Experimental Investigations on the Seismic Performance of Un-Retrofitted and Retrofitted RC Frames

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SUMMARY:
The need for evaluation and retrofit the existing damaged infrastructure has come into focus following the recent severe collapse of massive RC structures. A series of experimental and analytical research program is ongoing at the State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University of China, aimed at quantifying the seismic response characteristics of damaged structures. This paper discusses chiefly the results of experimental tests carried out on three RC 1/2 scale 2-storey 2-bays framed buildings, namely a standard frame designed according to the current seismic design code in china and two similar frame retrofitted with steel brace and FRP, respectively. Local and global response quantities such as failure pattern, failure mechanism, energy dissipation and the structure's global ductility are compared for the RC un-retrofitted and retrofitted frames. The results provide a data base for the assessment of retrofitted schemes and also provide insight into the dynamic response of different damage stages of RC frames.

Keywords: cyclic loading, steel brace, FRP, damage, RC frame

1. INTRODUCTION

Seismic retrofitting of earthquake-damaged structures is a key issue in any earthquake-prone region. Moderate to strong earthquakes, in fact, can cause extensive damage to structures and infrastructures. The need for evaluation the seismic adequacy of existing damaged infrastructure has come into focus following the recent severe damage and collapse of massive RC structures. In particular, the seismic rehabilitation of damaged concrete buildings in regions of high seismic region, which were designed prior to the advent of modern seismic design codes, is a matter of growing concern. The existing or damaged RC structures, especially frames, do not possess adequate lateral resisting systems. Such structures were not capacity designed and their response is scarcely ductile. One of the major challenges that faces structural engineers is how to determine the seismic performance of these buildings and decide whether they need rehabilitation or not and which rehabilitation scheme to be adopted.

Up to now, two retrofitting strategies emerged as being practical and efficient. The first one is to add new structural elements such as steel diagonal bracings adding the global stiffening and strengthening of the lateral resisting systems. The second one is to upgrade by selectively strengthening the deficient structural elements of the buildings including local modification of material properties and seismic details such as FRP. Generally, the first one is preferred and lateral force resisting elements such as steel braces are prevalently used to increase the seismic strength of framed building structures. Considering the ease of construction and the relatively low cost, steel braces appear to be an ideal strategy compared to the other shear resisting members.

To date, the seismic performance assessment of the existing RC multi-storey frames has widely been based on numerical simulations of simplified or complicated 3D finite element models. Comprehensive experimental tests carried out on RC multi-storey frames are yet scarce. The main objective of this study is to investigate the seismic reliability of RC frames equipped with steel braces and FRP subjected to seismic excitations with the intention of investigating their seismic fragility behaviour. For this, a series of two-storey and tow-bays RC frames designed according to the current seismic design code in china were selected as a case study. The seismic structural performance of the sample structures is assessed by employing cyclic lateral loads. Local and global response quantities are discussed hereafter for the RC bare and retrofitted frames. Moreover, the opportunities of using steel brace and FRP as an effective technique for the seismic retrofit of RC frames are herein evaluated experimentally.

2. TEST SPECIMEN

2.1. General description

The sample building structures are regular in elevation and consist of three 1/2 scale multi-storey RC framed systems; the frames have two bays (3.00m+1.20m) along the longitudinal direction (i.e. the direction of lateral loading) as a typical structural configuration representative of primary school in china. The interstorey heights are all 1.50m for the first and second levels, the roof height is 3.40 m. The two-dimensional framed system of the specimens comprise 150×250mm deep beams, the columns employ deep sections (200×250mm), respectively. Details of the bare RC building are shown in Figure 1.

