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Mechanical behavior of lattice steel reinforced concrete inner frame with irregular section columns under cyclic reversed loading

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ABSTRACT

A 1/2.5-scaled model of two-bay and three-story inner frames, which consisted of reinforced concrete beams and lattice steel reinforced concrete (SRC) irregular section columns, was constructed and tested under low cyclic reversed loading. Elasto-plastic features, integral and inter-story lateral stiffness degradation and the loading capacity of the structure were analyzed. Test results indicate that the lattice SRC inner frame has uniform lateral stiffness and the stiffness degradation process tends to be moderate. The relationship between story drift and the ratio of story stiffness degradation were obtained. The strength degradation appears to increase with the increment of displacement, but the effect is not obvious under the three cycles of each displacement level. The method of forming plastic hinge at the bottom of column is applicable for the calculation of story shear bearing capacity corresponding to the plastic moment of lattice SRC frame with irregular section columns. The elasto-plastic behaviors of the frame in positive and negative directions are similar. The ultimate elasto-plastic story drift rotation is larger than the limit value specified by the Chinese Code for The Seismic Design of Buildings (GB50011-2010), indicating that the capacity of collapse resistance of lattice SRC frame is higher. Compared with the reinforced concrete frame with irregular section columns, the ductility and energy dissipation capacity of lattice SRC frame structure are much better. The failure mechanism of the frame is the beam-hinged mechanism, which satisfies the seismic design principle of strong column and weak beam.

1. Introduction

Composite structures which mainly consist of composite beams, columns and beam-column connections have become increasingly popular in modern structural applications. The benefits of composite structures are higher strength capacity, better seismic behavior, better fire protection, and better resistance to local buckling, etc. Many experiments and investigations were carried out to study the behavior of composite structures. For composite beams, Nie et al. [1] conducted experiments and a finite element modeling study to investigate the effective width of the concrete slab and the depth of the composite stress block of composite beams. A new definition of effective width was presented for ultimate analysis of composite beams under sagging moments. Subedi and Coyle [2] performed an experimental research on seismic behavior of fully composite steel-concrete-steel beam elements by increasing surface roughness. Anandavalli et al. [3] performed a monotonic loading test on Laced Steel-Concrete composite (LSCC) beam. They found that the LSCC system has a high rotation capacity and maintained the structural integrity even at large deformation. Richard Liew et al. [4] described a method of plastic analysis that provides the proper accuracy to estimate the limited state behaviors of steel frames with composite floor beams subjected to the combined action of gravity and lateral loads. For composite columns, Sheehan et al. [5] presented a state of the art report to describe the structural response of concrete-filled elliptical steel hollow sections under eccentric compression. Shim et al. [6] tested a total of six prefabricated circular composite columns with low steel ratio to investigate the cyclic response. Young and Ellobody [7] investigated the structural performance of axially restrained concrete encased steel composite columns at elevated temperatures using the finite element model. For composite beam-column connections, Park et al. [8] studied the seismic performance of concrete-filled U-shaped steel beam-reinforced concrete (RC) column connections through cyclic reversed loading tests. The test results indicated that the specimens exhibited good strength, deformation, and energy absorption capacity. Simões da Silva et al. [9] studied the behavior of end-plate beam-to-column composite joints under monotonic loading tests. Beutel et al. [10] conducted an experimental investigation on the monotonic behavior of composite column-beam connections. The properties

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of connection, such as strength and stiffness were adequate to classify the specimens as rigid connections. Cheng and Chen [11] performed an investigation on the seismic behavior of steel beam to RC column connections with or without the floor slab and a three-story three-bay reinforced concrete in-plane frame with RC columns and steel beams was tested. Bugeja et al. [12] took an experimental study on the seismic performance of a composite moment frame system which consists of reinforced concrete columns and steel beam-reinforced composite concrete slab sections. In addition, six 1/1.5-scale sub-assemblages were tested under quasi-static reversed cyclic loading. Liang and Parra-Montesinos [13] performed the research on the seismic behavior of four RC column-steel beam subassemblies under large displacement reversals and dynamic analyses of RC-S systems under different ground motions. Chou and Uang [14,15] carried out the investigations on the seismic behavior of two full-scale subassemblies with SRC columns and steel beams and two exterior moment connections with a SRC column and a steel beam. The seismic performance of the connection details and the effects of continuous plate and transverse reinforcement on cyclic behavior of the connections were studied respectively. For composite frames, Plumier and Doneaux [16] performed a series of tests on sub-assemblages, on a plane frame and on a 3-D frame. Some of the tests were run quasi statically, and the others were finished on the shaking table. The seismic behavior of composite steel concrete moment frames involved in the ICONS project was studied. Alderighi and Salvatore [17] performed a numerical investigation to assess the structural fire performance of composite steel-concrete frames. Wang and Li [18] presented an experimental study on the behavior of several full-scale semi-rigid composite frames with two stories and two bays which consisted of steel columns and steel-concrete composite beams subjected to vertical loads. Two frame specimens with reinforced concrete columns and steel beams, which had different beam-column joint detailing, were analyzed utilizing the 3D-finite element method by Noguchi and Uchida [19]. Based on the test results, Nie et al. [20] developed a numerical procedure for the elasto-plastic behavior of steel concrete composite frame systems. Investigation results indicate that the proposed model has advantages for the integrated analysis of large scale multistory to high-rise composite frames. Bracci et al. [21] presented an evaluation on constructability, cost, and seismic performance of an alternative structural system for high seismic risk zones. The proposed system consists of composite reinforced concrete-steel special moment-resisting frames. Braconi et al. [22] presented an experimental study on the seismic performance of a full-scale three-bay two-story steel-concrete composite moment-resisting frame fabricated with partially encased composite columns and semi-rigid connections.

