

Seismic Reinforcement Experiment of Reinforced Concrete

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Abstract

There are many reinforced concrete (RC) buildings in various countries across the world at present. However, some old buildings do not have a high seismic grade limited by the current design capability. Therefore, it is a very important task to expand and transform existing RC frame structure. In the paper, the impacts of RC structures reinforced with different steel braces and shear walls on seismic performance of RC frame structures are studied. Six-truss single-storey and single-truss RC frame structure reinforced with angle iron brace, I-steel brace and concrete shear walls are adopted for low cyclic loading test. Through comparison and analysis of horizontal ultimate bearing capacity, initial lateral stiffness, structure failure mode, and energy dissipation capacity of frame structure, the effects of RC frame reinforced with different steel braces and concrete shear walls on seismic performance of frame structure are expounded, and they provide references for the application of steel braces and shear walls to seismic reinforcement engineering of RC frame structure.

Keywords

Reinforced Concrete; seismic performance; low cyclic loading test; steel braces.

1. Introduction

With acceleration of industrialization process, the function of some buildings used for industrial production has changed. Compared with structure reconstruction, expansion and transformation of RC frame structure has such advantages as saving resources, shortening construction period and controlling cost. Increasing steel frame above the existing RC frame structure and forming RC frame composite structure system is one of common methods in expansion and transformation engineering. The existing RC frames show certain degradation in stiffness and strength during the previous-stage service, and newly increased structure storey and equipment increase vertical load exposed on RC frame. Therefore, reinforcement of existing RC frame structure is one of important measures to ensure composite structure meet seismic resistance requirement. For structure reinforcement, not only should seismic performance improvement degree of structure be considered, but the production requirements and user's requirements that the structure should have also shall be met, such as building space requirement, lighting, etc. The common seismic reinforcement modes of RC frame structure mainly include increasing steel braces and concrete shear walls. Seismic performance test studies have been made by many foreign and domestic scholars on different reinforcement modes of RC frame structure. Through low cyclic loading test of RC frame structure reinforced with steel braces, Youssef et al conclude that not only does steel brace enhance lateral bearing capacity of RC frame, but also improves ductility of frame.

2. Experiment Overview

2.1. Specimen Design

The test model is a six-truss single-storey and single-truss RC frame specimen reinforced using different modes. Comparison specimens are unreinforced RC frame and RC frame reinforced with concrete shear wall, X-type angle steel brace, X type I-steel brace, reversed V type steel brace, and reversed V type I-steel brace. Numbers of specimens are RCF, RCF-SW, RCFX-1, RCF-X-2, RCF-V-1 and RCF-V-2. Geometric size of frame and reinforcement for six specimens are the same. The span is 1200mm and the storey height is 1500mm. the sectional dimension of frame beam is 200mm×160mm, and the sectional dimension of frame column is 160mm×160mm. Geometric dimension and reinforcement for specimens are shown in Fig. 1.

2.2. Mechanical Properties of Materials

Concrete grade of specimens is C30. At the time of pouring concrete frame, three standard concrete test cubes are manufactured (150mm×150mm×150mm), and they are cured in the same environment with specimens. For longitudinal bar of frame beam column, we use HRB400. The model of hoop is HPB300 and the model of profile steel is Q235B. As the test goes on, compressive strength test of concrete test cubes, sampling and extension test of steel bar and profile steel are carried out. Mechanical performance test results of concrete and steel are seen in Table 1 and Table 2.

