Retrofitting of Concrete Columns for Seismic Upgrade With Fibre Reinforced Polymers

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ABSTRACT

In the research reported here, glass and carbon fibre reinforced polymers (FRP) were used to retrofit circular columns to enhance their energy dissipation characteristics. Continuous fibres were used in the circumferential directions to confine the potential plastic hinge regions of the columns. The columns were tested under constant axial load and cyclic shear and flexural loads simulating earthquake forces. A comparison of the FRP-retrofitted columns with those without FRP showed a marked improvement in the seismic resistance of columns as a result of confinement provided by FRP reinforcement. Each specimen consisted of a 356 mm diameter and 1.47 m long column cast integrally with a 510 x 760 x 810 mm stub at one end. Results from eight specimens are presented in this paper. The axial load in the columns was either 0.27 P_o or 0.54 P_o, where P_o is the theoretical axial load carrying capacity of the column.

INTRODUCTION

With better understanding of earthquake forces and the mechanisms of resistance by the structures, it has become apparent that there is a large inventory of structures that are deficient in resisting probable earthquakes. Retrofitting of these structures has become a very significant part of the construction activity in North America. In addition, repair of damaged structures after an earthquake requires efficient rehabilitation techniques. Traditional retrofitting techniques are very cumbersome and expensive for many applications. In many instances, these techniques require closing of facilities for extended period of time and may also modify the structure such that the relative values of stiffness and strength of various components are significantly different from the original values.

Use of carbon and glass FRP for rehabilitation does not have the drawbacks listed above. Their use in the field, although growing rapidly, is still limited because of a lack of information from well-instrumented large scale tests. In the research reported here continuous fibres of carbon or glass were used in circumferential direction to enhance the energy dissipation characteristics of circular columns. The main purpose of this study was to strengthen deficient columns or repair damaged ones with FRP and compare their behaviour with those of similar columns that were not reinforced with FRP.

TEST PROGRAM

In the test series involving circular columns, a total of 12 specimens were tested under concentric axial load and cyclic lateral loads simulating earthquake. Each specimen consisted of a 356 mm diameter 1.47 m long column cast integrally with a 510 x 760 x 810 mm stub. Fig. 1 shows the idealized specimen. The lateral load sequence consisted of one cycle to a displacement of $0.75\Delta_1$, followed by two cycles each to Δ_1, $2\Delta_1$, $3\Delta_1$ ... so on, until the specimen could not maintain the applied axial load. Analytical deflection Δ_1 corresponded to the maximum lateral load along a load-deflection line that represented the initial stiffness of the column without the effect of axial load.

Brief results from only eight specimens are discussed in this paper. Details of these eight specimens are given in Table 1. Longitudinal reinforcement in all specimens consisted of six 25M (500 mm^2) deformed steel bars and the spirals were made of US No. 3 (71 mm^2) deformed steel bars. Yield strength values for No 3 and 25M bars were 510 MPa and 490 MPa, respectively. The ultimate strengths were 785 MPa and 680 MPa, and ultimate strains were 0.0894 and 0.1310, respectively for No 3 and 25M bars. Concrete strength varied between 40 MPa and 45 MPa during the time the specimens were tested. Glass FRP had the ultimate strength of 518 N/mm width of the fabric whereas for carbon FRP the strength was 912 N/mm. The rupture strains were 0.0197 and 0.0142 for GFRP and CFRP, respectively. Both FRPs behaved in an elastic manner until rupture.

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RESULTS AND DISCUSSION

Results from the tests are analyzed to provide shear vs. tip deflection (V-Δ) response of the column and moment vs. curvature (M-ϕ) response for the critical section of the column near the stub . Figures 2 to 9 show the moment-curvature responses of the eight columns listed in Table 1. Behaviour of several pairs of these columns can be directly compared to evaluate the effects of different variables.

Responses of specimens S-1NT and S-2NT show the effect of axial load level. An increase in axial load from 0.27 P_o to 0.54 P_o resulted in a significant reduction in the ductility and energy dissipation capacity of the column. Both of these columns contained the lateral confining steel that meets the ACI (1995) and the Canadian (CSA 1994) code requirements. A similar effect of axial load can be observed in specimens S-3NT and S-4NT although both specimens behaved in rather brittle manners since they contained only about 25% of the cod required spiral steel. Specimens S-1NT, S-2NT, S-3NT and S-4NT contained no FRP.

