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SHAKING TABLE TEST OF LARGE SCALE NONDUCTILE RC FRAMES RETROFITTED WITH FRP COMPOSITES

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ABSTRACT

Many of existing reinforced concrete (RC) frames which designed according to old seismic codes or for gravity loads has insufficient lateral load-carrying capacity and limited ductility. All of these RC frames can be defined as nonductile RC frames, and needs to be strengthened for reducing the risk of severe damage or even collapses in the future strong earthquakes. To date, the use of externally bonded fibre reinforced polymers (FRP) composites wraps is an effective means for rehabilitation and seismic retrofit of RC structures. To investigate and evaluate the seismic performance of nonductile RC frames retrofitted using FRP, the shaking table test of two 1/2 scale 4-storey and 2-bay bare and strengthened nonductile RC frames was conducted. The strengthened frame was retrofitted at the joint regions of first and second storey, due to the test results of bare frame shows that only joint regions of the lower two storeys were seriously damaged. The variation of failure mode, seismic response and performance between bare and FRP-retrofitted frame, and the development process from initial damage to failure of structures under different earthquake levels was discussed based on the experimental results. The results show that the seismic performance of retrofitted RC frame is significantly enhanced in comparison with the bare frame. Bare frame failed when the applied peak ground acceleration (PGA) equal to 0.6g, while the retrofitted frame has little damage after applied PGA larger than 1.0g. It also found that the structural horizontal displacement and inter-storey drift ratio of retrofitted frame was much smaller than bare frame at the same earthquake level.

KEYWORDS

FRP, RC frames, seismic retrofit, seismic performance, shaking table test.

INTRODUCTION

In pervious earthquake events, it have been reported that a number of existing reinforced concrete frames experienced severe damage, or even collapsed, due to insufficient ductility and energy dissipation capacity. Most of these frames designed according to pre1970 codes without considering seismic load. As a result, the designed frames have deficient lateral load resistance, insufficient energy dissipation and can rapidly lose their strength during earthquakes, leading to collapse. Therefore, strengthening such structures is essential and cannot be neglected. In the past decades, the use of externally bonded FRP composites materials has offered engineers a new solution for strengthening seismically deficient buildings. Comparatively, to other traditional strengthening techniques, FRP materials possess advantages such as high strength to weight ratio, high resistance to corrosion, excellent durability, ease and speed of in-situ application and flexibility to strengthen selectively only those members that are seismically deficient.

At present, considerable investigations have been conducted on FRP seismic retrofitted RC structures, but most of existing researches were forced on the axial compressive behaviour of FRP-confined concrete columns (Teng *et al.* 2003, 2007; Binici 2005; Smith *et al.* 2010; Wang *et al.* 2012a,b,c) and seismic performance of FRP strengthened RC frame members (Seible *et al.* 1997; Iacobucci *et al.* 2003; Fahmy *et al.* 2010; Antonopoulos *et al.* 2003; Al-Salloum *et al.* 2007, 2010a,b). Few studies have been conducted to investigate the behaviour of nonductile RC buildings strengthened with FRP (Balsamo *et al.* 2005; Erdem *et al.* 2006; Garcia *et al.* 2010; Zhu *et al.* 2011; Ozkaynak *et al.* 2011). Among the limited investigations on structural level, most studies were pseudo-dynamic or quasi-static lateral load tests. The results from these studies have confirmed the efficiency of FRP materials at preventing the occurrence of brittle failure modes and improving the seismic behaviour of the strengthened buildings. However, few studies investigated the efficiency for FRP at improving the seismic performance of large scale nonductile RC frames using shaking table tests.

This study experimentally investigated the efficiency of externally bonded carbon fibre reinforced (CFRP) sheets to improve the seismic performance of nonductile frames. Two 1:2 scale, 4 storeys, 2 bays nonductile RC frames were designed and investigated using shaking table test. One frame was bare frame as control specimen. Firstly, the control specimen was tested under gradually increased earthquake loading. Then the other frame was retrofitted based on the failure modes results of bare frame. Finally, the retrofitted frames were tested under the same gradually increased earthquake level. Based on the test results, the variation of failure mode, seismic response and performance between bare and FRP-retrofitted frame, and the development process from initial damage to failure of structures under different earthquake levels was discussed.