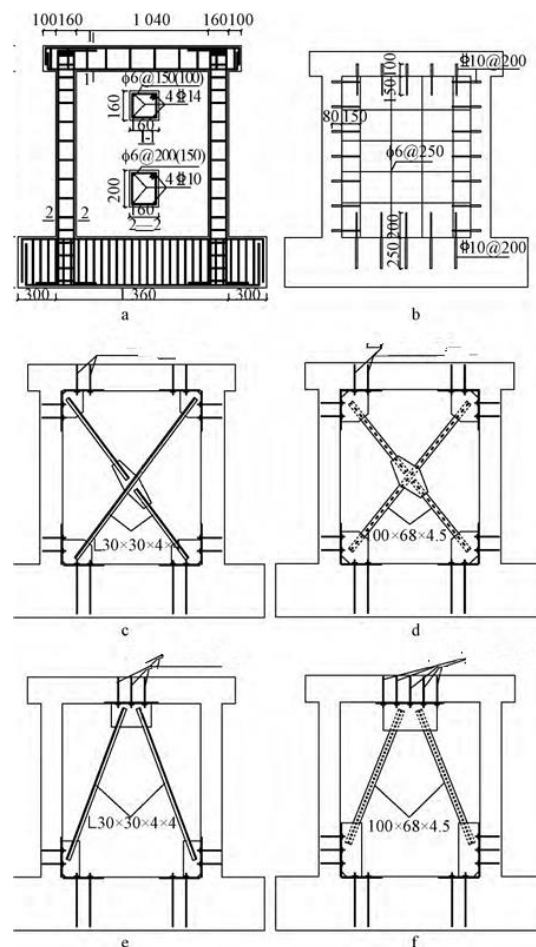


Figure 1. A-specimen RCF; b-specimen RCF-SW; c-specimenRCFX-1; d-specimen RCF-X-2; e-specimenRCF-V-1; f-specimen RCF-V.

Table 1. Mechanical Properties of Concrete Material

No.	Ultimate Load P_u/kN	Compressive Strength of Cube f_{cu}/MPa	Compressive Strength Mean f_{cuu}/MPa
1	719.7	32.0	31.6
2	665.8	29.6	
3	747.1	33.2	

Table 2. Material Mechanical Properties of Steel

Steel	Yield Strength f_y/MPa	Ultimate Strength f_u/MPa	Modulus of Elasticity $E_s/(10^4 MPa)$
Angle steel	247.7	367.6	21.1
I-steel	234.9	368.5	22.7
Φ10	434.3	556.1	20.1
Φ14	464.9	576.1	20.8

3. Loading Scheme

In the test, 200kN electro-hydraulic servo loading system (MTS) is adopted to impose horizontal load on frame specimens. One end of actuator is connected to the reaction wall, the other end is connected to top beam of specimen via four M22 high-strength bolts, and horizontal load is transmitted to specimen via top beam. Ground beam of specimen is fixed on the ground with M60 anchor bolts. Lateral supports are installed on both sides of top beam so as to prevent specimens from generating outer displacement during loading. Prior to the test, preloading of specimen should be applied to check whether loading device and measuring device worked normally or not. Force and displacement are adopted to control loading during test. Specimens are loaded according to load control grade before entering yield, each grade of load is applied for once circulation. When close to crack load value and yield load value, the loading grade difference decreases. After reaching yield load P_y , the load is applied according to displacement control, each grade of displacement is applied for three circulations. When the horizontal bearing capacity is loaded to below 85% of ultimate horizontal capacity or obvious failure of specimen occurs, the test ends.

4. Test Process and Failure Characteristics

4.1. Specimen RCF

In initial period of loading, when horizontal load is lower than ± 15 kN (push is positive direction and pull is negative direction), no crack appears on the specimen. When the load is ± 15 kN, fine horizontal cracks appear on the top of column and at the column bottom. When the load is ± 21 kN, horizontal cracks occur 1/3 of frame column from column bottom, and fine inclined cracks occur no beam column node. When the load is ± 27 kN, horizontal crack on the top and bottom is expanded and new cracks appear; cracks on beam column node are expanded and cross inclined cracks appear; and fine cracks appear at column bottom joint and ground beam. When the load is ± 40 kN, new horizontal cracks appear successively on the top and bottom and the middle part, inclined crack on beam column joint is expanded, frame enters yield stage and yield displacement is 30mm. The next stage is displacement control loading stage. When the load is

± 66 mm, width of horizontal crack on the column body increases, multiple throughout cracks appear on the beam column node and crack width increases obviously. Moreover, some concrete peels off, as is shown in Fig. 2a, the test ends.

