Before formal loading, a small displacement is applied to ensure that the structure can load normally. Then, the loading is carried out in displacement angle series of 0.25%, 0.5%, 0.75%, 1%, 1.5%, 2%, 2.75%, 3.5%, 4.25%, 5%, and 5.75%. Each displacement cycle is loaded three times.

3.3 Seismic performance analysis

3.3.1 Seismic performance analysis of beam-column joints

The finite element loading results are shown in the following figures. Figure 5 shows the plastic damage diagram of the energy consuming steel plate in the new prefabricated component with energy consuming steel plate, Figure 6 shows the concrete damage of the new prefabricated component with energy consuming steel plate, and Figure 7 shows the damage of the cast-in-place structure.

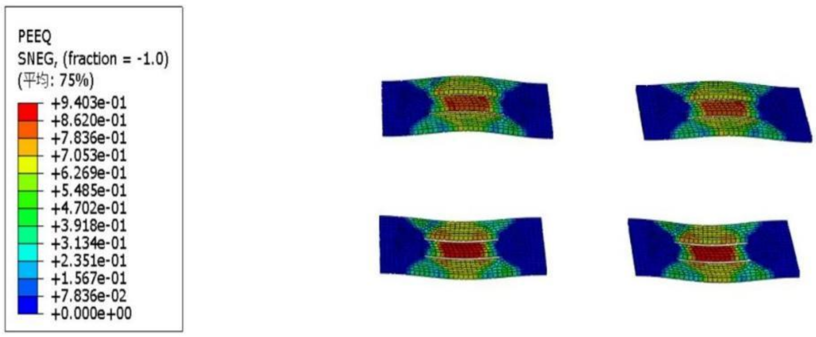


Figure 5. Accumulated plastic strain when energy consuming steel plates are damaged.

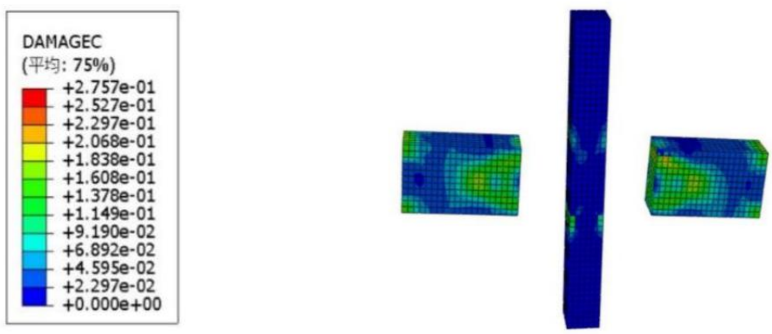


Figure 6. Plastic damage diagram of concrete in a new prefabricated structure with energy dissipating steel plates.

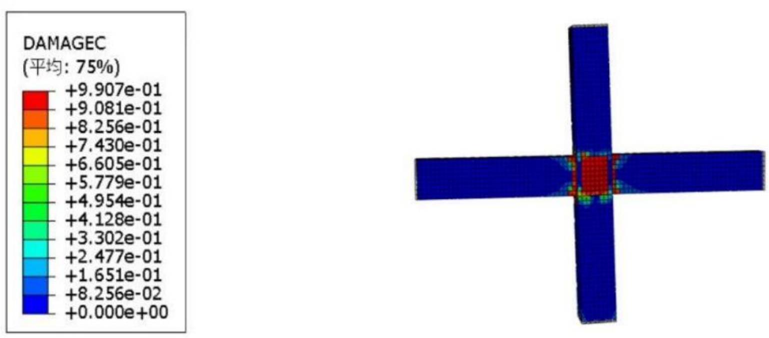


Figure 7. Plastic damage diagram of cast-in-place concrete structure.

Figure 8 shows the hysteresis curves of prefabricated beam-column node with energy dissipating steel plates and a common cast-in-place reinforced concrete node, while Figure 9 shows their skeleton curves.

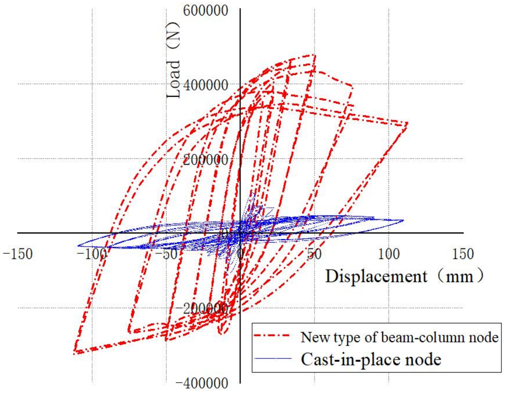


Figure 8. Hysteresis curve.

