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FRP-JACKETED AND SHAPE MODIFIED COLUMNS USING CHEMICAL POST-TENSIONING

C.P. Pantelides[1], Z. Yan[2], and L. D. Reaveley[3]

ABSTRACT

The axial compressive strength and ultimate compressive strain of columns inadequately designed for seismic forces can be improved by confinement with fiber reinforced (FRP) composites. To improve the confinement effectiveness of FRP composite jackets for square and rectangular columns, shape modification is performed by using prefabricated FRP shells combined with expansive cement concrete. Chemical post-tensioning using expansive cement concrete is used to change the FRP confinement from "passive" to "active". Experimental results of large-scale columns in compression with externally bonded FRP jackets, or post-tensioned FRP shells were performed on plain concrete columns. Square sections modified with FRP shells and expansive cement concrete to circular columns demonstrated a compressive strength increase by a factor of three and a ductility increase by a factor of two. Rectangular sections had a smaller but significant increase in both strength and ductility.

Introduction

Collapse of reinforced concrete buildings and bridges in large earthquakes is caused largely by failure of the supporting columns. Fiber Reinforced Polymer (FRP) composites have been used in the retrofit of concrete columns to improve their axial strength, displacement ductility or both. It is well-known that FRP composite jackets can provide effective lateral confinement for circular concrete columns, and substantially enhance their axial compressive strength and ultimate axial compressive strain; the latter is an important parameter in seismic resistant design. FRP confinement is much less effective for square and rectangular columns compared to circular columns; this has been verified in tests performed by Rochette and Labossière (2000), Pessiki et al. (2001), and Yan (2005). Stress concentrations at the corners and inefficient confinement at the flat sides cause reduction in the confinement of the section. Because of the presence of steel ties, rounding of the corner radius of the concrete section in existing square/rectangular columns is limited. In addition, lower FRP confinement effectiveness results in softening behavior for square and rectangular columns since the FRP composite ruptures prematurely; therefore, the high strength of FRP composite materials cannot be fully utilized. A possible approach to increasing the effectiveness of FRP-confined rectangular columns is to perform shape-modification that is to modify the column cross-section into an elliptical, oval, or circular section. One method for performing shape-modification is to use prefabricated (non-bonded) FRP composite shells combined with expansive cement concrete. For this method, a prefabricated elliptical/oval/circular FRP shell may be used as stay-in-place formwork for casting additional expansive cement concrete around the square or rectangular

[1,3]Professor, Dept. of Civil & Env. Engineering, University of Utah, Salt Lake City, UT 84112
[2]Engineer, Nishkian Menninger Consulting Structural Engineers, San Francisco, CA 94103

section to achieve shape modification. The advantage of using expansive cement concrete is that a post-tensioning effect could be applied to the FRP composite shell through chemical post-tensioning, which would in turn improve the compressive strength and strain capacity of concrete columns.

Expansive cement consists of a Portland cement component and a calcium-sulfoaluminate anhydrite component; the hydration of the latter causes expansion. This material has been used since 1960 for making chemically prestressed concrete. Klein et al. (1961) investigated the properties of expansive cement for chemical post-tensioning and found that factors influencing the magnitude and rate of the expansive reaction include: chemical composition of components, proportions of the two components in the total cementing material, richness of mix, conditions of curing, and degree of restraint. Benuska et al. (1971) further studied the curing effects on expansion and mechanical behavior of expansive cement concrete; their tests showed that expansive cement concrete was very good for prefabricated elements or structural elements and systems in which the optimum amount of chemical prestress required was relatively low.

The mechanism of expansive cement concrete is used with FRP composite shells for confinement enhancement. When expansive cement concrete is applied to prefabricated FRP shells, expansion of the cement grout is restrained by the FRP shell; the FRP composite is stressed in tension, thus creating a post-tensioning effect on the FRP shell and compressive stresses on the original concrete column inside the shell. It is obvious that this post-tensioning effect would increase the confinement behavior of FRP jackets and change the confinement action from "passive" to "active". In this paper, an experimental program is described, which was conducted for studying shape modification of square/rectangular specimens confined with FRP composites. Two FRP composite systems, a Carbon Fiber Reinforced Polymer (CFRP) system and a Glass Fiber Reinforced Polymer (GFRP) system were used. Column shape modification was performed by using prefabricated FRP composite shells with expansive cement concrete. Test results are presented regarding failure modes and the stress-strain behavior. A comparison is made between shape-modified specimens and those without shape modification.