4.2. Specimen RCF-SW

In initial period of loading, when horizontal load is lower than ± 60 kN, no crack appears on the specimen. When the load is ± 60 kN, fine inclined cracks appear on four corners of shear wall. When the load is ± 80 kN, fine horizontal cracks appear at the bottom of column. When the load is ± 120 kN, the quantity of horizontal cracks on the top and at the bottom of column increases. Moreover, horizontal cracks appear in the middle part of column. Width and quantity of inclined crack increases further on the shear walls, and the width and quantity of crack at the bottom of shear wall are more than those on the top of shear wall. When the load is ± 140 kN, two wider cross diagonal inclined cracks appear on the shear wall, and fine inclined cracks appear on the beam column node. When the load is ± 180 kN, the whole shear wall is full of cross inclined cracks, crack on beam column node is expanded, the width increases, the component enters yield and yield displacement is 18 mm. The next stage is displacement control loading stage. With constant increasing of displacement, cross inclined crack on the shear wall is expanded, the width increases, the quantity of crack on beam column node increases, and connected with cross inclined cracks on the wall, concrete on the shear wall peels off and reinforcement yields. When the load is ± 35 mm, shear wall concrete peels off seriously, cracks appear on the reinforcement, width of crack on the frame beam column node increases, and horizontal load drops rapidly, as is shown in Fig. 2b, the test ends.

4.3. Specimen RCF-X-1

In initial period of loading, when horizontal load is lower than ± 50 kN, no crack appears on the specimen. When the load is ± 65 kN, fine inclined cracks appear at column bottom. With the increasing of load, new horizontal cracks appear on the top and bottom of column successively. When the load is ± 80 kN, steel braces start yielding, and horizontal cracks on the top and bottom of column are expanded. When the load is ± 100 kN, steel brace yields, horizontal cracks appear in the middle part of column, and inclined cracks appear on the beam column node. When the load is ± 125 kN, steel brace yield is obvious, new horizontal cracks appear on the column body successively, crack on the beam column node is expanded, inclined cracks appear on the beam, specimens enter yield stage and yield displacement is 25 mm. The next stage is displacement control loading stage. When the load is ± 50 mm, obvious buckling appears for steel braces, steel braces connecting to the joint plate is broken owing to torsion from buckling, width of crack on the column body increases obviously, many throughout inclined cracks appear on the lower end of column, beam, beam column nodes, and some concrete peels off, as is shown in Fig. 3c, the test ends.

4.4. Specimen RCF-X-2

In initial period of loading, when horizontal load is lower than ± 120 kN, no crack appears on the specimen. When the load is ± 120 kN, fine horizontal cracks appear at the column bottom. With the increasing of load, new cracks appear at column bottom and top. When the load is ± 180 kN, inclined cracks appear on the ground beam corresponding to frame column. When the load is ± 220 kN, the column body is full of horizontal cracks, width of crack on column top and middle part of column is less than 0.1 mm, while crack at column bottom is expanded. Moreover, inclined crack is connected to inclined cracks of ground beam, and fine inclined cracks appear on beam column node. The next stage is displacement control stage. With the increasing of displacement, width of crack on column body changes little, while width of crack at column bottom and ground beam increases obviously. When the load is ± 35 mm, width of column

bottom and ground beam is bigger, structure failure appears, and observable failure appears on I-steel braces, as is shown in Fig. 2d, the test ends.

