STRENGTHENING CONCRETE COLUMNS USING NSM CFRP LAMINATES

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Abstract

In this paper, the performance of concrete columns strengthened with longitudinal near surface mounted (NSM) carbon fiber-reinforced polymer (CFRP) composite laminates is evaluated. A total of fourteen medium-scale plain specimens with square cross-section (150×150×500 mm) were prepared and tested under concentric and eccentric compressive loading up to failure. Nine of the specimens were strengthened with four CFRP laminates (10×1.2 mm), longitudinally. Different eccentricities, namely, 0, 10, 20 and 30 percent of width of the specimens were considered. The study was designed to evaluate the behavior of longitudinal NSM CFRPs in compression. Overall, the NSM CFRP laminates used in this study were crushed at 70% of their tensile strain rupture. It is concluded that the longitudinal CFRP laminates increased the load capacity of the specimens and were able to withstand the peak eccentric load without crushing, debonding, and local buckling.

1. Introduction

The performance of existing concrete columns under eccentric axial loading can be improved by applying fiber-reinforced polymer (FRP) composites in both axial and transverse directions [1-2]. As high-modulus carbon FRP (CFRP) laminates are available in the market, the idea of using longitudinal FRP for strengthening of concrete columns has got some attention, specially for slender concrete columns [3-4]. However, there are some doubts and questions regarding the adequacy of longitudinal FRPs in compression. It is believed that FRPs in compression are much weaker than in tension and they cannot support high level of compressive strain. Also, the buckling and debonding of longitudinal FRPs are additional concerns. This study was designed to clarify the aforementioned issues through assessing the behavior of short concrete columns strengthened with near surface mounted (NSM) CFRPs as well as evaluating the behavior of CFRP strips in compression due to eccentric loading.

2. Experimental Program

2.1. Test Matrix

A total of fourteen 500 mm long plain concrete specimens were prepared with a rectangular cross section (150×150 mm). Nine of these specimens were strengthened with four NSM CFRP laminates (10×1.2 mm), as shown in Fig 1. Different eccentricities, namely, 0, 10, 20 and 30 percent of width of the specimens were considered. The specimens are identified as “P-ex-y” or “N-ex-y” where P and N stands for plain and NSM specimens, respectively; while x and y defines load eccentricities and specimen number in corresponding eccentricity, respectively. Test matrix is provided in Table 1.

2.2. Material Properties

The Sika CFRP laminates were used in this study. Five tensile coupon tests were performed and all coupons showed a linear elastic behavior up to a sudden failure. The average tensile modulus of elasticity, ultimate tensile strength, and ultimate tensile strain of the laminates determined as 205 GPa, 2388 MPa, and 0.01069 mm/mm, respectively. In addition, three concrete cylinders (100 x 200 mm) were tested at the time of testing. The average strength of 37 MPa were obtained.

2.3. Fabrication

In order to place NSM FRP laminates inside of concrete specimens, four rectangular wooden sticks (15×5 mm) were attached to the wooden formworks by glue. Two weeks after casting concrete, the wooden sticks were removed from concrete specimens to provide grooves for embedding NSM laminates. The clear distance between grooves in each side of specimens was 30 mm and the clear distance from edge of concrete to groove was 55 mm. The surface of grooves was grinded to make it free of dust and wooden parts as well as providing more friction at the interface of concrete and adhesive. MasterEmaco ADH 1420 were used for installing NSM laminates in the grooves. For avoiding premature failure at ends of specimens due to stress concentration, two layers of 50 mm wide unidirectional basalt fabrics were wrapped at both top and bottom of each column using an epoxy resin.

2.4. Test Set up

In order to apply load, a 2MN universal testing machine was used. The loading method was displacement control with a rate of 0.625 mm/sec. A data acquisition system was designed to read data from eight channels at 0.1 sec time intervals, simultaneously. The channels cover two strain gauges, four LVDTs, load, and stroke. Two strain gauges were installed on the center of two NSM FRP strips, one in compression and one in tension side of each concrete specimen, as it is illustrated in Fig 1. Two vertical LVDTs were attached to each specimen with gauge length of 100 mm. In addition, two horizontal LVDTs were installed at the center of concrete tension and compressive faces. Fig 1 indicates the location of the sensors.