Steel reinforced concrete (SRC) structural system is an important branch of composite structure. Studies conducted on SRC structure system provide valuable information on the structural behavior of SRC members, connections and the overall system [23,24]. SRC irregular section column structure system is the SRC structure utilizing irregular section columns. The former researches indicated that RC irregular section column system has some obvious shortcomings, such as the low bearing capacity, and weak seismic performance [25–29]. Based on the previous experimental and theoretical studies of this structural system, SRC irregular section column structure has been proposed in recent years, and many investigations on the seismic behaviors of SRC irregular section column structure were undertaken. As a result, the advantages of this structure have been revealed, and the research and application of this structure in the practical engineering have increased extensively [30,31]. Liu et al. [32] and Xue et al. [33] conducted an experimental research and numerical analysis on two solid-web SRC frames with special columns. Li et al. [34] researched the mechanical performance of SRC short columns of T-shaped cross section. Yang and Zhang [35] presented an experimental study on a 1/2-scaled model of single span and two-story frame which consists of RC beams and T-shaped SRC columns.

Steel reinforced concrete frame with irregular section columns is referred to the frame with nonrectangular section columns, such as T-shaped columns, L-shaped columns, and T-shaped columns. The width of the columns is equal to the width of infilled walls, which makes a better use of available space and improves the aesthetic appearance of structure. Because of the existence of steel, the structure has better seismic behavior, higher bearing capacity, and can reduce the area of member section. As a result the story height and the net area can increase even further. The test models adopted by the pioneers cannot represent the traditional frame with irregular section columns comprehensively. The stiffness, bearing capacity and its degradation process have not been analyzed systematically. In this paper, a 1/2.5-scaled model of two-bay and three-story inner frame including reinforced concrete beams and lattice SRC irregular section columns was investigated under low cyclic reversed loading. The inter-story and integral stiffness degradation and loading capacity variation of the structure in different loading conditions were analyzed to provide a basis for the elasto-plastic seismic response analysis of the structure. In addition, the applicability of the design method intruded in the current Chinese Building Seismic Design Code (GB50011-2010) has been approved by the experimental study, which means that the principle of "strong column and weak beam" and "strong joint and weak member" can be achieved. Based on the above mentioned, the method of forming plastic hinges at the bottom of column was used to calculate the story horizontal bearing capacity of the structure. This study attempts to help promoting this new structural system in high seismic zones.

2. Test setup and specimens

2.1. Model design and construction

According to the seismic intensity degree 8, a 1/2.5-scaled specimen was designed corresponding to the bottom shear method, which consists of reinforced concrete beams and lattice SRC irregular section columns. The bottom level, the intermediate level, and the top level were selected as the first-, the second- and the third-story of the prototype respectively for the analysis. Model configuration and material properties of the model are shown in Fig. 1 and Table 1 respectively. Fabricated steel cages were fixed in forms, and the concrete was poured in a similar manner as in actual construction projects and was cured at an ambient temperature for 28 days. Fine aggregate commercial concrete was used for the test specimen. The average compressive strength of nine 150 mm concrete cubes was measured as 30.35 MPa after curing for 28 days. Steel of Q235B was used to construct the steel skeleton in columns, the T-shaped steels were welded by using steel plates in form of twin fillet welt based on the relevant specification, and 20 × 8 flat steels were used as the horizontal and cross diagonal web members to form steel trusses (Figs. 2 and 3). The average steel reinforcement ratio of the side column and middle column was 5.76% and 5.12% respectively. ϕ8 bars were used as the longitudinal steel bars in columns, and $\underline{\phi}$12 bars were used as the longitudinal steel bars in first- and second-story beams, $\underline{\phi}$10 bars were used as the longitudinal steel bars in third-story beams. ϕ6 bars were used as the stirrups in both columns and beams, in the 300 mm range of each column end, in the 400 mm range of each beam end and the whole joints zone. The stirrups were arranged at intervals of 40 mm, and in the other part of the test model, the stirrups were arranged at intervals of 80 mm.