The beneficial effects of using GFRP on the behaviour of columns can be observed from comparing specimens S-3NT and ST-2NT, and specimens S-4NT and ST-5NT. Specimens S-3NT and ST-2NT (Figures 4 and 6) contained the same amount of the longitudinal and lateral steel with similar detailing and were tested under similar levels of axial load (0.54 P_o). The only difference between the two specimens was the presence of two layers of GFRP in ST-2NT. Specimens S-3NT failed in the third load cycle (maximum displacement of Δ_1) whereas specimen ST-2NT underwent 12 cycles of load excursion with a maximum displacement of $6\Delta_1$. Response of specimen ST-2NT was even superior to that of specimen S-1NT in which the spiral steel met the seismic requirements of the ACI and CSA codes. Similar beneficial effects were obtained with the use of 1 layer of GFRP for the column tested under 0.27 P_o (specimens S-4NT and ST-5NT in Figures 5 and 9). Retrofitting with GFRP enhanced the energy dissipation capacities by up to 110 times in these columns. The thickness of glass fabric used was 1.25 mm.

Effects of using CFRP can be evaluated by comparing the responses of specimens S-3NT and ST-3NT and specimens S-4NT and ST-4NT (Figures 4 and 7 and Figures 5 and 8). Retrofitting with 1 layer of 1 mm thick CFRP wrap in specimen ST-3NT significantly enhanced the seismic resistance of the column (S-3NT is the comparable specimen without CFRP) under an axial load of 0.54 P_o. The energy dissipation was enhanced by more than 40 times as a result of retrofitting with CFRP wrap. Under an axial load of 0.27 P_o (S-4NT vs ST-4NT) the improvement in energy dissipation was more than 110 times as a result of retrofitting with 0.5 mm thick CFRP wrap.

It can be concluded from the response of specimens S-3NT, ST-2NT and ST-3NT that under an axial load of 0.54 P_o two layers of 1.25 mm thick GFRP wrap and one layer of 1 mm thick CFRP wrap provided equivalent improvements in the seismic performance of columns. For an axial load of 0.27 P_o, similar improvements were obtained with 1 layer of 1.25 mm thick GFRP wrap and one layer of 0.5 mm thick CFRP wrap (specimens S-4NT, ST-4NT and ST-5NT). In all cases, the behaviour of originally deficient columns retrofitted with FRP was superior to that of steel-reinforced columns that satisfied the ACI and CSA code requirements for confining steel for seismic resistance.

Concluding Remarks

Results from eight 356 mm diameter and 1.47 m long columns tested under simulated earthquake loads are presented. All the columns were reinforced conventionally with longitudinal and spiral steel. Two of the eight columns satisfied the seismic requirements for confining steel of the North American codes. Four columns that were deficient in spiral reinforcement were retrofitted with glass and carbon FRP. The following conclusions can be drawn from the experimental work.

An increase in axial load from 0.27 P_o to 0.54 P_o resulted in a large reduction in ductility and energy dissipation capacity of columns. Increase in spiral steel content enhanced a column's ability to dissipate flexural energy. Use of carbon and glass FRP wraps resulted in marked improvement in the performance of columns with respect to ductility, energy dissipation and strength. This simple procedure can be used to strengthen deficient columns to the extent that their performance under simulated earthquake loads matches or exceeds the performance of columns designed according to the seismic provisions of the North America codes. The amount of FRP reinforcement needed depends on the level of axial load and the expected performance of the columns. For the columns tested in this study, it was observed that two layers of glass fabric and one layer of carbon fabric provided similar confinement of the columns and hence similar improvement in their behaviour.

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TABLE 1: DETAILS OF TEST SPECIMENS

Specimen	Lateral Steel			Treatment	Axial Load P/P_o
	Size	Spacing (mm)	ρ_s (%)		
S-1NT	US #3	80	1.12	Control	0.54
S-2NT	US #3	80	1.12	Control	0.27
S-3NT	US #3	300	0.30	Control	0.54
S-4NT	US #3	300	0.30	Control	0.27
ST-2NT	US #3	300	0.30	Strengthened with two layers of 1.25 mm thick glass fabric	0.54
ST-3NT	US #3	300	0.30	Strengthened with one layer of 1 mm thick carbon fabric	0.54
ST-4NT	US #3	300	0.30	Strengthened with one layer of 0.5 mm thick carbon fabric	0.27
ST-5NT	US #3	300	0.30	Strengthened with one layer of 1.25 mm thick glass fabric	0.27

