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Passive Control RC Frame with FRP Reinforcement in Columns and its Potential Benefits against Earthquakes

Lieping YE[1,2], Xinzheng Lu[1,2], YI Li[1], Asad Ullah Qazi[1]

1 Department of Civil Engineering, Tsinghua University, Beijing, China

2 Key Laboratory of Structural Engineering and Vibration of China Education Ministry, Beijing, China

ABSTRACT: The major obstacle in the implementation of performance based earthquake design is to predict the dynamic characters of structures during the nonlinear stage with random deformation concentration. By introducing some high strength elastic structural elements, the change of dynamic characters of structures in severe earthquake will be effectively controlled. And FRP can meet such requirements that are both high strength and good deformation capacity. In this paper, a novel frame with FRP reinforcement in column (referred as passive control RC frame (PCRCF), is proposed. The column with FRP reinforcement will not yield which avoids the appearance of soft story failure, and the beams with normal steel reinforcement will absorb earthquake energy with plastic hinges. Numerical examples show that PCRCF has better earthquake performance and smaller residual deformation, which makes rehabilitation and strengthening of the frames be easier for PCRCF.

1. INTRODUCTION

In most reinforced concrete (RC) structures a large stiffness is desired in order to limit structural deformation under service load conditions. Although the philosophy, the strong column/weak beam, are expected to guarantee the elastic state of columns while the beams undergo inelastic deformations by formation of plastic hinges, however it is shown that the deformations at the base of the first story columns must be excessive to initiate the frame sway (Paulay et al. 1992). Therefore the formation of plastic hinges at the base of the first story columns is inevitable as shown in Figure 1. Although in some instances the formation of plastic hinges at the column bases may not be so critical regarding the safety of the structure, but it requires extensive rehabilitation efforts. Moreover, the frame does not possess the recentring ability after undergoing severe lateral drift during strong shaking. And the chances of complete demolition of the structure are always there in case of excessive yielding at the column base sections, while the possibility of exceeding the moment capacity at the top of columns still exists, as shown in Figure 2.

The purpose of this paper is to demonstrate the alleviation and prevention of the formation of plastic hinges in frame columns by introducing FRP reinforcement in RC frame column, which is called here after as passive controlled RC frame (PCRCF) with FRP reinforcement.

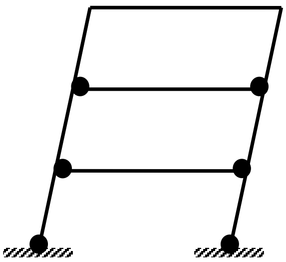

Figure 1. Strong column/weak beam configuration

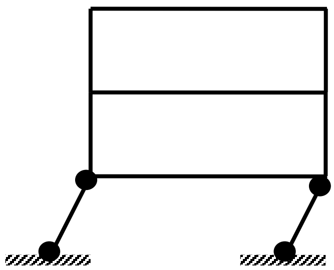

Figure 2. Soft first story failure

2. CONCEPT OF PCRCF

A conventional designed moment resistant frame usually can not successfully develop its ability against unexpected earthquake loadings due to limited flexural strength and by the formation of plastic hinges at the base of the first story columns. By introducing FRP reinforcement in columns, passive controlled RC frame (PCRCF) can safeguards its column base section from excessive yielding and resultantly can adjust structural characteristics by using the reserve flexural strength at the column base sections. Further the yielding will only occur at beams ends. Due to elasticity of FRP reinforcement in columns recentring capacity can be improved with the reduced residual lateral displacement under extreme lateral loading.

So far a large number of passive control systems with fiber reinforced polymer (FRP) reinforcement have been developed and installed. Concrete ductility with FRP tendons has been studied by Namman & Jeong (1995), Alsayed & Alhozaimy (1999) as well as hybrid FRP reinforcement with inherent ductility by Harris et al. (1998). However with the development in the Engineered Cementitious Composites (ECC) a frame system with intrinsic collapse prevention capabilities has also been proposed by Fischer & Li (2003) by utilizing ECC and FRP reinforcement in columns.

The suggested ideal frame deformation sequence is shown in Figure 3. Besides reduced residual displacements the frame showed absence of potential collapse mechanism by avoiding yielding at the column base sections.