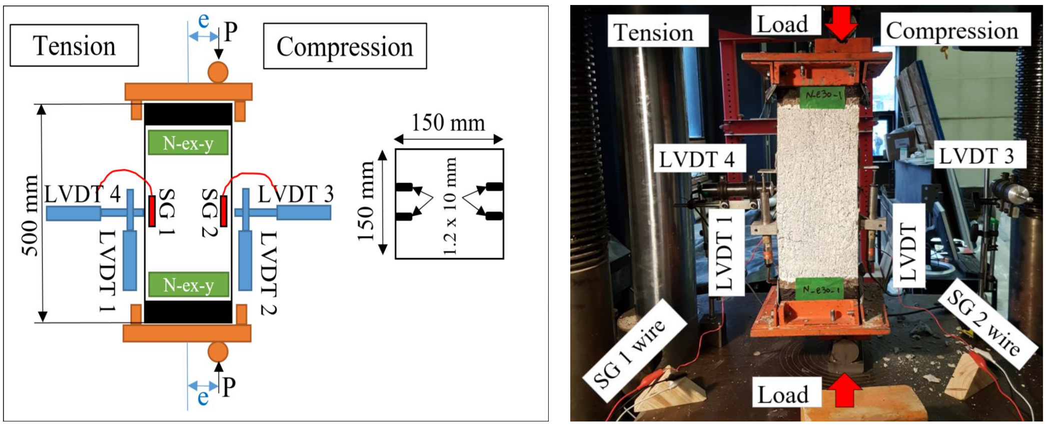

Figure 1. Test set up

A pin-pin condition was provided using specific steel caps and rollers at both ends of the specimens. The steel caps were provided by assembling four moveable steel angles attached to a base plate using bolts in one side and one notched thick steel plate using welds on the other side. At the same time two steel rollers were placed on the loading machine to be placed at location of notches. As eccentric load increases, rollers and steel caps works together to allow rotation in column ends, simultaneously. In order to prevent incompatible rotation of steel caps and concrete columns, angles were completely tightened and fixed to the ends of the specimen. Fresh grout bags were also placed at the interface of the specimen and the steel cap. Once the quick set grout bags were set completely, the concrete specimen and steel caps were placed in the testing machine between the rollers. In addition, eccentric loading was accommodated by moving thick notched plates on the steel caps at desired distance of 0, 15, 30, and 45 mm corresponding to 0, 10, 20, 30% eccentricities.

3. Results and Discussion

The summary of the test results is presented in Table 1. The strain sign convention is positive for tensile and negative for compressive strains at FRP laminates. Seven modes of failure were observed as shown in Table 1, including concrete spalling in compression (CS), concrete crushing in compression defined as the point at which the strain of compressive concrete reaches 0.0035mm/mm (CC), compressive FRP crushing (CFC), tensile FRP rupture (TRF), concrete destruction (CD), and longitudinal splitting (LS). Buckling and debonding of FRP laminates were not observed. In addition, W, W/O, and B in Table 1 indicate the failure condition that the compressive FRP with strain gauge, the one without strain gauge, or both were crushed, respectively. For specimens that were tested under concentric compressive load, whether strengthen or not, the mode of failure was crushing of concrete. In all eccentricities, strengthened specimens sustained more load in comparison with plain columns. For 15 mm eccentric load, plain concrete burden severe damages and split in half or longitudinally destroyed suddenly after very first compressive cracks. In this eccentricity, after crushing of concrete at peak load, crushing of both FRP strips at compression side of strengthened columns happened. For 30 mm eccentricity, however, one of the FRP strips crushed at peak load and caused a weakness in section and, at the end, complete failure happened by crushing of concrete. For 45 mm eccentricity, crushing of FRP strips were observed as the final failure step while they tolerated an average strain of 0.0117 mm/mm.