4.5. Specimen RCF-V-1

In initial period of loading, when horizontal load is lower than $\pm 120\text{kN}$, no crack appears on the specimen. When the load is $\pm 120\text{kN}$, fine horizontal cracks appear at the column bottom. With the increasing of load, new cracks appear on the column body successively. When the load is $\pm 50\text{ kN}$, steel brace starts buckling, inclined cracks appear on the beam column node, cracks on the column top and bottom are expanded, and horizontal cracks appear in the middle part of column body. When the load is $\pm 80\text{ kN}$, steel brace buckling is obvious, multiple horizontal cracks appear on column body, inclined cracks on beam column node are expanded, fine inclined cracks appear on the beam, specimens enter yield stage, and yield displacement is 30mm . The next stage is displacement control loading stage. When the load is $\pm 70\text{ mm}$, obvious buckling appears for steel braces, multiple throughout cracks appear on beam column nodes, cracks appears in mid-span of beam, width of horizontal cracks at the bottom end of column increases, and some concrete peels off, as is shown in Fig. 2e, horizontal bearing capacity declines, and the test ends.

4.6. Specimen RCF-V-2

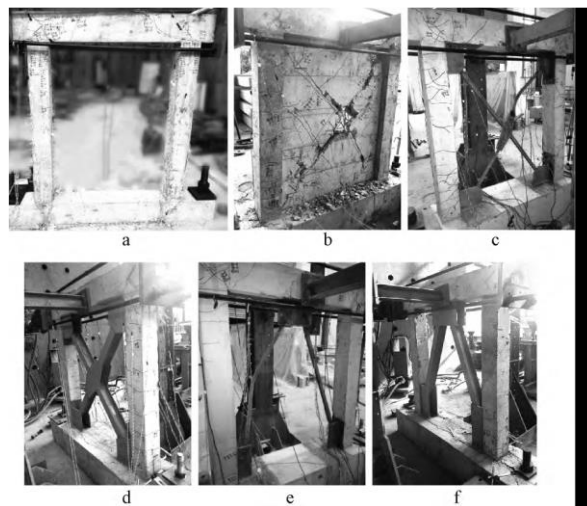
In initial period of loading, when horizontal load is lower than $\pm 120\text{kN}$, no crack appears on the specimen. When the load is $\pm 120\text{kN}$, fine horizontal cracks appear at the column bottom. With the increasing of load, new cracks appear on the column body successively. When the load is $\pm 180\text{kN}$, inclined cracks appear on the ground beam corresponding to frame column. When the load is $\pm 220\text{kN}$, column top and bottom are distributed with horizontal cracks, width of horizontal cracks on the top of column is small, crack at column bottom is expanded, and inclined cracks are connected with that of ground beam. The next stage is displacement control stage. With the increasing of displacement, width of crack on column top and beam column node changes little, while width of crack at column bottom and on ground beam increases obviously. When the load is $\pm 35\text{mm}$, width of crack at column bottom and on ground beam is larger, structure failure appears, and no observable cracks appear on I-steel braces, as is shown in Fig. 2f, the test ends.