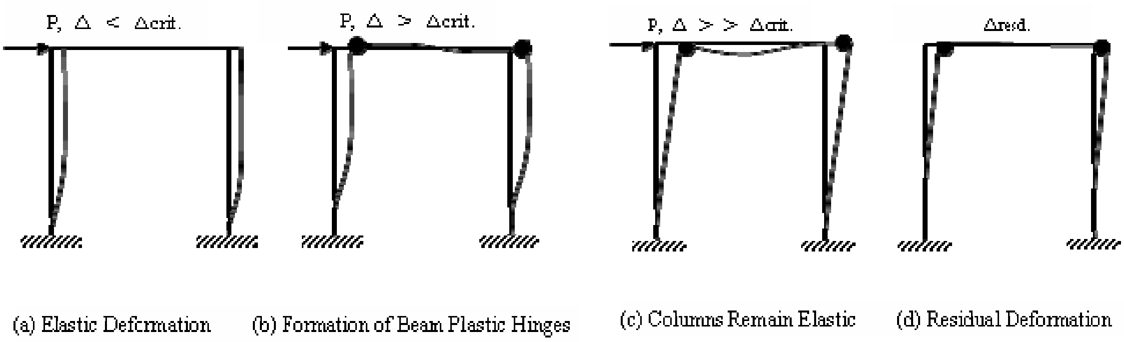

Figure 3. Deformation sequence of Passive Control RC Frame

In the present study it is suggested that the ideal frame mechanism can be achieved by using ordinary conventional concrete with FRP reinforcement.

3. ANALYSIS MODELS AND METHOD

3.1. *Models of the Ordinary RC and Passive Control RC Frames*

To demonstrate the PCRCF mechanism and to investigate the behavioral difference between ordinary frame and the PCRCF, two six-story two-bay frames, one ordinary frame (OF) and another PCRCF (PF), were analyzed. The behaviors and failure mechanism of both the frames are estimated with nonlinear static analysis. The Figure 4 represents the selected geometry cross. The section dimensions along with reinforcement ratios are given in tables 1.

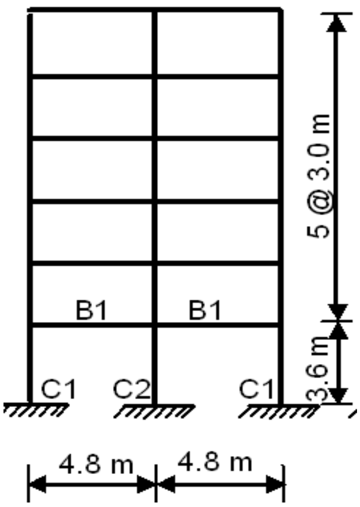

Figure 4. Geometry of the studied frames

Table 1. Cross-section areas and longitudinal reinforcement ratios of six story OF and PF.

Story/ Floor	Column Sections (mm)	Column ρ* (%)	Beam Sections (mm)	Beam ρ** (%)
1^{st}	C1 (400X450) C2 (400X500)	1.0 1.2	B1 (250X450)	1.1
2^{nd}	C1 (400X450) C2 (400X500)	1.0 1.2	B1 (250X450)	1.1
3^{rd}	C1 (400X400) C2 (400X450)	1.0 1.2	B1 (250X450)	1.0
4^{th}	C1 (400X400) C2 (400X450)	1.0 1.2	B1 (250X450)	1.0
5^{th}	C1 (400X400) C2 (400X450)	1.0 1.2	B1 (250X450)	1.0
6^{th}	C1 (400X400) C2 (400X450)	1.0 1.2	B1 (250X450)	0.9

* Total area of steel or FRP/Gross section area; ** Area of tension steel or FRP/Effective section area

The concrete in all columns has a compressive strength of 30MPa while concrete in beams has a compressive strength of 25MPa. The yield strength for steel is 400MPa. Since this research is a theoretical work, the FRP bars are set to have the same elastic modulus as steel, so as to avoid the unexpected influence due to different stiffness. And FRP has no yield stage and will fracture when stress is larger than FRP bar strength σ_f=1800 MPa.

Both the frames were analyzed on MSC.Marc using THUFIBER model. In the THUFIBER model, the section discretization scheme with 64 concrete fibers while keeping 4 steel or FRP fibers in each case were investigated to confirm the convergence requirement with a relative force tolerance of 0.1, as shown in the Figure 5. The cover and the core concrete fiber areas were different however as 25 mm clear cover was selected for all the sections.

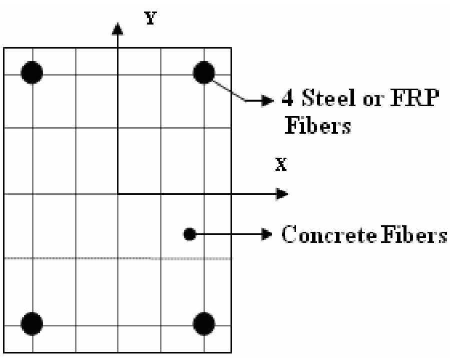

Figure 5. Section discretization

3.2. *Damage Degree Markers*

In order to evaluate the damage degrees in the two frames, a series of damage degree markers are list in Table 2 and 3 based on the following proposed indexes: ε_o and εu are strains at compressive and ultimate strength of the concrete, ε_y is yield strain of the longitudinal reinforcing steel and σ_f is yield strength of the longitudinal reinforcing steel or FRP.