Experimental Program

Specimens

The experimental program involved three groups of specimens: S, R2 and R3; "S" denotes a series of square specimens; "R2" and "R3" denote a series of rectangular specimens with cross-sectional aspect ratio of 2:1 and 3:1, respectively. All specimens were 914 mm high. No steel reinforcement was used inside the concrete in order to develop more easily a constitutive model of the actively confined concrete, and to simulate the worst case scenario of columns with corroded longitudinal steel reinforcement and inadequate steel hoops. Each group included an unconfined (baseline) specimen, two specimens with the original cross-section confined by externally bonded CFRP or GFRP composites, and two shape-modified specimens by using prefabricated CFRP or GFRP shells and expansive cement concrete to fill the gap between the original square/rectangular section and circular/elliptical FRP shell. Table 1 lists the details of all specimens; the identification of the specimens uses a three-code base. The first part of the code is the shape of the column (Square or Rectangular), and the aspect ratio of the rectangular cross-

section (2:1 or 3:1). The second part of the code indicates the type of FRP composite (CFRP or GFRP) and the number of layers (2 or 6); 0 denotes that no FRP was applied. The third part denotes the type of material used to achieve shape modification (E denotes Expansive cement concrete and 0 denotes no shape modification, i.e. the specimen has the original square or rectangular geometry). The modified cross-section of the original square specimen was circular and the modified cross-section of the original rectangular specimen was elliptical; the cross-sectional aspect ratio was close to the original prior to shape modification.

Material properties

Two types of concrete were used in this study: regular concrete and expansive cement concrete. Regular concrete was used to cast the original specimens; expansive cement concrete was used to perform the shape modification. The compressive strength of the original concrete specimens was 15 MPa. The expansive cement used in this research was Type-K and Komponent. The two principal constituents of Komponent are calcium sulfoaluminate and gypsum or calcium sulfate. The formation of ettringite crystals, which result from hydration of the two ingredients is what causes the expansion. When expansion is restrained, for example by a pre-fabricated FRP composite shell, expansive cement concrete induces tensile stresses in the FRP composite shell that cause chemical "post-tensioning". The mix design for the expansive cement concrete is listed in Table 2. The 28-day compressive strength of the expansive cement concrete was 10 MPa. Two FRP composite materials were used to confine the concrete columns. One was *SikaWrap Hex 103C* which is a high strength, unidirectional carbon fiber fabric with epoxy resin. The other was *Aquawrap G-06,* which is a unidirectional pre-impregnated glass fiber fabric with urethane resin. Both FRP composite materials were cured at ambient temperature conditions. The material properties determined from tensile coupon tests, per ASTM Standard D3039, are shown in Table 3.

For shape-modified specimens, prefabricated FRP composite shells were made prior to casting of expansive cement concrete. Strain gauges were installed on the composite at midheight of the specimens and a data acquisition system was used to measure the hoop expansion of the FRP composite shells during the curing period of the expansive cement concrete. Figure 1 shows the measured hoop strain versus time starting at casting of the expansive cement concrete. The hoop strain approached a constant value asymptotically after 60 days and this value is defined as the initial hoop strain, which refers to the state before axial compressive load was applied. The initial hoop strain depends on the aspect ratio of the prefabricated FRP shells, which is defined as the ratio of the major axis length to that of the minor axis of the elliptical cross-section. In general, circular jackets achieved the highest expansion while the elliptical shell with the highest aspect ratio had the smallest expansion. Also, GFRP shells achieved a higher expansion compared to CFRP shells.

Loading and instrumentation

All specimens were subjected to a monotonic uniaxial compressive load until failure under displacement control with a constant loading rate of 1.3 mm per minute. The tests were performed using a 9 MN actuator with a stroke of 0.6 m. Two Linear Variable Differential Transducers (LVDTs) were installed to measure axial compressive strains; strain gauges were

used to measure the transverse strains over the circumference of the cross-section.