EXPERIMENTAL PROGRAM

Geometry of RC Frames and Material Properties

The bare and retrofitted test frames have the same dimensions and reinforcement details. The frames were 1/2 scale, four-storey, two-bay in X direction and one-bay in Y direction, and were designed with old Chinese codes to simulate nonductile frame. General view and the details of dimensions and reinforcement, are given in Fig.1

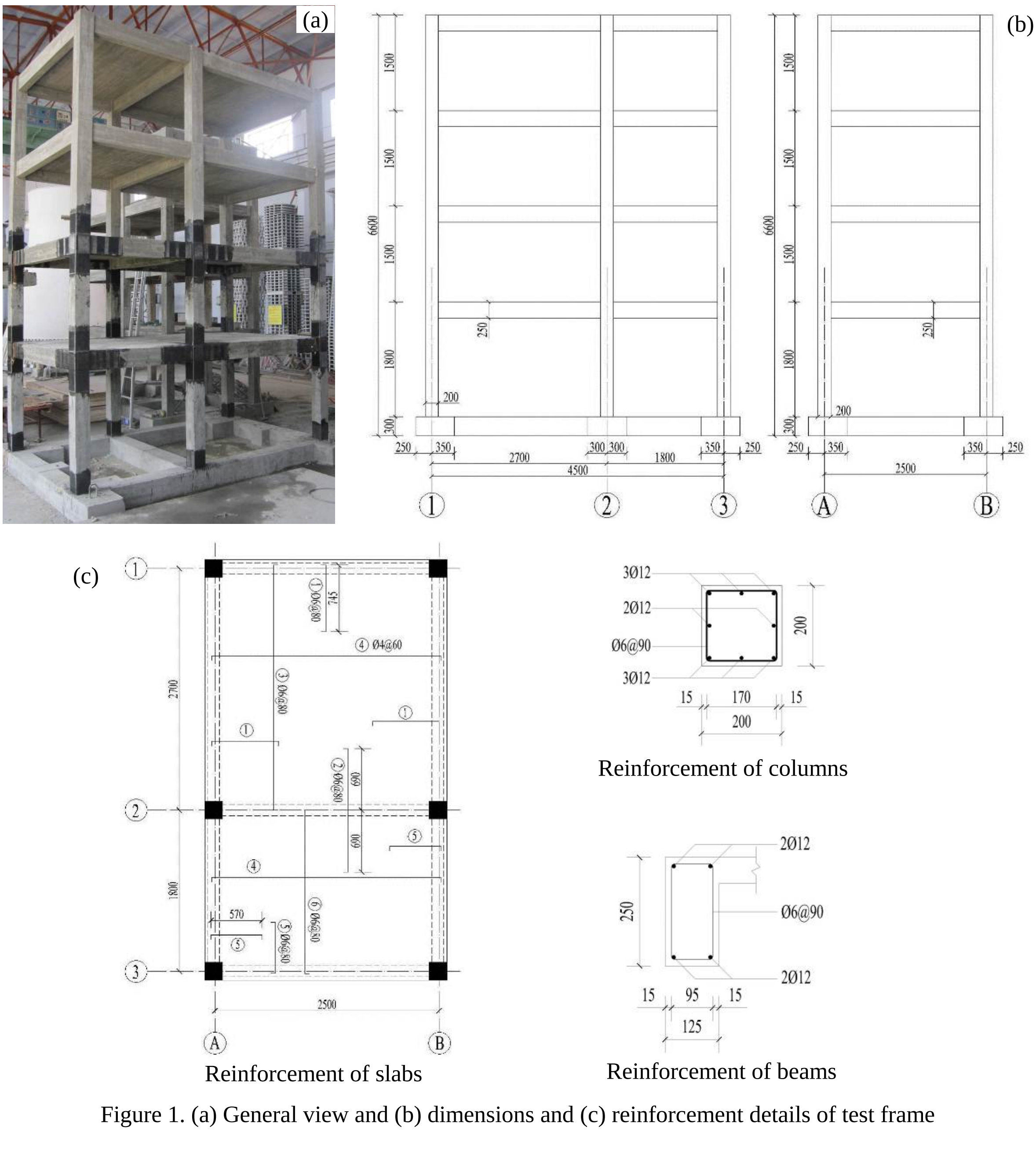


Figure 1. (a) General view and (b) dimensions and (c) reinforcement details of test frame