5. Test Result Analysis

5.1. Hysteresis Curve

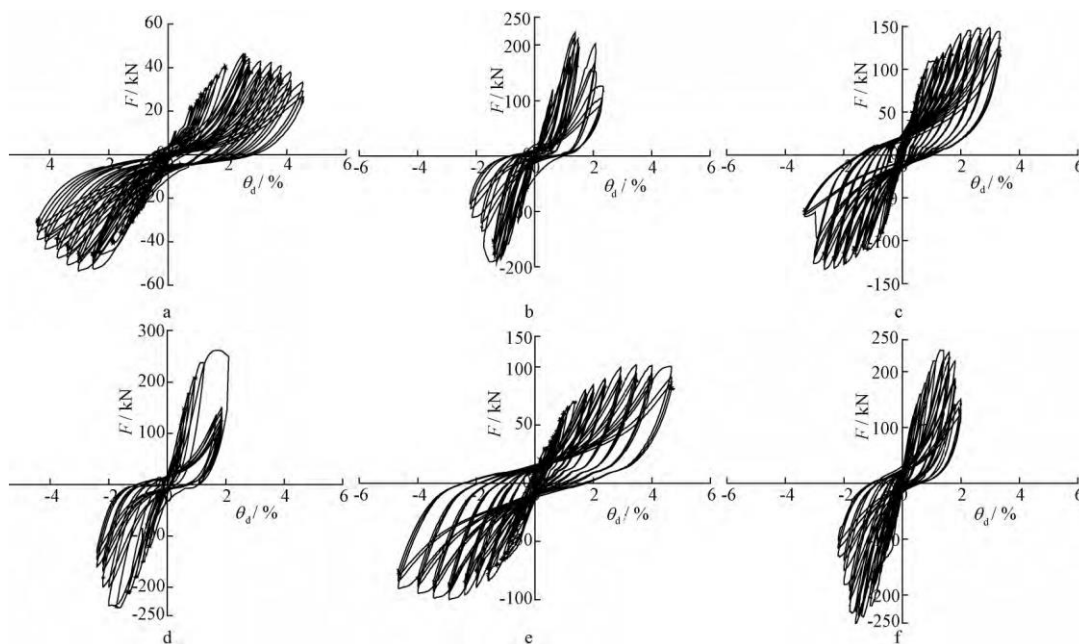
Hysteresis curve of horizontal load and peak sideway ratio of specimens is seen in Fig. 3. In the figure, storey-storey sideway ratio θ_d is the ratio between column top sideway and storey height of specimen. Hysteresis curve of specimen RCF approximates a line before the appearance of crack and no residual deformation appears for the specimen. It indicates that specimens are in the elastic stage. With appearance and expansion of specimen cracks, secant stiffness of hysteresis curve decreases, residual deformation occurs, the area of hysteresis loop increases, and the specimens enters elastic-plastic stage and reaches yield state gradually. Owing to specimen slippage and cohesive slippage of anchored reinforcement, hysteresis curve shows "close up" phenomenon. When hysteresis curve reaches the peak, horizontal load enters slow decline section and is at an elastic stage. Under horizontal repeated load, cracks appear on the wall and RC frame, specimens enter elastic-plastic stage, secant stiffness of hysteresis curve decreases, and residual deformation of specimens appear. When the horizontal load reaches a peak, it declines at a higher speed, as is shown in Fig. 3b. For specimen RCF-X-A and specimen RCF-V-1 reinforced with angle steel braces, hysteresis curve shows approximate line, specimens are at elastic stage and no residual deformation appears before cracks appear on concrete frame and angle steel brace yields. With appearance and expansion of cracks, and

buckling of steel braces, secant stiffness of hysteresis curve starts to decrease, the area of hysteresis loop increases obviously, horizontal load decrease becomes slow after reaching the peak. Where, the breakage of X type angle steel brace causes significant reduction of hysteresis curve, as is shown in Fig. 3c and Fig. 3e. For specimen RCF-X-2 and specimen RCF-V-2, hysteresis curve shows approximate line before cracks appear on concrete frame. With appearance and expansion of cracks on the concrete frame, secant stiffness of hysteresis curve starts to decrease, and the area of hysteresis loop increases. After horizontal load comes to the peak, cracks on ground beam are expanded rapidly, which results in fast drop of horizontal load, as is shown in Fig. 3d and 3f.



a—RCF; b—RCF-SW; c—RCF-X-1; d—RCF-X-2;
e—RCF-V-1; f—RCF-V-2

Fig 2. Specimen failure characteristics



a-specimen RCF; b-specimen RCF-SW; c-specimen RCF-X-1; d-specimen RCF-X-2; e-specimen RCF-V-1; f-specimen RCF-V-2.