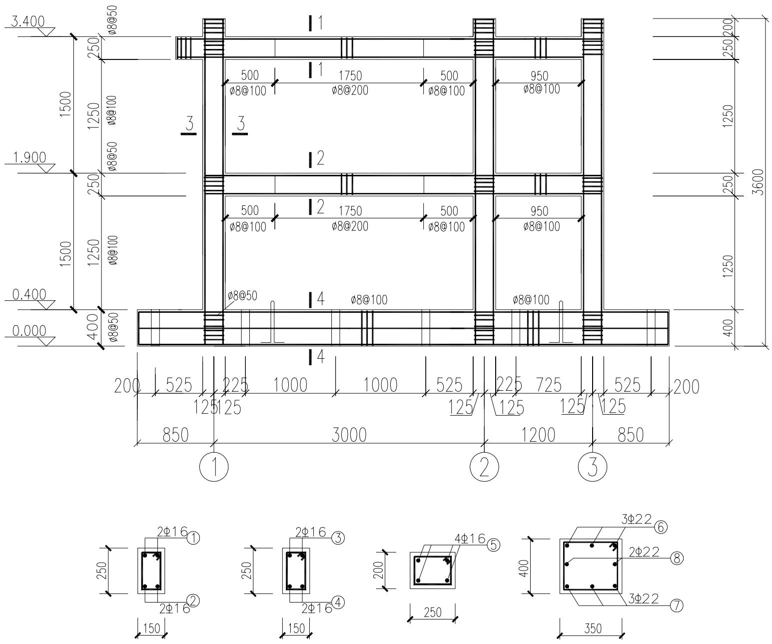


Figure 1. Specimen of RC frames

The materials used for the structure were characterized by experimental tests: the average strength of steel bars was equal to fy=300MPa; tests performed on samples extracted during concrete casting of each floor showed an average concrete compressive strength of fcu,k=25.1MPa, the standard deviation of the concrete cubes is 1.6MPa. The Young modulus E=29800MPa.

2.2. Retrofitting braced system

The steel braces as the first alternative for retrofitting the frame after a series of cyclic loading. These are connected to the RC joints via steel plates, and installed in the larger bays of the frame according to the damage distribution. The steel grade of the pipes is Q345, i.e. the nominal yield *f*y=345MPa.

The total length of the braces is 2050mm. The design of such braces was carried out within the framework of displacement-based methods, the target interstorey drift was assumed equal to 0.2 % along with the lateral deformed shape of the frame. The section was capacity designed and he details of the steel brace are outlined in Figure 2.

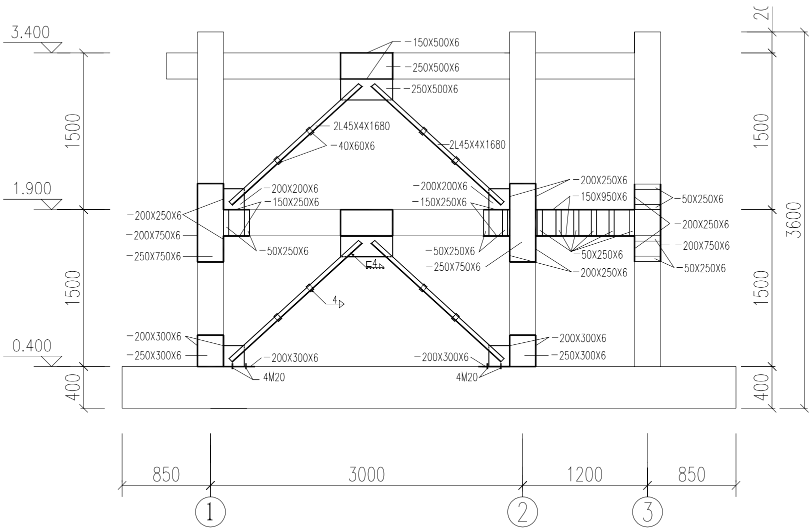


Figure 2. Specimen of steel brace retrofitted RC frames

2.3. Retrofitting FRP system

The selection of fiber texture and retrofit design criteria were based on deficiencies underlined by both the test on the damaged structure and the numerical results provided by the post-test assessment. They indicated that a retrofit intervention was necessary in order to increase the structural seismic capacity. To pursue this objective, the retrofit design strategy focused on two main aspects: increasing the global deformation capacity of the structure and fully exploiting the increased deformation capacity by avoiding brittle collapse modes. Thus, the retrofit design was aimed at maximizing the benefits of the externally bonded FRP reinforcement along the direction of dominant stresses by increasing either the column confinement or the shear capacity of exterior beam–column joints. The rehabilitation strategy are outlined in Figure 3.