Experimental Results and Discussion

Failure modes

For FRP-confined square/rectangular specimens without shape modification, failure typically starts with concrete crushing followed by fracture of the FRP composite jacket. In rectangular and square sections, FRP breakage appeared at one of the corners, in a small area near the column midheight; a concrete cone was seen after peeling the broken FRP composite jacket (Yan 2005). The failure was brittle due to the presence of the corner and flat side effects, which result in weaker confinement. Figure 2(a) shows the typical failure mode for a rectangular FRP-confined specimen with an externally bonded FRP jacket. In contrast to specimens with bonded FRP jackets, the failure of shape-modified specimens with non-bonded FRP shells and expansive cement concrete was fracture of the FRP jackets first, followed by cracking of the expansive cement concrete and concrete core. FRP fracture extended over the entire height of the column, showing the extensive participation of the FRP jacket in confinement. At the end of the test, most specimens remained in one piece, and shear and compression cracks were seen in the expansive cement concrete. Figure 2(b) shows the typical failure mode for a shape-modified specimen with a non-bonded FRP shell and expansive cement concrete. Specimens with non-bonded FRP shells and expansive cement concrete had a higher strain ductility compared to specimens with bonded FRP jackets, demonstrating the higher effectiveness of the post-tensioned FRP shells. The degree of damage of shape-modified specimens with non-bonded FRP shells and expansive cement concrete varied with aspect ratio. Specimens with a smaller aspect ratio reached a higher capacity and a higher degree of damage.

Axial stress-strain response

Figure 3 presents the axial compressive stress versus axial compressive strain response for each group, including the baseline specimens and the specimens confined with CFRP composite jackets and post-tensioned CFRP shells. The axial displacements were measured using the average of two LVDTs, and the axial stress was computed by dividing the axial compression load by the cross-sectional area. It is seen that CFRP-confined square specimen S-C2-0 showed a limited hardening behavior and both CFRP-confined rectangular specimens R2-C2-0 and R3-C2-0 demonstrated a softening behavior; a drop of axial stress was observed after the initial axial strength was reached, and the degree of softening increased as the aspect ratio increased. For shape-modified specimens with post-tensioned CFRP shells, the stress-strain curves show ascending branches without softening behavior. In some cases, the initial slope of the stress-strain curve for shape-modified specimens is less than that of specimens without shape modification. This is because the unconfined compressive strength of expansive cement concrete was smaller than that of regular concrete, and the confining effect from the FRP composite shell was not significant in the initial phase of axial loading. Similar observations were made for GFRP-confined specimens, as shown in Fig. 4. From Fig. 4(c), limited increases were obtained for shape-modified specimen R3-G6-E compared to the one with the bonded FRP jacket, R3-G6-0, showing that the GFRP composite is more sensitive to the cross-sectional aspect ratio.

To characterize the compressive stress-strain behavior of FRP-confined concrete columns, three important parameters are identified: axial strength f_{cc}', ultimate axial strain ε_{cu}', and ductility ratio μ, as shown in Table 4. The ductility ratio is used to evaluate the ductility performance of FRP-confined concrete and is calculated as the ratio of the total area under the stress-strain curve to the area bounded by a slope of the initial elastic stiffness and the plastic plateau (Rochette and Labossière 2000); for specimens with hardening behavior the plastic plateau passes through the unconfined concrete strength f_{co}'; for specimens with softening behavior the plastic plateau passes through the peak axial strength f_{cc}'. In Table 4, the volumetric ratio of the FRP composite jacket for each specimen ρ is also presented; ρ is the ratio of the area of the FRP composite jacket to the cross-sectional area of the concrete specimen. From Figs. 3, 4 and Table 4 it is clear that the shape-modified specimens showed increases in axial strength, ultimate axial strain, and ductility. The level of improvement of the compressive behavior depends on the aspect ratio. Figures 3 and 4 show that improvement is significant for shape-modified square specimens S-C2-E and S-G6-E since their modified shape was circular; the improvement was less for shape-modified rectangular specimens R3-C2-E and R3-G6-E; the effect of shape modification is reduced as the section becomes flatter. To improve the confinement effectiveness an oval shape is preferred. However, the practical use of a prefabricated FRP shell with a low aspect ratio such as an oval shape always increases the amount of concrete, and creates possible foundation issues resulting in cost increases.

