# ANALYTICAL EVALUATION OF SEISMIC PERFORMANCE OF NON-DUCTILE RC FRAMES RETROFITTED USING CFRP COMPOSITES

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## Abstract

The objective of this study is to evaluate the effectiveness of different CFRP rehabilitation schemes in promoting the seismic performance of existing non-ductile RC frames. Three non-ductile RC frames with different heights representing low-, medium-, and high-rise buildings were investigated. Six typical rehabilitation patterns using CFRP composites were considered and the static pushover and dynamic time-history analyses were conducted for predicting the seismic behavior of frames before and after retrofitting. The seismic performance is evaluated in terms of the inter-story drift (ID) ratio, the base shear-top displacement and the maximum applied peak ground acceleration (PGA). It was found that for low-rise frames, the seismic performance is enhanced effectively by only retrofitting the columns of the ground floor. However, for medium-, and high-rise frames, rehabilitation of columns only was not as effective as rehabilitation of both columns and beams. The CFRP rehabilitation should result in the weak floor transfer of frames.

**Keywords**: CFRP; Dynamic analysis; Non-ductile RC frames; Perform-3D; Rehabilitation; Seismic performance; Static pushover analysis

## 1. Introduction

Most of the existing reinforced concrete (RC) frames designed according to old building codes or gravity loads have the risk of collapses when subjected to the future strong earthquakes, due to insufficient lateral reinforcement of frame columns, beams, and joints. Such frames lack of lateral ductility and load-carrying capacity, namely non-ductile frames.

In order to reduce the risk of structural collapses, there is an urgent need to strengthen existing RC frames to meet the requirements of the revised seismic codes.

In the past decades, fiber-reinforced polymer (FRP) composite materials have been widely used to retrofit or strengthen RC structures due to their light weight, high strength, and ease of application[1-2]. The FRP composite materials are usually used by wrapping or partially wrapping the structural elements such as columns and beams to increase their ductility and shear strength capacity. As a result, most of existing researches have been conducted on the FRP retrofit of RC frame members, but few studies have investigated the seismic behaviour of FRP retrofit frame structures [3-9]. Research on the principles and theoretical developments of the conceptual retrofit strategy and seismic retrofit design method of existing RC frames are still much more limited.

The objective of this study is to investigate the effect of different FRP retrofit strategy on the seismic behaviour of non-ductile frame structures. Three non-ductile RC frames with different heights representing low-, medium-, and high-rise buildings, respectively, were designed and investigated. Six typical retrofit patterns such as retrofit the columns and/or beams along the lower half of the structure height and/or full height were studied for each frame. The pushover and time-history analysis were conducted based on Perform-3D software to evaluate the seismic performance of the retrofitted frames. The conclusions were drawn by assessing the seismic performance enhancement in terms of the inter-story drift ratio, base shear-top displacement, and the maximum applied peak ground acceleration resisted by the frames.

## 2. Details of designed buildings for evaluation

To accurately evaluate the condition and the seismic performances of existing RC frames, three bare frames designed according to the old codes were selected for this research. The buildings had 5, 10, and 15 storeys to represent low-, medium-, and high-rise non-ductile RC frames, respectively. All frames had the same rectangular plan of 18 m × 30 m, which consisted of 3 and 5 symmetrical bays, respectively, where the bay width was 6 m. The floors were designed to carry their own weight as well as live load. The three frames had the same storey height of 4.5 mm at the first story and a constant height of 3.6 m at the rest of floors. The total heights of the three frames were 32.4, 72.9, 113.4 m, respectively. The dimensions of the beam section were assumed to be the same for the three structures, and the column section also remained constant along the whole building height for 5-, 10-story buildings, while for 15-story frame, the column dimensions were varied along the height according to the change of axial load acting on each group of columns. For existing buildings, the compressive strength of concrete was assumed to be 24 MPa and the yield strength of longitudinal and hoop steel reinforcement was set to be 360 MPa and 260 MPa. The elastic modulus of concrete and steel was taken as 30 GPa and 200 GPa, respectively. The density and Poisson’s ratio was taken as 25 $kN/m^3$ and 0.2, respectively.