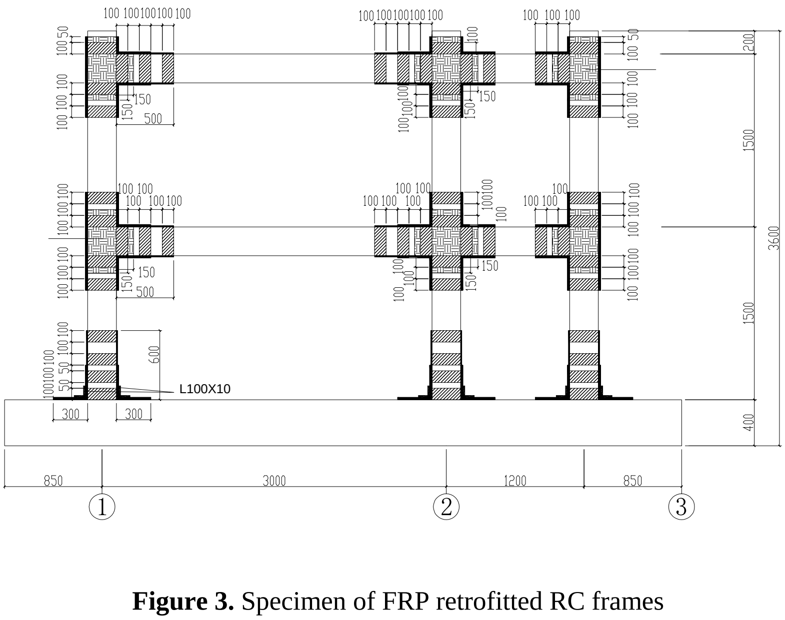
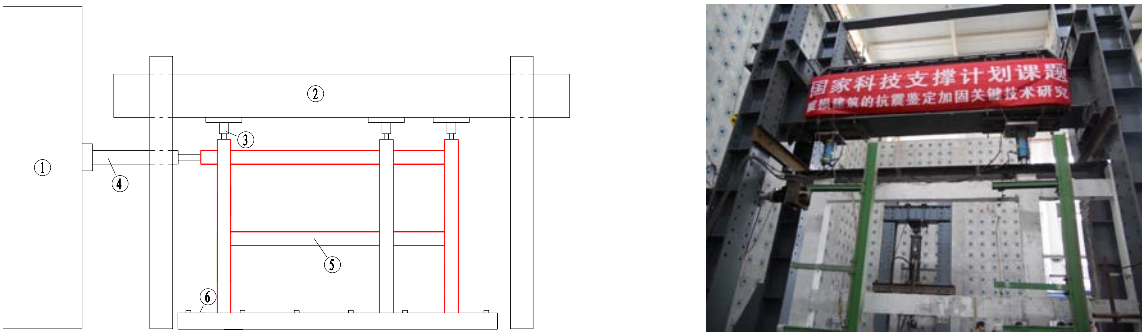


Figure 3. Specimen of FRP retrofitted RC frames

3. TEST SET-UP & LATERAL LOADING

Cyclic tests were carried out on the RC frames to identify the structural response, such as strain, displacement, dissipated energy and equivalent structural damping. Such tests were carried out before and after the retrofitting work, respectively.

Strain gauges were used to monitor the deformation of the steel and concrete, 96 or more strain gauges were used for each 1/2-scale RC model. They were used for the bars of the RC columns, beams, joints and. steel brace and FRP sheets. Displacement transducers were installed in the beam-to-column connections in the RC frames to check the rotation. Transducers were also placed on each storey of the RC frame along the direction of lateral loading used to monitor the deformations of whole frames during the tests. The total number of Displacement transducers installed to monitor the framed systems during the experimental tests is 16. Details of the test setup and cyclic loading are outlined in Figure 4.



1. Reaction wall 2.Steel beam 3.Hydraulic jack 4.Actuator 5.RC frame 6.Strong floor

Figure 4. Loading test of RC Specimen

The experimental test on the frame consists of displacements cyclically imposed at the top of the specimen. The program of loading is shown in Figure 5. The load patterns were force and displacement hybrid controlled, and were applied through one hydraulic jacks connected to the RC reaction wall. The jacks possess a stroke of ±250mm, their maximum force capacity is 500 kN, in compression and tension, respectively. The amplitude of the cycles varies from the yield displacement to collapse one, and for each amplitude three cycles of displacements have been imposed. The frequency of the applied signal is equal to 0.05Hz to realize a quasi-static test. The vertical load of about 150 kN has been applied to each column using the hydraulic jack as previously described. The vertical loads were expected to be constant.