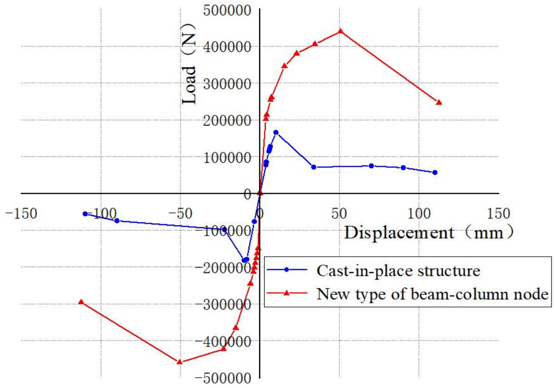


Figure 9. Skeleton curve.

By comparing the hysteresis curve and skeleton curve of the new prefabricated beam-column nodes with energy consuming steel plates and ordinary cast-in-place reinforced concrete beam-column nodes, it is found that the hysteresis curve of the new prefabricated beam column nodes with energy consuming steel plates is more full, and their bearing capacity and displacement ductility are also better.

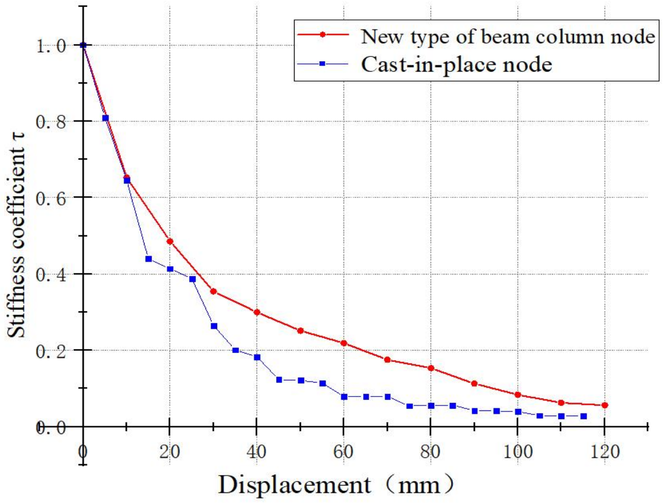


Figure 10. Stiffness degradation curve.

Figure 10 shows the stiffness degradation curves of prefabricated beam column node and cast-in-place node with energy consuming steel plates. The new type of prefabricated beam column nodes with energy consuming steel plates in the initial stage of loading have similar initial stiffness to ordinary cast-in-place reinforced concrete beam column nodes, indicating that the new type of prefabricated beam column nodes with energy consuming steel plates have reached the principle of equivalent stiffness to cast-in-place nodes. In the middle stage of loading, the stiffness degradation rate of cast-in-place reinforced concrete nodes is significantly faster than that of the new prefabricated beam column nodes with energy consuming steel plates, and their final structural stiffness is also lower than that of the new prefabricated beam column nodes with energy consuming steel plates. For cast-in-place concrete nodes, when cracks appear in the concrete, the rate of stiffness decrease significantly accelerates. As the plasticity of the concrete gradually accumulates, the core concrete at the beam column connection eventually experiences shear failure. In the new prefabricated beam column nodes with energy consuming steel plates, before the concrete at the beam end begins to yield, the energy consuming steel plates yield first, and the structural damage and plastic development are transferred to the energy consuming steel plates. The energy consuming steel plates play a role in transferring plastic hinges, effectively protecting the concrete in the core area.

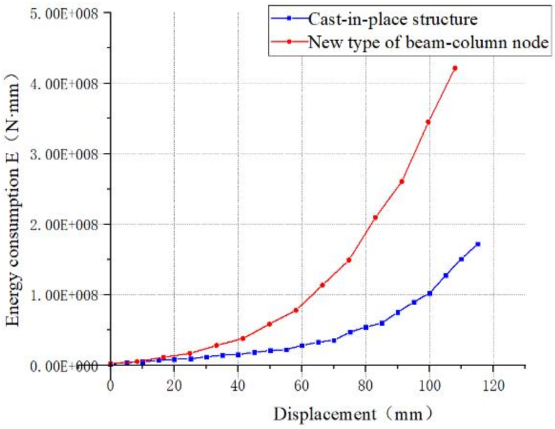


Figure 11. Accumulated hysteresis energy consumption.

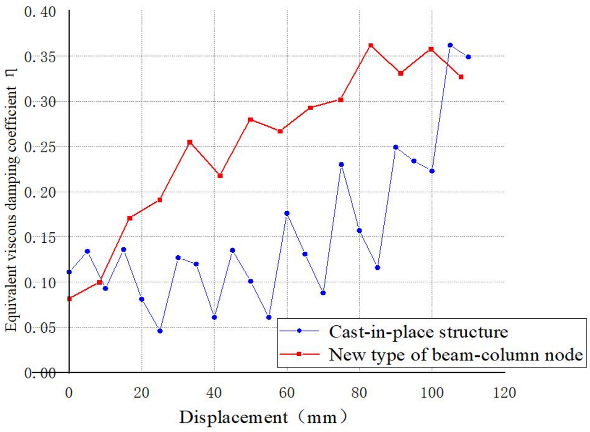


Figure 12. Equivalent viscous damping coefficient.