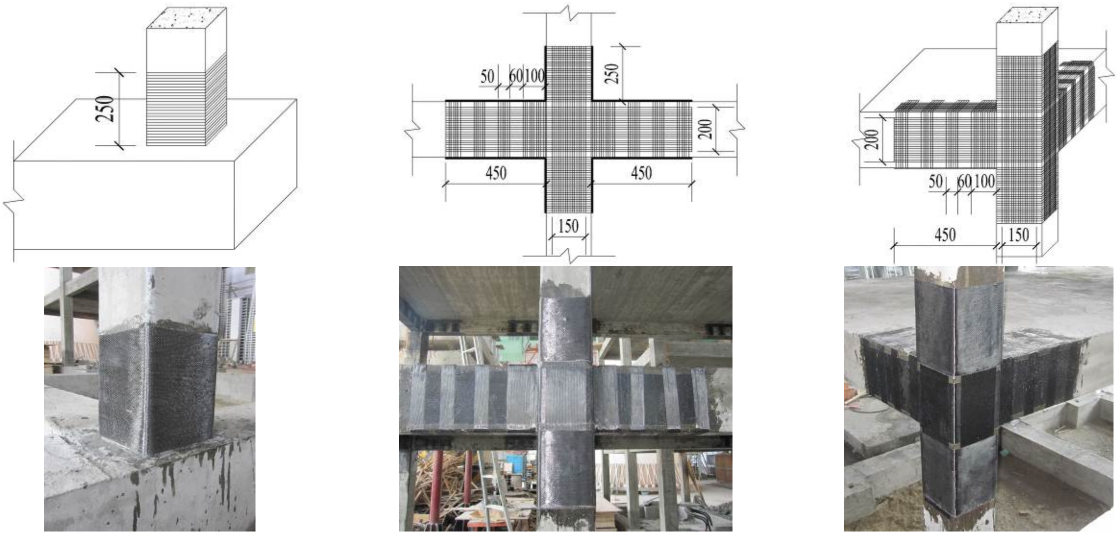
The material properties of steel and concrete were obtained based on the average results of test. The yield and ultimate strength were 412 MPa and 816 MPa for 6 mm diameter plain bars, 535 MPa and 615 MPa for 12 mm diameter deformed bars, respectively. The compressive strength of standard concrete cylinders was 20.3 MPa. The normal thickness, ultimate strength, and elasticity modulus of CFRP wraps were 0.167 mm, 4340 MPa, and 240 GPa, respectively.

Selection of Ground Motion Record and Test Programme

Three actual ground motion records (El Centro, Kobe, Northridge) were chosen as the applied input earthquakes. The time interval of all the three earthquake records was 0.02s. However, due to the time similarity coefficients of test model approximate equal to 0.5, so the time interval of input earthquake records at testing should be compressed to 0.01s. The test programme consisted of unidirectional horizontal input shaking in X and Y direction respectively, and bidirectional horizontal input shaking in X and Y directions at the same time. The input peak ground accelerations (PGA) increased from 0.15g to 1.0g. Natural frequencies of the structure were obtained using white noise as input signal before and after each test.

Retrofit Strategy and Instrumentation System

Firstly, the bare frame was tested as control specimen. Then, the other frame was retrofitted based on the test results of bare frame. The test results of bare frame shows that the columns and beam-column joints of lower first and second storey were serious damaged. Consequently, only the columns and joint regions of lower 2 storeys were retrofitted using CFRP wraps. The CFRP retrofit strategies are given in Fig.2.



(a) Columns in the ground floor (b) Exterior beam-column joints (c) Corner beam-column joints

Figure 2. CFRP retrofit strategies

The foundation of the test frames were anchored to the shaking table through high strength steel bolts. During test, the displacement and acceleration in X and Y directions were recorded. The displacement was recorded by LVDTs at base and at joint regions of each storey. The accelerations at base and at each storey in two directions were recorded by accelerometer. The strains of concrete and CFRP at the beam-column joint regions were also measured by strain gauges.