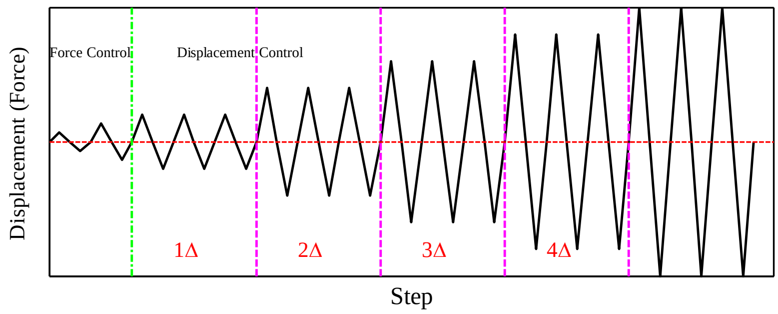


Figure 5. Program of lateral cyclic loading

4. EXPERIMENTAL TEST RESULTS

In Figure 6, the failure mode of steel brace and FRP retrofitted specimens are shown. It is evident that the damage mechanism in initial stage of three specimens is about the same: cracks opening at the bottom and top of the columns, followed by the failure of the transverse beam. But in the later stage, the brace buckling and FRP tinseling are the characteristic response of the two retrofitted specimen.

Figure 6. The failure mode of steel brace (a) and FRP (b) retrofitted frames

Complete cyclic history of the three specimens is shown in Figure 7. As far as the shape of cycles is concerned, a marked pinching is observed, which shows as the behavior is dominated by low dissipation mechanisms. For high values of displacements a decreasing of the global stiffness has also been observed, whereas, a limited degradation in terms of force has been identified for cycles with the same amplitude.

Table 4.1. Response comparison of three RC frames under the lateral cyclic loading

Retrofitting Scheme	Yield Point		Collapse Point		Global Ductile
	Yield Force(kN)	Yield Disp.(mm)	Max. Force (kN)	Max. Disp. (mm)	
Bare	94.24	19.69	120.7	61.2	3.1
Steel brace	160.47	21.55	194.1	87.5	4.1
FRP	118.79	22.34	159.3	89.9	4.0

The comparisons of the yield and collapse displacement, ductile index are shown in Table 4.1. It is evident both from Figure 7 and Table 4.1, that the steel brace retrofitted frame have the best seismic performance, and the FRP retrofitted one is the second.