Table 2. Damage markers at beams ends for OF and PF

Damage markers	Material strains		Damage	Repair	Structural safety	After repair credible performance
	Ordinary steel	Concrete				
1	$\varepsilon << \varepsilon_y$	$\varepsilon << \varepsilon_o$	Minimal	No Repair		
2	$\varepsilon \le \varepsilon_y$	$\varepsilon \le \varepsilon_o$	Light	Repairable		
3	$\varepsilon_y \le \varepsilon \le 0.015$	$\varepsilon \le \varepsilon_o$	Moderate	Repairable	Safe	Satisfactory
4	$0.015 < \varepsilon \le 0.03$	$\varepsilon_o < \varepsilon \le \varepsilon_u$	Substantial	Repairable		
5	$0.03 < \varepsilon \le 0.05$	$\varepsilon \ge \varepsilon_u$	Severe	Excessive		

Table 3. Damage markers at columns ends for OF and PF

Frame	Damage markers	Material strains		Damage	Repair	Structural safety	After repair credible performance
		Reinforcement	Concrete				
OF/PF	1	$\varepsilon << \varepsilon_y$ or $\sigma < \sigma_f$	$\varepsilon << \varepsilon_o$	Minimal	No Repair		
	6	$\varepsilon_y \le \varepsilon \le 0.005$	$\varepsilon \le \varepsilon_o$	Light	Repairable	Safe	Satisfactory
OF	7	$0.005 < \varepsilon \le 0.01$	$\varepsilon_o \le \varepsilon \le \varepsilon_u$	Moderate	Repairable		
	8	$0.01 < \varepsilon \le 0.015$	$\varepsilon_o \le \varepsilon \le \varepsilon_u$	Substantial	Excessive	Unsafe	Unsatisfactory
	9	$0.015 < \varepsilon \le 0.02$	$\varepsilon \ge \varepsilon_u$	Severe	Irreparable		
PF	10	$\sigma < \sigma_f$	$\varepsilon \le \varepsilon_o$	Light	Repairable	Safe	Satisfactory
	11	$\sigma < \sigma_f$	$\varepsilon_o < \varepsilon \le \varepsilon_u$	Moderate	Repairable		

3.3. *Load*

The frames are uniformly loaded with 30 kN/m gravity loading including self weight of beams at all the floor levels. For pushover analysis inverted triangular lateral loads at each floor level are applied. The loads are applied statically until failure state is attained. For time history analysis, the data of Northridge earthquake was used (http://peer.berkeley.edu) which has a PGA of 0.604G.

4. PUSHOVER ANALYSIS

Six story frames pushover curves are drawn in Figure.6 and damage degree and performance limit states are compared (Figure 7). PF showed better performance than OF because it has more lateral load and deformation capacity. Severe damage (marker 9) in the first story columns at base sections is observed at 347kN lateral load and at 226mm lateral displacement, while PF resisted 383kN lateral load and its beams end section reached substantial damage (marker 4).

Failure mechanism occurred in OF at 356kN lateral load when the top of the frame laterally displaced to 566mm. At this stage PF resisted 480kN lateral load and mechanism did not occur. However the beams end sections reached severe damage (marker 5) in PF. PF column base approached fracture at 506kN lateral load and at 751mm lateral displacement which is almost 1.3 times larger in magnitudes than the corresponding values observed at failure in OF. Further, collapse occurred at 356kN lateral load and 654 mm lateral displacement in OF. Hence more lateral deformation capacity of columns in PF avoided formation of collapse mechanism.