Fig 3. Hysteresis curve

5.2. Skeleton Curve

Curve formed by connecting 1st cycle peak of each grade cyclic loading of hysteresis curve is taken as structure skeleton curve. Skelton curve can directly reflect yield load, ultimate load and ductility of structure under horizontal load. Horizontal load-peak sideway ratio skeleton curve of specimen is shown in Fig. 4. Initial lateral stiffness of shear wall and I-steel brace reinforcing specimens RCF-SW, RCF-X-2 and RCF-V-2 is enhanced greatly, the initial lateral stiffness increasing degree of angle steel brace reinforcing specimens RCF-X-1 and RCF-1 is lower than that of shear wall and I-steel brace reinforcing specimens, and initial lateral stiffness increasing degree of using X type angle steel brace reinforcing specimens is superior to that using reversed V type angle steel brace. Compared with unreinforced specimen RCF, the horizontal ultimate strength of specimen RCF-X-1 reinforced with X type angle steel brace is enhanced by 250%, the horizontal ultimate strength of specimen RCF-X-1 reinforced with reversed V angle steel brace is enhanced by 140%, while the horizontal ultimate strength of specimen RCF-X-1 reinforced with I-steel brace and shear wall is enhanced by 400%. After reaching horizontal ultimate bearing capacity, horizontal bearing capacity of specimen RCF-SW, RCF-X-2, and RCF-V-2 drops rapidly, while horizontal bearing capacity of specimen RCF-X-1 and RCF-V-1 declines slowly.

The effect of using I-steel braces and concrete shear wall reinforcement on increasing initial lateral stiffness and horizontal ultimate bearing capacity of structure is similar. When specimen reaches failure, horizontal bearing capacity of structure declines fast, and lateral displacement that the structure reaches is equal. The effect of using angle steel braces is lower on increasing horizontal ultimate bearing capacity and initial lateral stiffness of structures, while structure deformability is far higher than that of I-steel brace and concrete shear wall reinforcing structure. When reinforced with I-steel brace, horizontal ultimate bearing capacity of X type and reversed V type reinforcing specimen is similar, it is because horizontal ultimate bearing capacity of these two specimens depends on failure of outer frame, and I-steel brace has no significant impact on horizontal ultimate bearing capacity of reinforced frame structure.

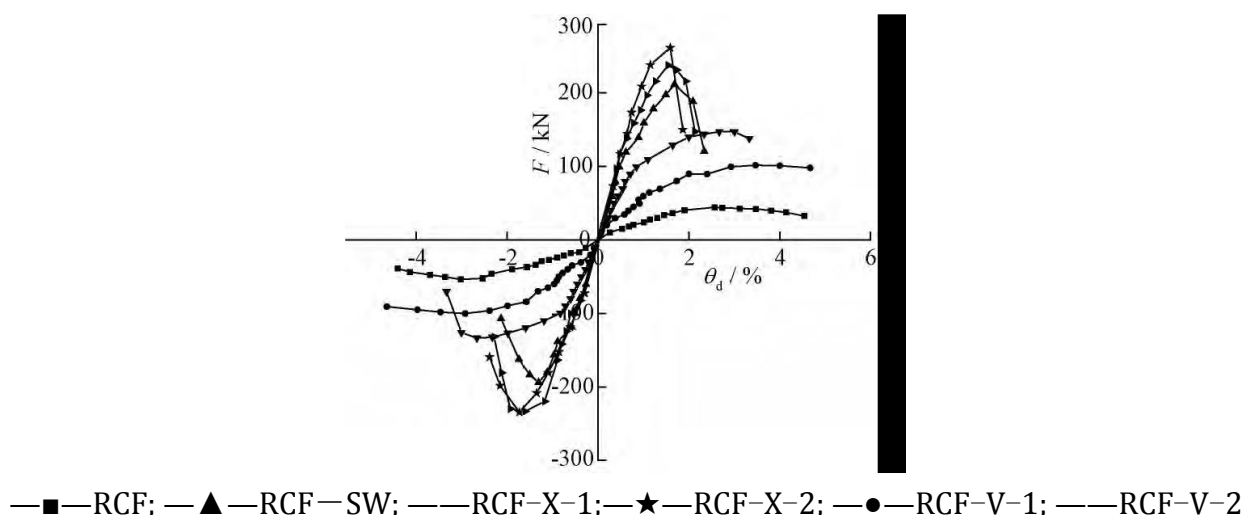


Fig 4. Skeleton curve

5.3. Stiffness Degradation

Under horizontal cyclic load, RC frame structure experiences concrete crack, yield and failure. The lateral stiffness drops gradually with increasing of displacement and cycle times, and stiffness degradation law can reflect seismic performance change process of RC frame structure. In the paper, structure stiffness degradation is analyzed using secant stiffness K . According to