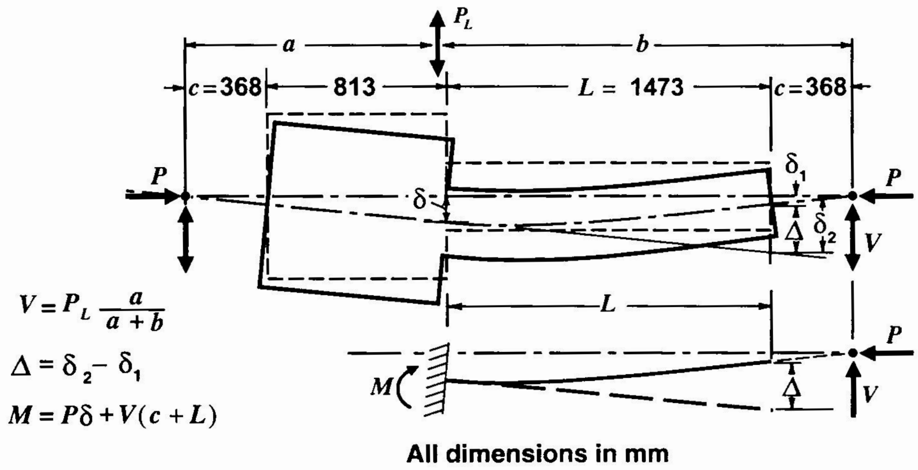

Fig. 1. Idealization of Specimen.

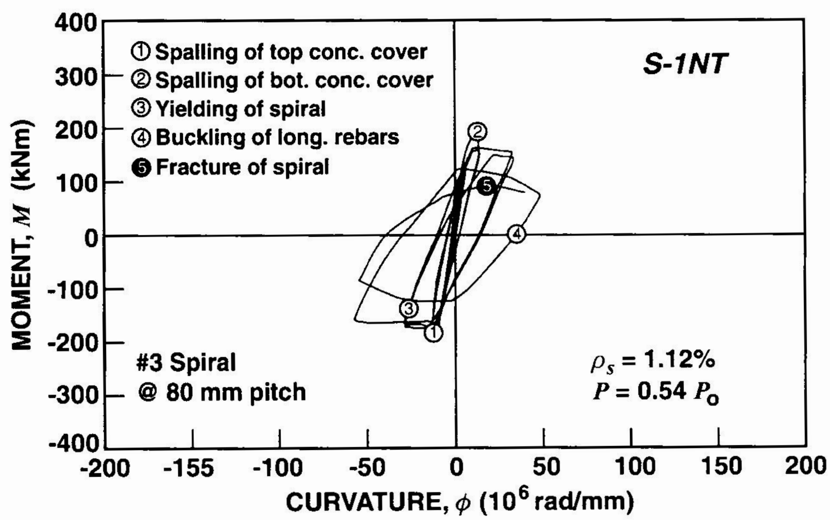

Fig. 2. Moment-Curvature Response of Specimen S-1NT.

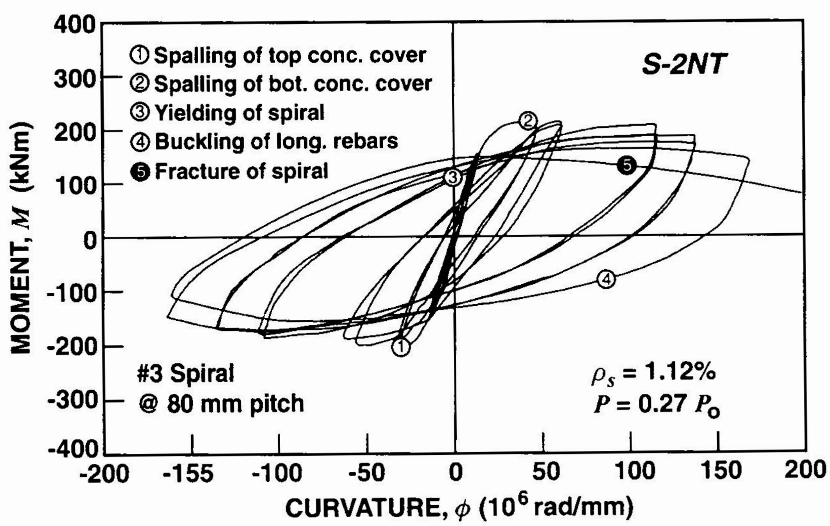

Fig. 3. Moment-Curvature Response of Specimen S-2NT.