The cumulative energy consumption curve (Figure 11) and viscous damping coefficient (Figure 12) of the new prefabricated beam column node with energy dissipating steel plate in the above figures are compared with those of ordinary cast-in-place reinforced concrete beam column nodes. The comparison shows that the energy dissipation capacity of the new prefabricated beam column node with energy dissipating steel plate is significantly better than that of ordinary cast-in-place reinforced concrete beam column nodes, and its damping coefficient is also higher than that of cast-in-place reinforced concrete beam column joints. This indicates that the new prefabricated beam column node with energy dissipating steel plate has a significant energy dissipation advantage compared to cast-in-place reinforced concrete beam column nodes.

3.3.2 Failure sequence analysis of prefabricated frame structures

This article uses finite element analysis software to establish a new type of prefabricated frame structure with energy dissipating steel plates, and compares it with cast-in-place concrete frame structures of the same size, as shown in Figures 13 and 14. Its floor height is 3m, and the clear span of the beam is 4.4m. A horizontal displacement load is applied to the upper layer of the structure to study the failure evolution process of the two structures.

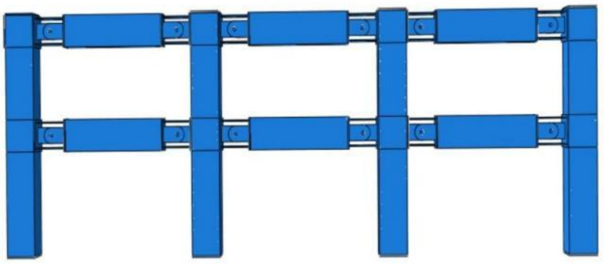


Figure 13. A new prefabricated frame structure with energy dissipating steel plates.

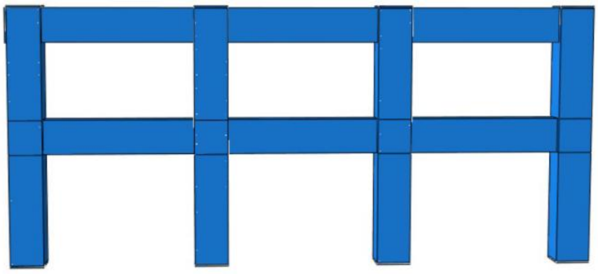


Figure 14. Cast-in-place frame structure.

The lateral force resistance performance of the structure is described by the base shear vertex displacement curve, including the hysteresis effect, deformation capacity, failure mode, etc. By analyzing the shape and characteristics of the curve, we can understand response characteristics of the structure during the earthquake. Figure 15 shows the base shear force vertex displacement diagram of a new prefabricated frame structure with energy dissipating steel plates and a cast-in-place concrete frame structure.

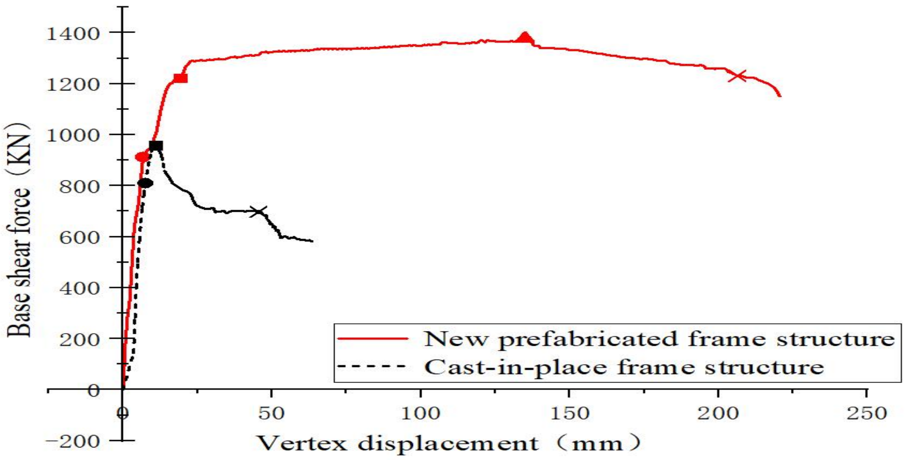


Figure 15. Base shear force-vertex displacement curve.

● Damage to the concrete at the beam end and lower core area begins to occur.

■ The bearing capacity reaches its peak, and the concrete in the upper core area begins to show damage.

× Shear failure of concrete in the core area, resulting in structural failure.

● Partial energy consuming steel plates have reached yield strength.

■ The structural bearing capacity reaches the yield point.