Table 1. Summary of test results

No.	ID	Peak Load (kN)	Maximum strain SG1 (mm/mm)	SG1 to rupture strain ratio	Maximum strain SG2 (mm/mm)	SG2 to rupture strain ratio	Failure mode	FRP crushing
1	N-e0-1	686.9	-0.00180	0.17	-0.00155	0.14	CS	-
2	N-e0-2	862.1	-0.00435	0.41	-0.00215	0.20	CS	-
3	N-e10-1	660.7	0.00425	0.40	-0.00689	0.64	CC → CFC	B
4	N-e10-2	556.0	0.00543	0.51	-0.00390	0.36	CC → CFC	B
5	N-e10-3	661.6	0.00488	0.46	-0.00637	0.60	CC → CFC	B
6	N-e20-1	537.0	0.00587	0.55	-0.00608	0.57	CFC → CC	W/O
7	N-e20-2	552.9	0.00591	0.55	-0.00407	0.38	CFC → CC	W
8	N-e30-1	408.0	0.00662	0.62	-0.01133	1.06	CC → CFC	W
9	N-e30-2	389.8	0.00458	0.43	-0.01207	1.13	TFR/CC → CFC	W/O
10	P-e0-1	791.0	-	-	-	-	CS	-
11	P-e0-2	647.4	-	-	-	-	CS	-
12	P-e10-1	589.1	-	-	-	-	CS → CD	-
13	P-e10-2	509.3	-	-	-	-	CS → CD	-
14	P-e10-3	690.5	-	-	-	-	CS → LS	-

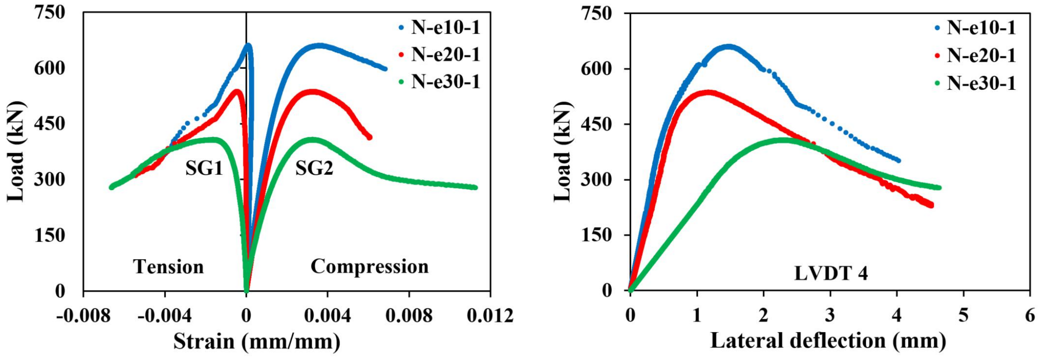

Figure 2. Load vs strain and lateral deflection of NSM specimens

The ratios of the ultimate strain of NSM at compression side (SG2) to the average tensile rupture strain of FRP coupons (0.01069 mm/mm) are presented in Table 1. The average ratio of N-e10, N-e20, and N-e30 with compressive FRP crushing (CFC) is 0.53, 0.48, and 1.10 (average ratio = 0.70). It means the NSM CFRP laminates used in this study were crushed at 70% of their tensile strain rupture. For 45 mm eccentricity, the ratio is over one, which could be due to different modulus of elasticity in tension and compression. Overall, the results indicate that contribution of compressive FRPs in strengthening of columns is not negligible and has more effects in higher eccentricities.

4. Conclusions

In this study, fourteen medium-scale short concrete columns were tested under eccentric loading to assess the performance of NSM FRP laminates in compression. Eccentricity was the main parameter that affect the mode of failure and behavior of strengthened columns. Five modes of failure were observed including crushing of concrete in compression, crushing of FRP in compression, tensile rupture of FRP, splitting of concrete in half, and longitudinal splitting of concrete. It was observed that compressive FRP strips were contributed in capacity of column and experienced considerable strains without debonding or buckling. It was observed that the longitudinal CFRP laminates increased the load capacity of the specimens and were able to withstand the peak eccentric load without crushing, debonding, and local buckling. Moreover, the ratios of the ultimate strain of NSM at compression side to the average tensile rupture strain of FRP coupons was obtained. The average ratio of N-e10, N-e20, and N-e30 with FRP crushing was 0.53, 0.48, and 1.10; and the average ratio was 0.70. Overall, the results indicate that longitudinal NSM CFRPs are able to reach high level of strains in compression and their contribution is not negligible.

References

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