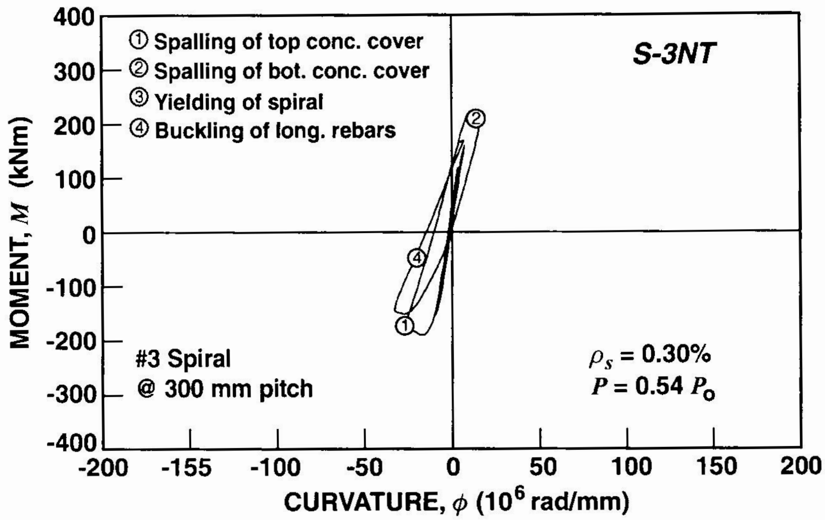

Fig. 4. Moment-Curvature Response of Specimen S-3NT.

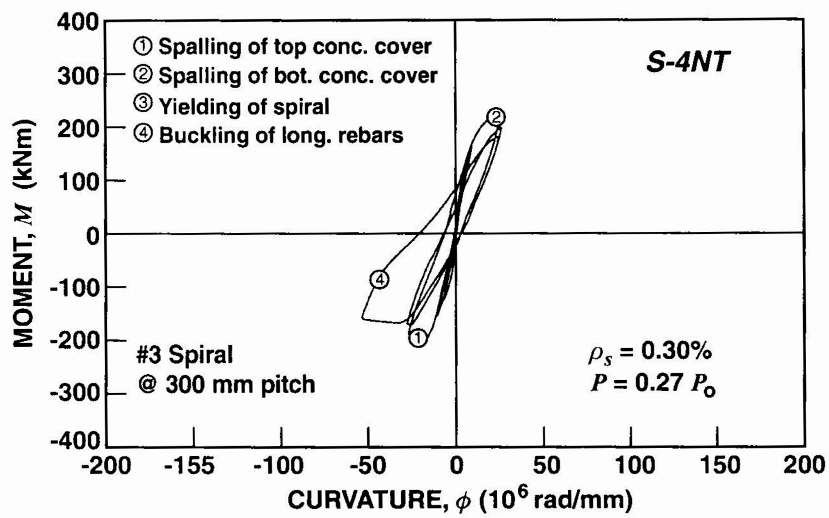

Fig. 5. Moment-Curvature Response of Specimen S-4NT.

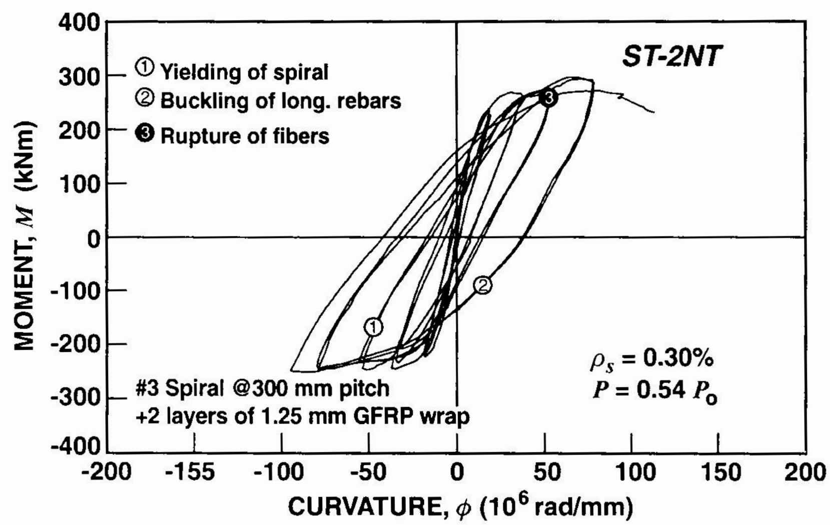

Fig. 6. Moment-Curvature Response of Specimen ST-2NT.