▲ The structural bearing capacity reaches its peak, and the energy consuming steel plate begins to suffer damage.

× The energy consuming steel plate is completely damaged, resulting in structural failure.

The base shear vertex displacement curves of cast-in-place concrete frame structures and prefabricated frame structures with energy dissipating steel plates indicate that in the initial stage of small displacement loading, the base shear vertex displacement curves of prefabricated frame structures with energy dissipating steel plates and cast-in-place concrete frame structures overlap highly, indicating that the two structures have similar stiffness in the initial stage; When the loading displacement further increases, the bearing capacity of the cast-in-place concrete frame structure first decreases, and its bearing capacity deteriorates rapidly, indicating that the cast-in-place concrete frame structure has already been damaged, the steel bars have begun to yield, the plasticity of the concrete gradually accumulates, and ultimately shear failure occurs, resulting in structural functional failure. At this point, the load-bearing capacity of the prefabricated frame structure with energy consuming steel plates did not decrease, but continued to rise. When the energy consuming steel plates in the prefabricated frame structure with energy consuming steel plates began to enter the yield stage, the increase in structural load-bearing capacity began to slow down; As the plasticity of energy consuming steel plates accumulates, the concrete in prefabricated frame structures with energy consuming steel plates begins to exhibit plasticity and the bearing capacity begins to decrease; When some energy consuming steel plates completely yield, the concrete in the prefabricated frame structure with energy consuming steel plates begins to suffer damage, and the rate of bearing capacity decline becomes faster. Through curve comparison, it can be observed that the ultimate bearing capacity and displacement capacity of the prefabricated frame structure with energy dissipating steel plates are significantly higher than those of the cast-in-place structure.

4. Conclusion

This article conducts finite element quasi-static analysis on a new type of prefabricated beam-column node with energy dissipating steel plates and its frame structure, and compares it with its cast-in-place structure to verify that the proposed new component has better seismic performance. The specific conclusions are as follows:

(1) The maximum bearing capacity and ultimate displacement capacity of the new prefabricated beam column nodes with energy consuming steel plates are superior to those of ordinary cast-in-place reinforced concrete nodes, and their energy consumption capacity is better. The damage of ordinary cast-in-place reinforced concrete nodes mainly focuses on the core concrete at the connection between the beam and column nodes, while the damage and plastic development of the new type of prefabricated beam column nodes with energy consuming steel plates are concentrated on the energy consuming steel plates and the concrete at the beam end. The core concrete in the connection area between the beam and column is almost not damaged.

(2) The failure development sequence of a new type of prefabricated frame structure with energy consuming steel plates is more in line with engineering concepts. The damage is mainly concentrated on the energy consuming steel plates and the concrete at the beam end. The core concrete in the node connection area only experiences minor damage, while the failure mode of traditional cast-in-place concrete frame structures is shear failure of the core concrete in the node connection area. The mechanism of action of energy consuming steel plates causes the plastic hinge of the frame structure to move outward to the beam end, which not only protects the concrete in the core area of the node, but also improves the lateral stiffness and energy dissipation capacity of the structure.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] Bruneau M, Reinhorn A. 2006. Overview of the resilience concept. Proceedings of the 8th US National Conference on Earthquake Engineering, San Francisco.

[2] Zhang A, Chen X, Jiang ZQ, et al. 2022. Experiment on seismic behavior of earthquake-resilience prefabricated cross hinge column foot joint. *Journal of Constructional Steel Research.* DOI:10.1016/j.jcsr.2021.107056

[3] Ghayeb HH, Razak HA, Sulong NHR. 2017. Development and testing of hybrid precast concrete beam-to-column connections under cyclic loading. *Construction and Building Materials*, 151: 258-278.

[4] Ghayeb HH, Abdul Razak H, Ramli Sulong NH. 2020. Seismic performance of innovative hybrid precast reinforced concrete beam-to-column connections. *Engineering Structures*, 202: 109886.

[5] Li L, Mander JB, Dhakal RP, et al. 2008. Bidirectional cyclic loading experiment on a 3D beam-column joint designed for damage avoidance. *Journal of Structural Engineering-ASCE*, 134(11): 1733-1742.

[6] Aninthaneni PK, Dhakal RP, Marshall J, et al. 2018. Nonlinear cyclic behavior of precast concrete frame sub-assemblies with "dry" end plate connection. *Structures*, 14: 124-136.

[7] Fortney PJ, Shahrooz BM, Rassati GA. 2007. Large-scale testing of a replace-able "fuse" steel coupling beam. *Journal of Structural Engineering*, 133(12): 1801-1807.

[8] Lu XL, Chen Y, Mao YJ. 2011. Restorable functional structure, a new concept of seismic design of structures. *J. Tongji Univ. (Nat. Sci. Ed.)*, 39(7): 941-948.