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Study on seismic behavior of steel frame with external hanging concrete walls containing recycled aggregates

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HIGHLIGHTS

- Precast concrete walls containing recycled aggregates were applied to steel frame.
- Experiment on steel frame with external hanging concrete walls (SFECW) was conducted.
- The influence of external wall and stiffness of beam-column joints was analyzed.
- Suggestions were proposed to improve performance of the SFECW based on failure modes.
- The effect of key parameters was discussed to promote the use of recycled concrete.

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ABSTRACT

The suitability of precast concrete walls containing recycled aggregates as the enclosure system of steel structure was investigated. The experiment on steel frame with external hanging concrete walls containing recycled aggregates (SFECW) was carried out under horizontal low-cyclic loading, and the influence of beam-column joints forms on the SFECW was considered. The failure modes, structural capacity, lateral stiffness, ductility and energy dissipation capacity were analyzed. The experimental results show that the external walls can remarkably increase the structural capacity, stiffness and energy dissipation capacity, and the connecting stiffness of beam-column joints has negligible effect. There were obvious buckling deformation of the steel column base and serious cracking and damage of the wall at the hanging points, and the corresponding suggested improvements were proposed. Furthermore, the load-displacement curves and failure modes of the SFECW were investigated by the finite element method, and the influence of key parameters such as the position of hanging points, the strength grade of recycled concrete, the thickness of wall, the height-span ratio and axial compression ratio on the SFECW were discussed. The FEA results indicate that the design parameters associated with the external wall are less affected to hysteresis performance of the SFECW, which provides scientific basis for the design and practical application of the SFECW.

1. Introduction

At present, it is the inevitable course for the sustainable development of the steel structure industry to promote the fabricated steel structure residential buildings that are secure, economical, practical, energy saving and comfortable. And, lightweight walls used for steel structure residential buildings mainly include autoclaved lightweight aerated concrete (ALC) walls, glass-fiber reinforced composite (GRC) walls, fiberglass-reinforced plastics (FRP) walls, light-gauge steel stud walls and other varieties of light composite walls etc [1–10]. The lightweight walls are characterized by light weight, simple connection and a high degree of assembly. In addition to playing a role as the enclosure for thermal insulation, waterproof and sound insulation, from the structural point of view, the walls, in collaboration with steel frames, will resist the force when the steel frames withstand horizontal load. It is clear that mechanical performances such as the stiffness, structural capacity, and energy dissipation capacity are significantly improved compared with the pure steel frame. There are mainly two ways of

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the connection between steel frame and walls, infilling and external hanging.

Shaking table test for the steel frame with ALC external hanging walls was carried out by Fang et al. [1]. The study shows that the external ALC walls possess good overall stiffness and sufficient safety strength, and it can increase by 25% in the stiffness of the steel frame. Based on the experiment of different connection methods of steel frames with ALC panels, Wang and Li [2] and Wang et al. [3] found that, when the ALC walls are embedded in square CFST frames by U-shaped connectors and angle steels, the strength and stiffness are much larger than those of the ALC walls when they are hanged on square CFST frames. This study provides a new connection form for the combination of ALC wall and steel frame. To improve the degree of assembly of light-gauge steel stud external enclosure walls, Geng et al. [4] conducted research to hang light-gauge steel stud wall on steel frame by drilling screws and long bolts, and suggested that the long bolts should be used in the connection of the light-gauge steel stud wall with steel frame in engineering application to avoid damage of the connection prior to the wall. By tests and finite element analysis of steel frame with external sandwich composite panels hanged on, Wang et al. [8] found that the sandwich composite panels not only boast good thermal insulation but also can increase the ultimate structural capacity and lateral stiffness of the structure. A GFRP infill-panel (GIP) designed for reinforcement and post-disaster emergency repair of existing steel frames was invented by Kim et al. [9] and Kwon et al. [10], and found out that the GIP wall can greatly improve the strength and stiffness of steel frame and it is feasible to be used for steel structure reinforcement.