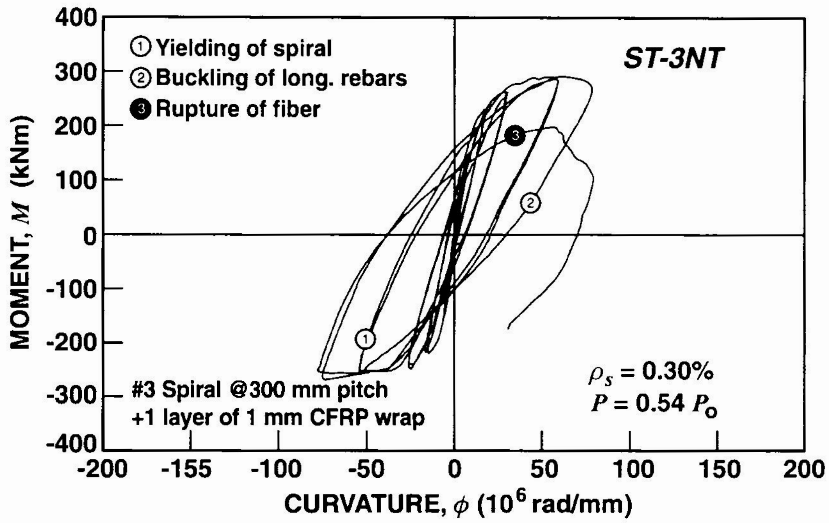

Fig. 7. Moment-Curvature Response of Specimen ST-3NT.

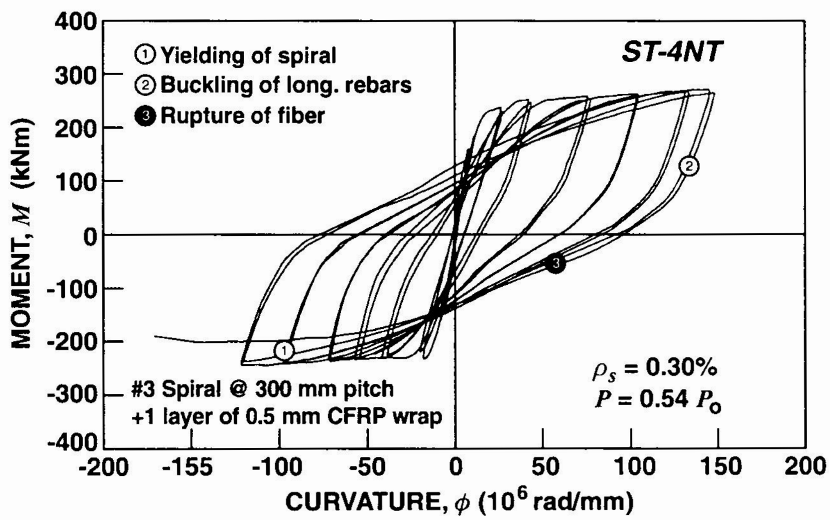

Fig. 8. Moment-Curvature Response of Specimen ST-4NT.

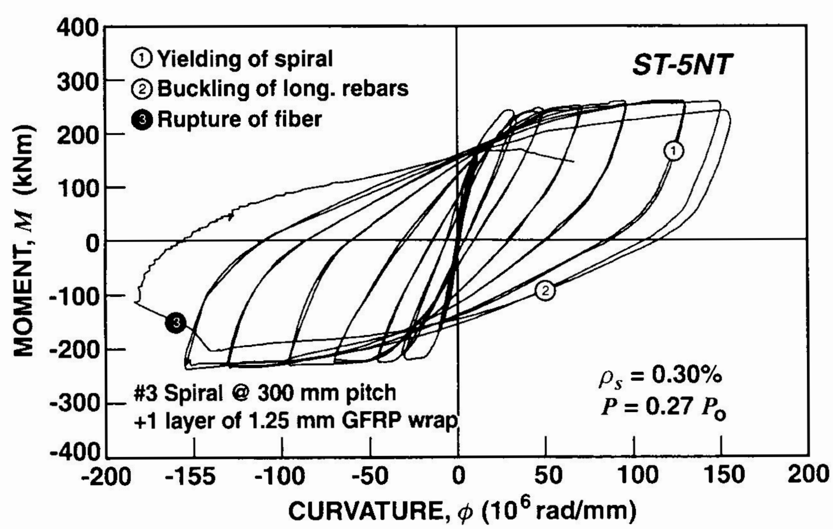

Fig. 9. Moment-Curvature Response of Specimen ST-5NT.