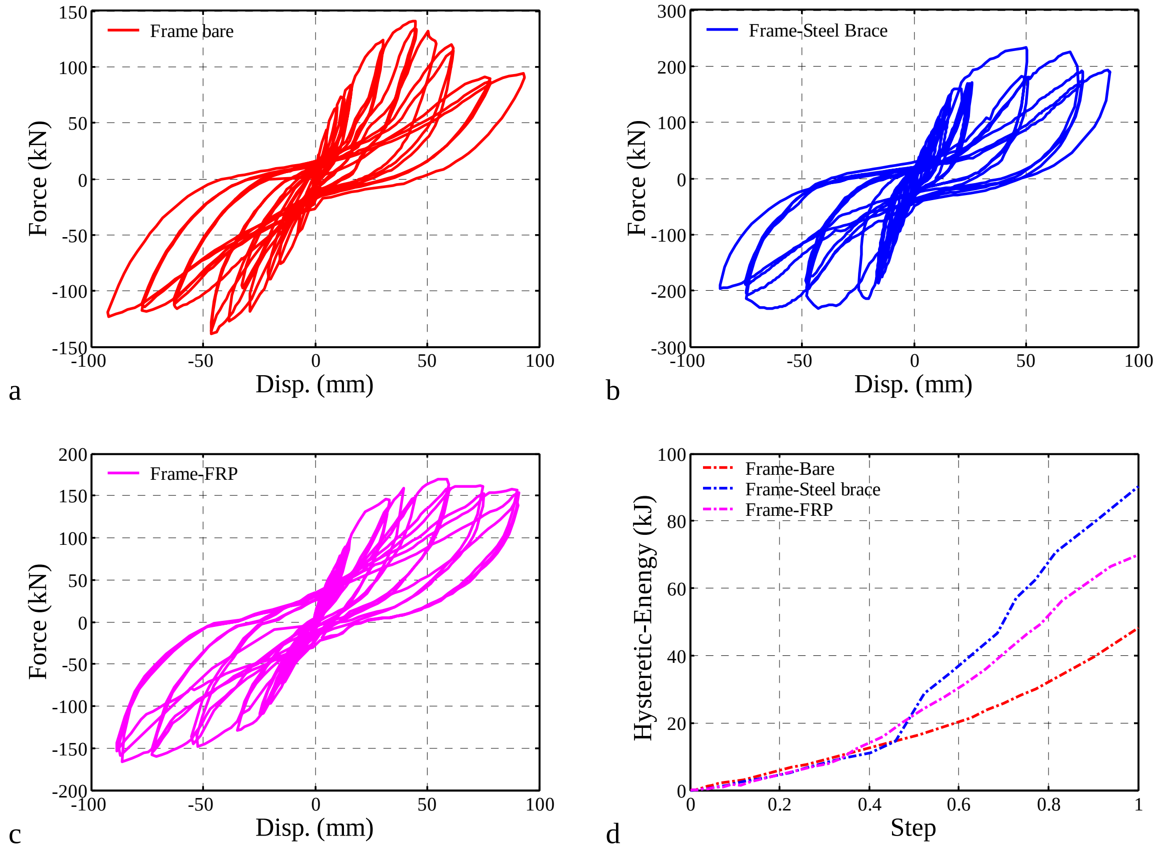


Figure 7. The hysteretic curve (a, b, c) and energy dissipation (d) of three RC frames

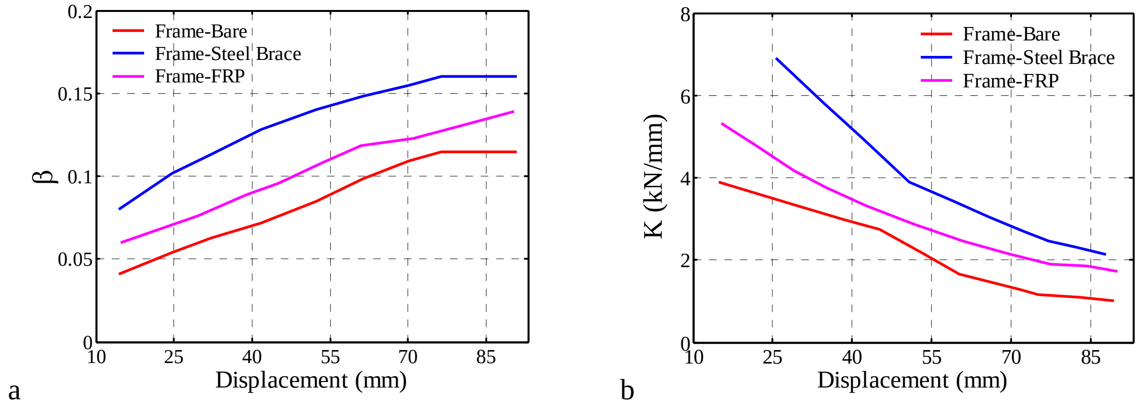


Figure 8. The equivalent damping (a) and stiffness degradation (b) during the cyclic loading

The cyclic response curves of the sample systems were utilized as shown in Figure 8 to investigate the energy dissipation capacity and the stiffness degradation of the specimens. The equivalent viscous damping and stiffness was computed from the experimental test data as follows:

$$\beta = \frac{1}{2\pi} \cdot \frac{E_{diss}}{E_{el}} \tag{4.1}$$

$$K = \sum_{i=1}^{3} P_{j,i} / \sum_{i=1}^{3} \Delta_{j,i} \tag{4.2}$$

Where Ediss is the cyclic dissipated energy, Eel is the elastic deformation energy for a linear equivalent elastic system, respectively. P, Δ are the force and displacement in the jth cyclic, respectively.

5. CONCLUSIONS

The paper deals with 1/2-scale tests on RC structure in the bare, steel brace and FRP retrofitted configurations. The retrofit criteria and calculation procedures used to design the amount and layout of steel braces and FRP required to improve the seismic performance of the structure are presented and discussed. The experimental results provided by the structure in the bare, steel brace and FRP-retrofitted configurations highlight the effectiveness of the steel brace and FRP technique in improving the global performance of damaged RC structures in terms of ductility and energy dissipation capacity.

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