RESULTS AND DISCUSSIONS

Failure Modes

The failure modes of bare frame are given in Fig.3. The frame has no obvious damage and cracks when the inputted PGA level equal to 0.15g. After applied PGA equal to 0.30g, the interface of beam-column cracked at the lower two storeys and some joint regions appeared diagonally cracks, as shown in Fig.3.(a1), (b1). With the applied unidirectional horizontal PGA level increased to 0.4g, more beam-column joint regions were damaged. The width and length of existing cracks increased, and the concrete crushed at the end of columns or joint regions, as shown in Fig.3. (c1), (d1), (e1). After the bare frame experienced bidirectional horizontal input shaking under PGA level equal to 0.4g, the damage of beam-column joint regions were more serious. More cracks appeared and larger area of concrete was crushed at joint regions. The longitudinal and lateral reinforcement exposed at some joint, as shown in Fig.3. (a2) to (e2). The maximum input PGA level that can be resisted by the bare frame was 0.6g. Under this earthquake level, the frame was serious damaged, especially at joint regions of the first and second storey. Large areas of concrete crushed and a lot of steel reinforcement exposed at joint regions of the lower two storeys. Finally, the joint regions at lower storeys became plastic hinges and the structure became mechanism, as shown in Fig.3. (a3) to (e3).