## 3. Retrofit strategy

In order to evaluate the effect of varying distributions of FRP rehabilitation on the seismic performance of non-ductile RC frames and select an appropriate retrofitting method, six different retrofit strategies were investigated for each of the studied structures. The studied patterns included retrofit columns only (1) in the first floor for low- and medium-rise frames and in the lower 5 floors for high-rise frame and (2) in the lower 3, 5 and 10 floors for low-, medium- and high-rise frames, respectively, and (3) along the full height; and retrofit all the beams along the full height and selected columns with the same positions as patterns (1) to (3). A high tensile strength uni-directional carbon fiber-reinforced polymer (CFRP) material with the nominal thickness of 0.167 mm was designed to retrofit the frame columns and beams. The columns were retrofitted by wrapping 5 layers of CFRP composites in the lateral direction. The beams were retrofitted using two patterns. For low- and medium-rise frames, the beams were retrofitted by external bonding 3 layers of CFRP composites at their upper and bottom surfaces along the longitudinal axes to increase flexural capacity while for high-rise frame, beside the strengthened in flexural capacity the shear capacity was also strengthened by using one layer of CFRP U-wraps with the spacing center of 100 mm. The ultimate tensile strength and corresponding strain and elasticity modulus of wrapped CFRP composite were 4340 MPa, 0.0178 and 244 GPa, respectively.

## 4. Modeling of the bare and CFRP-strengthened frames

Nonlinear static pushover and dynamic analyses were performed using Perform-3D, which is a software widely used by many researchers to evaluate the seismic performance of building structures. Because of the symmetry in plan, all the three frames were modelled in 2D for computational efficiency. Beams and columns were modelled using a nonlinear beam-column element of distributed plasticity with fiber section. To increase the accuracy of the analysis, each section consisted of discrete steel and concrete fibers. The steel reinforcement and concrete characteristics were modelled based on the axial stress-strain models. An ideal elastic-plastic material was used to model the longitudinal steel reinforcement and a trilinear constitutive model was adopted to represent the concrete material. For the normal RC members, the characteristics of the stress-strain model were obtained from the stress-strain model proposed by Guo et al.[10] for plain and reinforced concrete while for CFRP-strengthened members, the characteristics were determined using the model proposed by Wang et al.[11-13] for FRP-confined reinforced concrete. The masses at each storey were lumped at the beam-column joints. Elastic damping value of 5% was set for all frames. The hypothesis of stiff floor slabs and the second order (P-delta) effects were also included in the analysis.

## 5. Validation of the analytical results

The experimental data from a quasi-static lateral load test and a shake table test (http://risedr.tongji.edu.cn/sysjk.asp) were used to validate the reliability and accuracy of the analytical results of the bare frame developed in Perform-3D software.

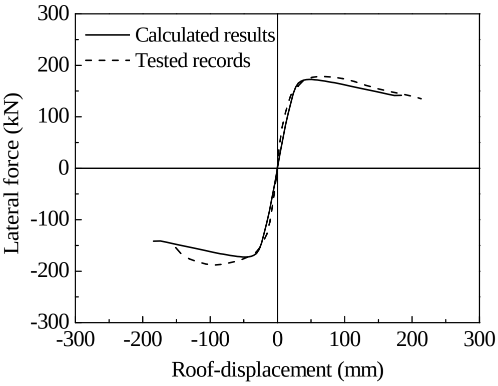
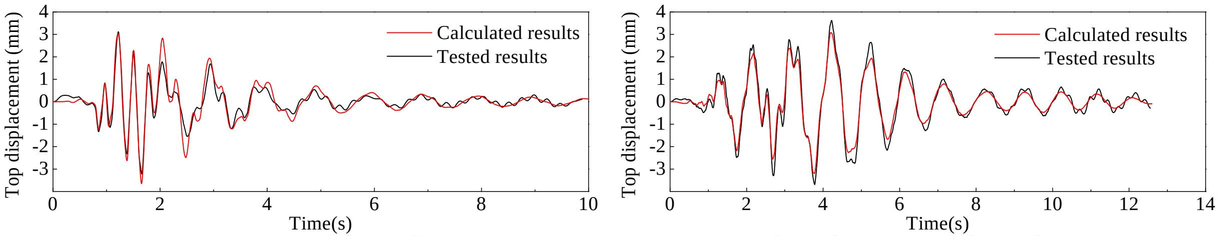