Fig. 5, it is known that stiffness of specimen RCF-X-1 and RCF-V-1 drops slowly under the effect of horizontal cyclic loading after structure enters elastic-plastic stage, stiffness drops slowly at initial stage before and after crack appearance of RCF-SW, but specimens is gradually destroyed with expansion of crack on the shear wall. The stiffness drops fast, and stiffness of specimen RCF-X-2 and RCF-V-2 also drops faster.

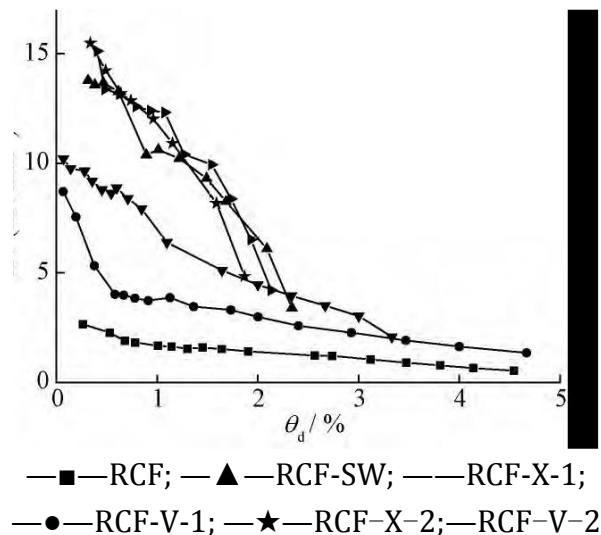


Fig 5. Stiffness degradation curve

6. Conclusion

Through the above experiments, the following conclusions are drawn:

- 1) When RC frame is reinforced with steel braces, increasing sectional area of brace can enhance horizontal ultimate bearing capacity and initial lateral stiffness of structures. The effect of weak steel brace reinforcing mode on increasing horizontal ultimate bearing capacity and initial lateral stiffness of RC frame structure is poor. Horizontal bearing capacity of structure drops slowly after reaching the peak, and structures have good deformability after being reinforced; using strong steel braces and concrete shear walls enhances horizontal ultimate bearing capacity and initial lateral stiffness of RC frame structure greatly. Strong steel brace reinforcing mode results in outer frame failure ahead of braces, and poor homogeneity and ductility of concrete shear wall, so horizontal bearing capacity of structures drops fast after reaching the peak, and deformability of reinforced structure becomes poor.
- 2) Failure mode of RC frame structure reinforced with weak steel braces and concrete shear walls is rational, and failure of weak steel braces and shear walls appears ahead of failure of outer frame components; while RC frame structure reinforced with stronger steel braces results in failure of outer frame ahead of strong steel brace failure under horizontal load, and the failure mode does not conform to the design requirement.
- 3) Accumulative hysteresis energy dissipation of frame structure at elastic stage is less. After entering plastic stage, accumulative hysteresis energy dissipation of structures increases significantly. Under the same grade sideway ratio, hysteresis energy dissipation of frame structure reinforced with steel braces and shear walls is significantly higher than that of unreinforced structure. With the increasing of sideway, shear wall failure of frame structure reinforced with shear wall appears, outer frame failure of frame structure reinforced with strong steel brace appears, and structure will not dissipate energy any longer, while frame structure reinforced with weak steel braces keeps a better energy dissipation capacity after steel brace buckling.

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