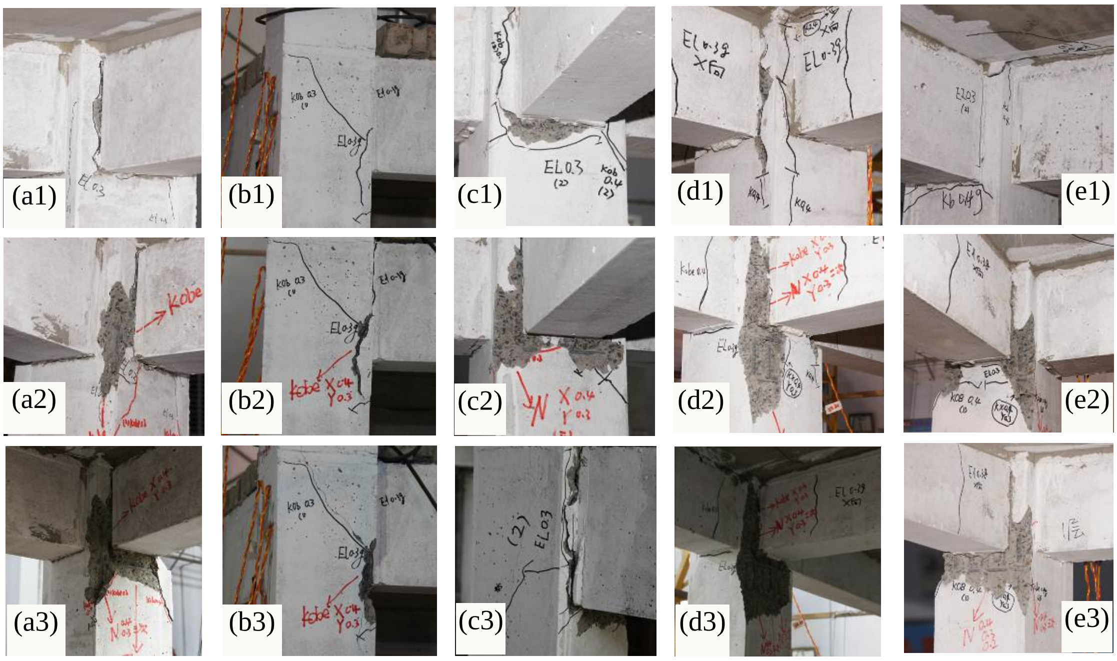


Figure 4. Failure modes of bare RC control frame model

Based on the failure modes of bare frame that only joint regions of the lower 2 storeys were serious damaged, the second frame was strengthened by wrapping FRP at the corresponding regions, as shown in Fig.2. Then the retrofitted frame was tested under the same load programmes as bare frame. The failure modes of FRP retrofitted frame are given Fig.4. When the input PGA level was 0.15g to 0.30g, clear brittle fracture sound of epoxy resin was heard but no visible damage was found after shaking. The frame still has no obvious damage under action of input earthquakes with 0.40g PGA level. The bond between CFRP and concrete is well at the retrofitted storey and no obvious cracks found at the top unstrengthened two storeys. When the input PGA level equal to 0.70g, the beam-columns interface cracked at the top two storeys and also some joint regions and the end of beams appeared several diagonally cracks. However, the retrofitted regions of lower two storeys still have obvious damage, only several core regions of joint appeared few cracks, as shown in Fig.4. (a1) to (c1) and (a2) to (c2). Due to the can be applied maximum PGA of the shaking table is equal to 1.0g, consequently the maximum PGA level experienced by retrofitted frame was 1.0g. After shaking under 1.0g PGA level, the retrofitted frame still has no serious damage. The general view of the whole structure was still as excellent as before, as shown in Fig.4.(e). Joint regions of retrofitted storeys have no visible damage. The damage concentrated on the joint regions of without retrofitted top two storeys, the number and width of cracks increased and concrete crushed at several joint regions, but the damage level only was similar with the bare frame under the 0.4g input PGA level, as shown in Fig.4.(d1), (d2). After test the wrapped CFRP was found difficult to strip, due to the bonding between CFRP and concrete still remain good. Removal of the CFRP wrap revealed that the concrete at retrofitted beam-column joint regions only has slight damage. The retrofitted joints before and after removal CFRP warp are given in Fig.4.(a3) to (d3) and (a4) to (d4).

The comparison of failure modes between bare frame and CFRP retrofitted fame reveal that the seismic performance of nonductile frame was significantly enhanced. The maximum input PGA that can be resisted by the retrofitted frame was approximately 2 times that of bare frame.

Displacement Response

To evaluate the efficiency of CFRP at improving the seismic performance of nonductile frame, the displacement response between bare and retrofitted frame was compared, as shown in Fig.5. and Fig.6.

Figure 4. Failure modes of CFRP retrofitted RC frame model

Figure. 5 shows the comparison of peak relative displacement at each storey between bare and CFRP retrofitted frame under similar earthquake level. It can be seen that the peak relative displacement at each storey of CFRP retrofitted frame is much smaller than that of bare frame under the similar input PGA level. Even the input PGA level of retrofitted frame was larger than that of bare frame, but the displacement of former is still smaller than that of latter. It is indicated that externally bonding FRP composites can effectively reduce the displacement response of nonductile frame.

The comparison of maximum inter-storey drift ratio at each storey between bare and retrofitted frame udner similar input earthquake level, are given in Fig.6. It is observed that the inter-storey drift ratio at each storey of retrofitted frame is smaller than that of bare frame under the similar earthquake level, especially in Y direction. For bare frame, the maximum inter-storey drift ratio is approximately approach to the limit value of ultimate inter-storey drift ratio (1/50) stated by Chinese code for seismic design of building under input 0.3g PGA level earthquakes. With the applied PGA level increased to 0.6g, the inter-storey drift ratio increased to approximately 3.5% which is much larger than the limit value. However, for CFRP retrofitted frame, the maximum inter-storey drift ratio is only about equal to 1.5% when the input earthquake PGA level has increased to 0.7g.

The results shown in Fig.5 and Fig.6 indicate that external bonding CFRP at the joint regions can effectively reduce the displacement response of frames under the same earthquake level. The seismic performance of nonductile frame is effectively improved after retrofitted by wrapping CFRP.

CONCLUSIONS

This paper experimentally investigated the seismic performance of large scale nonductile RC frame before and after retrofitted by externally bonding CFRP. The investigations were conducted on shaking table test. Experimental results demonstrated that the adopted local strengthening strategy using CFRP can significantly increase the resisted maximum PGA by the nonductile frame. Retrofitted using CFRP also resulted in a considerable reduction of peak relative displacement at each storey and inter-storey drift ratio under the similar earthquake level. Generally, the seismic performance of nonductile frame was obviously improved after retrofitted by external bonding CFRP.