**Fig.1 Lateral force versus roof displacement**

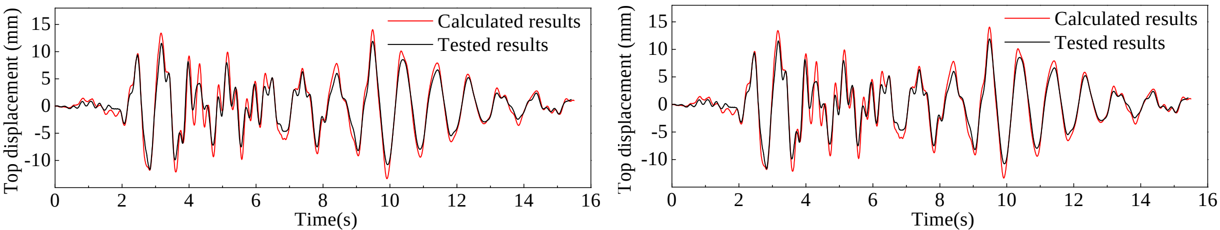
The quasi-static test which conducted by Xu et al. was used to validate the results of pushover analysis. The tested specimen was a 2D bare RC frame with 2 bays and 3 storeys. It was found that the analytically natural period of the specimen was 0.0817 s which was close to the test result of 0.091 s. Moreover, the inter-storey drift ratios at peak lateral force obtained from analysis were 1/100, 1/80 and 1/99 for the first to third floor, respectively, which were also close to the test results of 1/80, 1/71 and 1/87, respectively. Fig. 1 shows the comparison of lateral force versus roof displacement curves between experimental and analytical. The results indicate that analytical results agree well with the test results.

The shaking table test which was conducted in Tongji University by Lu et al. was used to validate the accuracy of time history analysis. The tested specimen was a 3D bare RC frame which consisted of one bay twelve storeys regular in plan and elevation. Four scaled ground motion records (i.e. EI Centro, Kobe, Shanghai artificial and bedrock earthquake ground motion records) were used in the test. The experimental and analytical displacement histories of the bare frame are compared in Fig. 2 (a) to (d) for four earthquake records. It can be seen from Fig. 2 that the predicted and tested displacements compare reasonably well along the entire time duration of the excitation.



(a)EI Centro wave in the X direction

(b)Kobe wave in the X direction



(c)Shanghai bedrock wave in the X direction

(d)Shanghai artificial wave in the X direction

**Fig.2 Comparison of the calculated results versus tested data**

The results provided in Fig. 1 and Fig. 2 as well as the discussion in the preceding two paragraphs leads one to conclude that the analytical results of pushover and time-history analysis performed using Perform-3D software are reliable and accurate for this study.

# 6. Analyses results

## 6.1 Nonlinear static and dynamic analysis of the frame

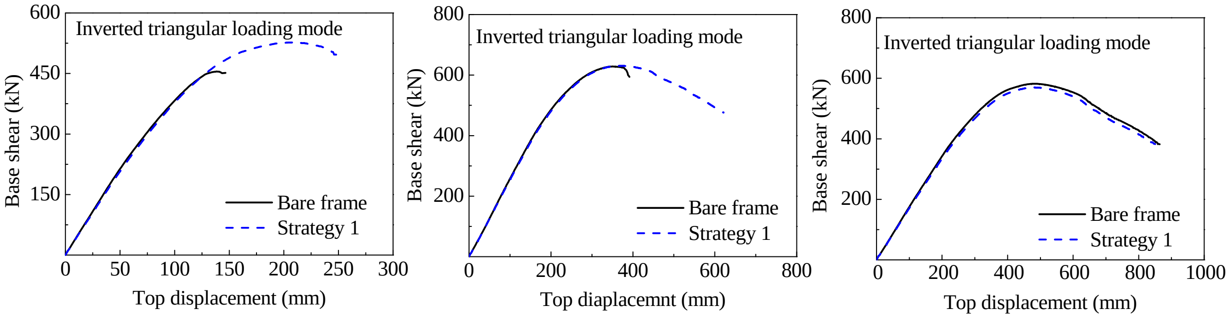
In the nonlinear static pushover analysis, a constant gravity load, equal to the total dead load plus 50% of the live load based on the China seismic design code for buildings (GB50011-2010), is applied to each frame. For accurate evaluation the seismic performance of frames, three lateral forces distribution patterns were applied to each frame (i.e. inverted triangular distribution, uniform distribution and multi-model distribution). The analytical results indicated that the multi-model distribution of load produces the largest structural stiffness and shear capacity compared with the other two distributions and the inverted triangular distribution produces the smallest values for low- and medium-rise frames, while for high-rise frame the multi-model distribution and the uniform distribution of lateral load produce approximately the same analytical results which higher estimate the capacity of frame compared with the inverted triangular distribution.