With respect to infilled walls, there are a lot of researches on different shear walls infilling steel frame, such as steel plate shear wall, reinforced concrete (RC) shear wall, steel reinforced concrete shear wall and composite steel-concrete shear wall etc [11–20]. After investigation and finite element analysis of steel plate shear walls infilled steel frame, Guo et al. [11,12] found that by setting stiffeners on steel plates, out-of-plane deformation can be constrained and the ultimate structural capacity of the structure can be improved. By experimental study on infilled RC shear walls in the rigid and semi-rigid steel frames, Tong et al. [13] and Sun et al. [14] clarified the complex interaction and force transfer mechanism between the RC wall and steel frame. To solve the problem that the deformation capacity of steel frame is constrained due to the too large stiffness of infilled RC wall, Ju et al. [16] proposed setting a gap between steel frame and RC wall, and the width of which should meet relative deformation requirements of steel frame and RC wall. Wu et al. [17] and Guan et al. [18] studied infilled steel reinforced concrete shear walls in steel frames and the influence of the steel reinforced reinforcement ratio, axial compression ratio and height-width ratio of wall was identified. By test and finite element analysis of composite steel-concrete shear wall infilled steel frame, Jiang et al. [19] and Rahnavard et al. [20] found that the overall buckling deformation of steel plates covering the concrete panel can be better constrained, and the compression resistance capability of the concrete walls can be improved due to the mutual restraint between the steel plate and the concrete panel.

In theoretical research, the simplified equivalent single strut model was proposed by Smith [21], in which the equivalent compression strut is substituted for the infilled wall. The equivalent model is widely accepted by scholars. Subsequently, based on the equivalent single strut model, the equivalent three-strut model is put forward with the effect of the contact length between infilled wall and steel frame taken into account. Jin et al. [22] modified the effective width formula of the equivalent single strut model and obtained the equivalent single strut model which is suitable for steel frame with lightweight enclosure walls embedded. Saneinejad and Hobbs [23] proposed the inelastic design theory of the steel frame with infilled wall and gave a multi-layer filled wall steel frame model based on equivalent diagonal brace. Based on the experimental study of the semi-rigid steel frame with RC wall embedded, and drawing on the tension strips model of steel plate shear wall, Sun et al. [24] put forward the diagonal strip model of the semi-rigid steel frame with RC wall embedded.

The existing steel frame enclosure walls, such as ALC walls and energy-saving composite walls, function as the enclosure, at the same time, the strength and stiffness of steel frame have also improved, which is mainly determined by the connection forms of walls and steel frames and the difference of wall materials. In addition, the concept of thermal insulation and energy conservation is taken into account in the sandwich composite walls and light-gauge steel stud walls etc. The recycled concrete characterized by recyclable, lightweight, energy-saving, anti-crack and thermal insulation. If it can be applied as the enclosure wall of steel frame, the environmental pollution caused by waste concrete emissions and the consumption of natural resources and energy can be reduced. At present, a large number of researches on the basic mechanical properties of recycled concrete had been performed [25–28]. Through experimental study on recycled concrete components, such as recycled concrete beams, columns and beam-column joints, it has been found that the recycled concrete beams, columns and other components are similar to the ordinary concrete components in terms of seismic behavior. Although the structural capacity of recycled concrete components is slightly lower than ordinary ones, it still can be used as the main components of the structure to withstand force. The researches provide a theoretical basis for the engineering application of recycled concrete [29–31]. Peng et al. [32] studied the rectangular squat recycled concrete walls and clarified the influence of axial load on peak load and ultimate drift angle of the recycled concrete walls. Ma et al. [33] conducted an experimental study on the insulation wall made of recycled aggregate. Compared with ordinary concrete shear wall, the structural capacity of the recycled aggregate wall is slightly improved and the deformation and energy dissipation capacity are remarkably improved.

In the aspect of the use of recycled concrete with steel reinforced, steel tubes and fiber-reinforced polymer (FRP) and so on, Fathifazl Ma et al. [34] investigated the shear capacity of steel reinforced recycled concrete (SRRC) beams subjected to multiple variables, and evaluated the applicability of the existing codes for predicting shear strengths of concrete beams to SRRC beams, and Ma et al. [35] researched the effect of several design parameters on the seismic behaviour of SRRC short columns, and proposed a modified ACI design method to calculate the nominal shear strength of SRRC short columns. By the test of recycled aggregate concrete-filled steel tube columns, Tang et al. [36] clarified the effect of the axial compressive ratio, steel strength, and steel thickness on the seismic performance of the steel tube columns. And, Zhou et al. [37] points out that external confinement using steel tubes and FRP can significantly improve the mechanical performance of recycled aggregate concrete.

In this paper, the concrete walls containing recycled aggregates were applied into steel frame structure with weak lateral stiffness. As the external enclosure system of steel frame, the walls were also used for lateral force resistance component to participate in resistance to wind and earthquake, forming the green and environmentally friendly, low carbon and energy-saving steel frame structure with external hanging concrete walls containing recycled aggregates (SFECW). The quasi-static test was carried out to analyze the effect of the external wall and the connecting stiffness of beam-column joints on the structural capacity, lateral stiffness, ductility and energy dissipation capacity of the SFECW, and to expound the transfer mechanism of internal force and the distribu-