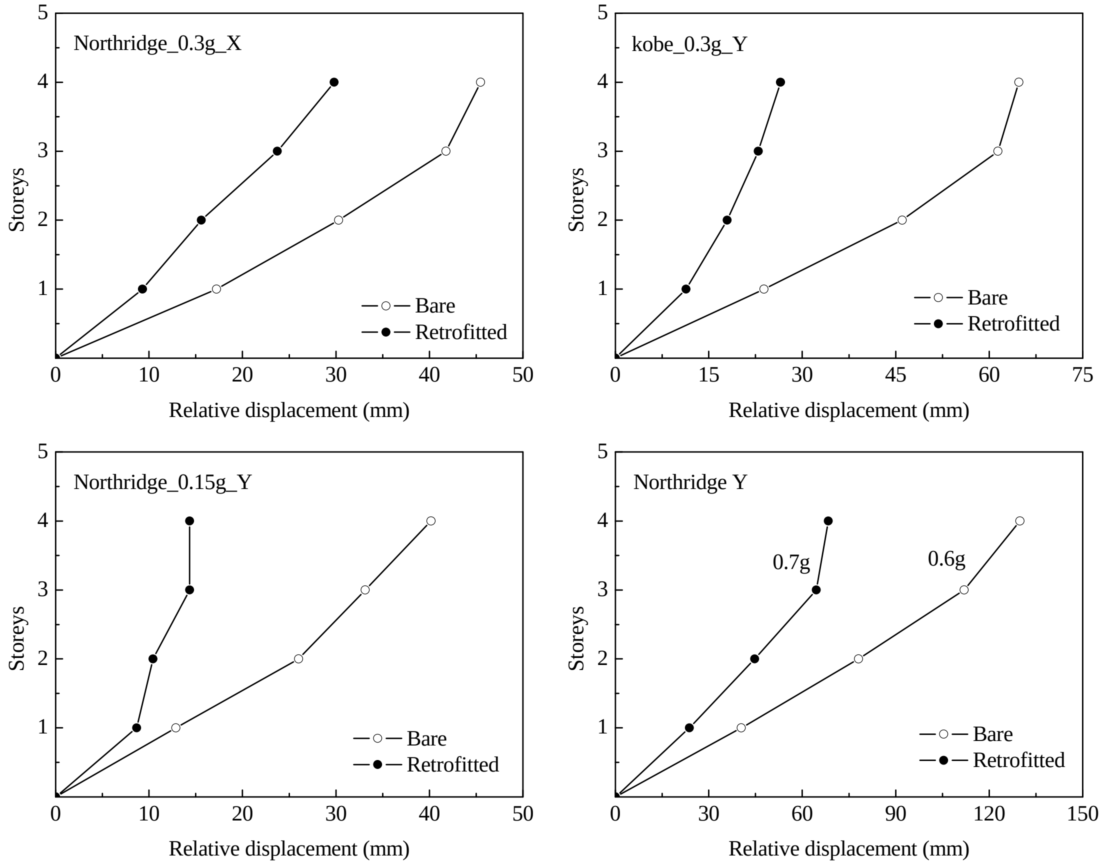


Figure 5. Comparison of peak relative displacement at each storey between bare and CFRP retrofitted frame under similar earthquake level

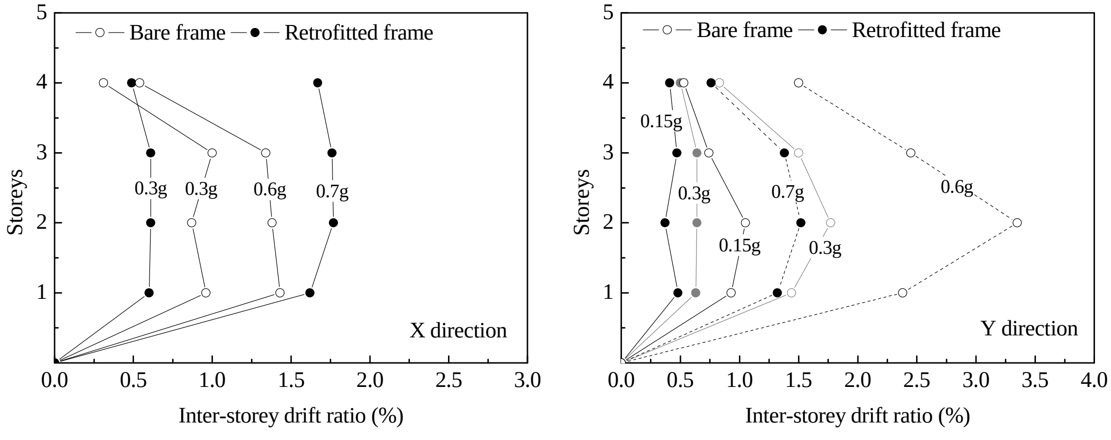


Figure 6. Comparison of inter-storey drift ratio between bare and CFRP retrofitted frame under similar earthquake level

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