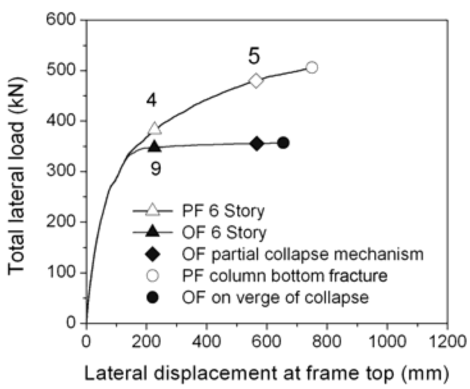

Figure 6. Performance comparison of OF and PF

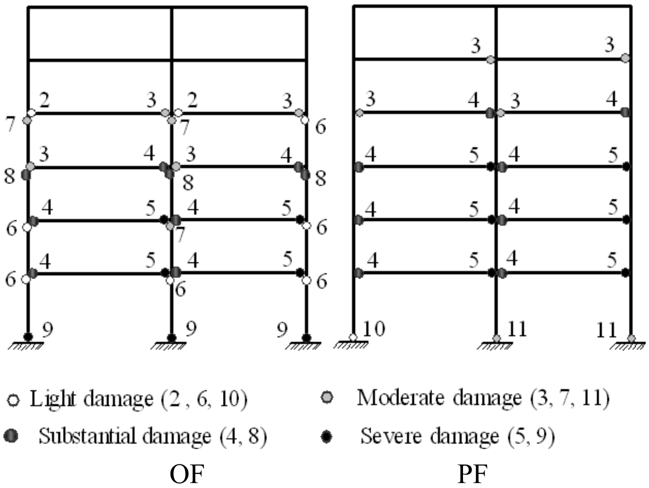

Figure 7. Damage degree indexes when top displacement reach 566mm

5. TIME HISTORY ANALYSIS

For the six story OF and PF, Northridge response is shown in Figure.8. Maximum lateral displacements nearly matched between OF and PF, but Less lateral shift is evident in PF. Besides, less residual displacement in PF can be indicated from the Figure.9. Virtually elastic columns in PF resulted with lowering in lateral displacements at the end of the dynamic event.

Figure.10 illustrates the damage observed in the six story frames. Comparison of the damage illustrates the difference in the response mechanism. In OF substantial to severe damage (marker 8 to 9) is apparent at the first story columns base section. Further at the top of the fourth story columns light damage (marker 6) also observed.

This damage pattern at column ends again highlights imminence of the partial failure mechanism. PF columns base reached light to moderate (marker 10 to 11) damage. In PF since columns are having more flexural strength than beams hence are saved from yielding. It is also noticeable that the beams suffered comparable damage in both the OF and PF. Partial failure mechanism did not occur in PF. Further formation of total failure mechanisms is delayed in PF.

6. CONCLUSIONS

In this paper the mechanism of the passive control RC frame with FRP reinforcement and its expected potential benefits against earthquakes has been compared with the ordinary RC frame.

From the above mentioned mechanism demonstration the following conclusions can be drawn.

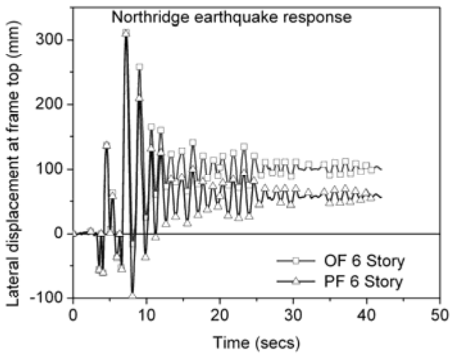

Figure 8. Top displacement history under Northridge input of six story OF and PF

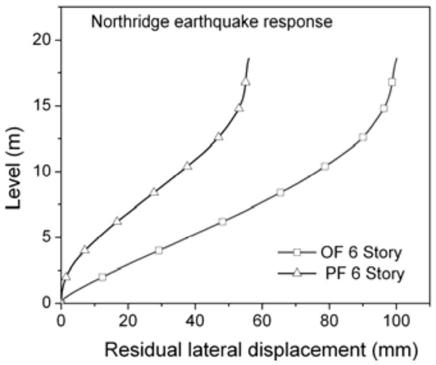

Figure 9. Residual lateral displacements under Northridge input of six Story OF and PF

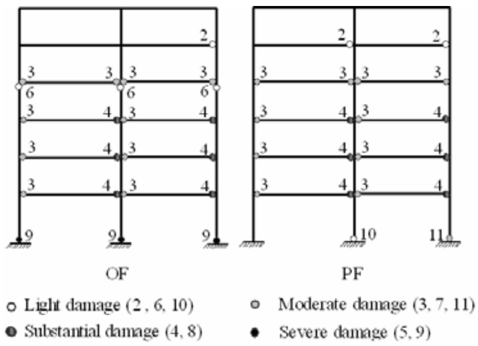

Figure 10. Damage degree under Northridge input of six story OF and PF

1) PCRCF can prevent soft story failure mechanism and provide more increased lateral load resistance capacity by simple replacement of ordinary conventional steel in the frame columns with FRP reinforcement.
2) PCRCF with FRP reinforcement shows signs of distress mainly at the beam end sections which are potentially safe from stability point of view of entire frame as compared with ODF where column base sections are badly yielded.
3) PCRCF with FRP reinforcement can reduce the residual displacement in the frames after going through lateral displacement.

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