In the nonlinear dynamic time-history analysis, two earthquake records (i.e. El Centro and Taft earthquake records) and one artificial earthquake record were applied to the studied frames based on the China seismic design code for buildings (GB50011-2010). In the analysis, the maximum applied peak ground acceleration (PGA) that can be resisted by the studied frames was evaluated for different retrofit strategy and earthquake records.

## 6.2 Comparison of seismic performance between bare and retrofitted frames

In pushover analysis, the analytical results of each frame with different retrofit strategy exhibits the similar curves under the three lateral load distribution patterns as well as due to the space limitations only the case of frames retrofit using pattern 1 and subjected inverted triangular lateral load distribution was provided as an example to evaluate the seismic performance enhancement. For the same reason, in dynamic analysis, only the results of the frames under El Centro earthquake ground motion were shown to investigate the efficiency of the retrofit strategy.

Fig.3 shows the comparisons of base shear-top displacement for the bare and retrofitted frames. It can be seen that the two curves almost coincide at the early stage, indicating that strengthened using external CFRP wraps approximately has no influence on the initial stiffness of structures. It can also be seen that the retrofitted low- and medium-rise frames have a large displacement capacity without exhibiting much loss of strength but the first retrofit strategy has little increase in the seismic performance of high-rise frame. The analytical results exhibited that for high-rise frame retrofitted all the beams and columns in the lower half of structural height (i. e. retrofit strategy 4 and 5) can significantly increase the seismic performance. The provided results and the previous discussion indicate that strengthening the columns only in lower half of structural height is enough for low- and medium-rise frames, while all the beams and the columns in the lower half needed be strengthened for high-rise frames.



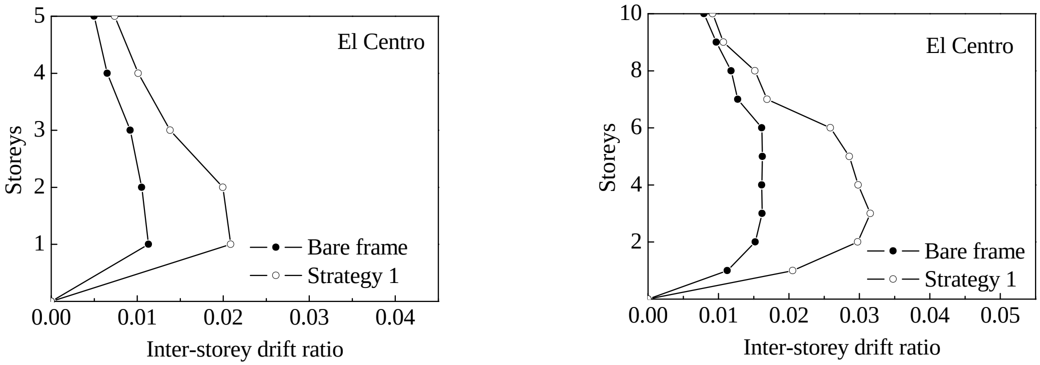
**(a) Low-rise frame** **(c) Medium-rise frame** **(c) High-rise frame**

**Fig.3 Comparisons of base shear versus top displacement for the bare and retrofitted frames**

The analytical results of dynamic time-history analysis indicates that due to the stiffness of frames approximately has no change, consequently the frame exhibit approximately the same displacement histories responses under the same earthquake records, however the maximum PGA that can be resisted by the frames is considerably increased after retrofitting. For example, the can be resisted maximum PGA is 0.24 g, 0.63 g and 0.80 g for low-, medium- and high-rise bare frames, respectively, while it is 0.38 g, 0.91 g and 0.82 g after retrofitting using strategy 1. The increases are 58%, 44% and 2.5% for three frames respectively. The results also indicate that for low- and medium-rise frames retrofit columns only in the lower half can effectively increase the seismic performance of these structures.

Fig.4 shows the inter-storey drift ratio distribution along the structure height for low-, and medium-rise frames subjected to the maximum scaled EI Centro earthquake intensities that can be resisted. From the figures, it is noted that retrofitted frames using strategy 1 can considerable increase the inter-storey capacity of the structures, which would lead to more ductile buildings with higher energy dissipation capacity compared with existing bare frames.

It is also observed that for medium-rise frame, the maximum inter-storey drift is located in the sixth floor before retrofitting, while it is located in the third floor after retrofitting. It is indicated that retrofitted frames using FRP wrap may lead the weak floor transfer of the frame structures.

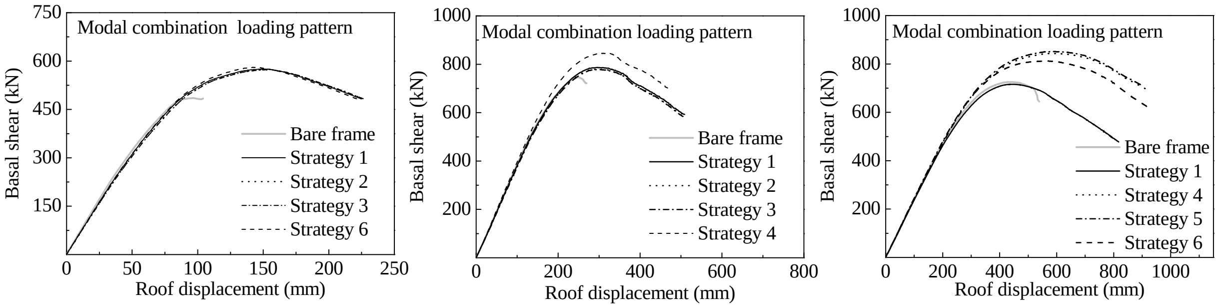


**(a) Low-rise frame** **(b) Medium-rise frame**

**Fig.4 Inter-storey drift ratio of frame before and after retrofitting using strategy one**

## 6.3 Comparison of different retrofit strategy

Due to the space limitations, only the analytical results of portion retrofit strategy were provided. Fig.5 shows the comparisons of basal shear versus roof displacement curves of frames under different retrofit strategy. It can be seen that strengthened columns only or strengthened the entire beams and columns exhibit little difference in structural behaviour for low-rise frames (i. e. Fig. 5(a)). For medium-rise frames, strengthened the columns only is still can considerable increase the seismic performance of the columns but strengthened both columns and beams performs much better (i. e. Fig. 5(b)). For high-rise frames, retrofit both columns and beams can increase the seismic performance of frames obviously, but retrofit columns only has little enhancement in the seismic performance of structures.



**(a) Low-rise frame** **(c) Medium-rise frame** **(c) High-rise frame**

**Fig.5 Comparisons of basal shear-roof displacement of frames under different retrofit strategy**

**Table 1 Maximum PGA resisted by the frames before and after retrofitting**

| Rehabilitation scheme | Existing | Scheme one | Scheme two | Scheme three | Scheme four | Scheme five | Scheme six |
|---|---|---|---|---|---|---|---|
| Low-rise frame | 0.24g | 0.38g | 0.6g | 0.59g | 0.39g | 0.58g | 0.58g |
| Medium-rise frame | 0.63g | 0.91g | 0.9g | 0.9g | 0.96g | 0.95g | 0.95g |
| High-rise frame | 0.8g | 0.82g | 0.81g | 0.81g | 1.22g | 1.26g | 1.1g |

Table 1 shows the maximum PGA resisted by the frames before and after different retrofitting strategy for low-, medium-, and high-rise frames. The results indicate that all the retrofitting strategy can increase the seismic performance and the retrofit strategy 2 performs best for low-rise frame. For medium-rise frame, retrofit all beams and portion columns resulted in much increase in seismic performance than retrofit columns only and the retrofit strategy 4 performs the best. For high-rise frames, retrofit columns only has no increase in the resisted maximum PGA while when retrofit all beams and portion columns the maximum PGA that the frame can be resisted is significantly increased and among the six retrofit strategy the fifth pattern performs best.

Based on the results provided and discussed above and considering the applicability and efficiency, the conceptual retrofit strategy for RC frames is suggested that for low-rise frames retrofit columns in the bottom 3 floors, while for medium- and high-rise frames should retrofit all beams and columns in the lower half of the structural height.

## 7. Conclusions

This paper investigated the efficiency different FRP retrofit strategy in improving the seismic performance of nun-ductile RC frames. Three frames representing low-, medium- and high-rise buildings were designed and studied. Nonlinear static and dynamic analyses were conducted using Perform-3D software. Based on the conducted analyses, the following conclusions can be drawn:

1. For existing RC frames, external bonding CFRP wrap can obviously improve the ductility and shear capacity of frames without changing the initial stiffness of structures.
2. The maximum PGA resisted by frames is obviously improved and the weak floor should be changed after retrofitting by CFRP composites.
3. Based on the analytical results, the conceptual retrofit strategy for RC frames is suggested that for low-rise frames, the first floor columns should be retrofitted, while for medium- and high-rise frames, all beams and columns in the lower half of the structural height should be retrofitted.

## 8. Acknowledgement

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