Conclusions

Strengthening of reinforced concrete columns in buildings and bridges is an important rehabilitation technique for achieving collapse prevention in large earthquakes. Shape modification by using expansive cement concrete and prefabricated post-tensioned FRP composite shells can improve confinement of square and rectangular concrete columns; it can change the FRP confinement from “passive” to “active”, and achieve a higher axial compressive strength and ultimate compressive strain compared to square and rectangular columns with the same number of externally bonded FRP composite layers. For moderately FRP-confined square or rectangular columns, the shape modification method could change the stress-strain behavior from softening to hardening and achieve a higher strength and ductility. Square sections modified with FRP shells and expansive cement concrete to circular columns demonstrated a compressive strength increase by a factor of three and a ductility increase by a factor of two. Rectangular sections had a smaller but significant increase in both strength and ductility. The experimental results showed that the effectiveness of shape modification depends on the aspect ratio of the section; the optimal shape for FRP confinement is circular; for rectangular sections, change to a circular requires a large volume of expansive cement concrete, FRP composite, and modifications to the foundation. For strengthening rectangular columns by shape modification, the influence of factors such as volume increase, increase in surface area, and required strength, ductility, and ultimate strain need to be considered to obtain an optimal solution.

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Table 1. Details of column specimens

Group	Specimen	Cross- section before shape Modification (mm)	Length of major axis after shape modification (mm)	Length of minor axis after shape modification (mm)	Aspect ratio	FRP type and number of FRP layers
S	S-0-0	279×279	-	-	1:1[(1)]	Unconfined
	S-C2-0	279×279	-	-	1:1[(1)]	2L CFRP
	S-G6-0	279×279	-	-	1:1[(1)]	6L GFRP
	S-C2-E	279×279	406	406	1:1[(2)]	2L CFRP
	S-G6-E	279×279	406	406	1:1[(2)]	6L GFRP
R2	R2-0-0	203×381	-	-	2:1[(3)]	Unconfined
	R2-C2-0	203×381	-	-	2:1[(3)]	2L CFRP
	R2-G6-0	203×381	-	-	2:1[(3)]	6L GFRP
	R2-C2-E	203×381	648	368	1.8:1[(4)]	2L CFRP
	R2-G6-E	203×381	660	362	1.8:1[(4)]	6L GFRP
R3	R3-0-0	152×457	-	-	3:1[(3)]	Unconfined
	R3-C2-0	152×457	-	-	3:1[(3)]	2L CFRP
	R3-G6-0	152×457	-	-	3:1[(3)]	6L GFRP
	R3-C2-E	152×457	775	279	2.8:1[(4)]	2L CFRP
	R3-G6-E	152×457	762	298	2.6:1[(4)]	6L GFRP

[(1)] Square, [(2)] Circular, [(3)] Rectangular, [(4)] Elliptical cross-sections.

Table 2. Mix design per m^3 of expansive cement concrete

Property		Weight (KN)	Volume (m^3)
CEMENT	TYPE K EXPANSIVE CEMENT	2.20	0.07
	KOMPONENT	1.04	0.03
WATER	WEIGHT/VOLUME	2.34	0.24
ROCK	ASTM C-33 (SSD) 10mm PEA GRAVEL	3.26	0.13
SAND	ASTM C-33 (SSD)	13.42	0.53

Table 3. Material properties of CFRP and GFRP composites

FRP Composite	Tensile Strength (MPa)	Tensile Modulus (MPa)	Tensile Strain (mm/mm)	Ply Thickness (mm)
CFRP	1220	8.69×10^4	0.014	1.0
GFRP	228	1.69×10^4	0.014	1.6

Table 4. Experimental results

Group	Specimen	ρ (%)	$f_{cc}'(f_{co}')^*$ (MPa)	ε_{cu}' (mm/mm)	μ
S	S-0-0	-	15.2	0.002	0.90
	S-C2-0	2.55	26.2	0.010	1.15
	S-G6-0	11.64	22.1	0.020	0.93
	S-C2-E	1.80	49.1	0.022	2.38
	S-G6-E	8.00	44.4	0.021	2.03
R2	R2-0-0	-	14.8	0.002	0.90
	R2-C2-0	2.68	24.1	0.023	1.14
	R2-G6-0	12.27	21.9	0.021	0.91
	R2-C2-E	1.50	27.4	0.011	1.69
	R2-G6-E	7.10	31.2	0.018	2.72
R3	R3-0-0	-	14.6	0.002	0.90
	R3-C2-0	3.11	21.6	0.021	0.78
	R3-G6-0	14.22	21.6	0.021	0.89
	R3-C2-E	1.80	25.6	0.008	1.45
	R3-G6-E	8.00	22.8	0.021	0.93

* f_{co}' = compressive strength of unconfined concrete specimens: S-0-0, R2-0-0 and R3-0-0; f_{cc}' = axial strength of FRP-confined concrete specimens.

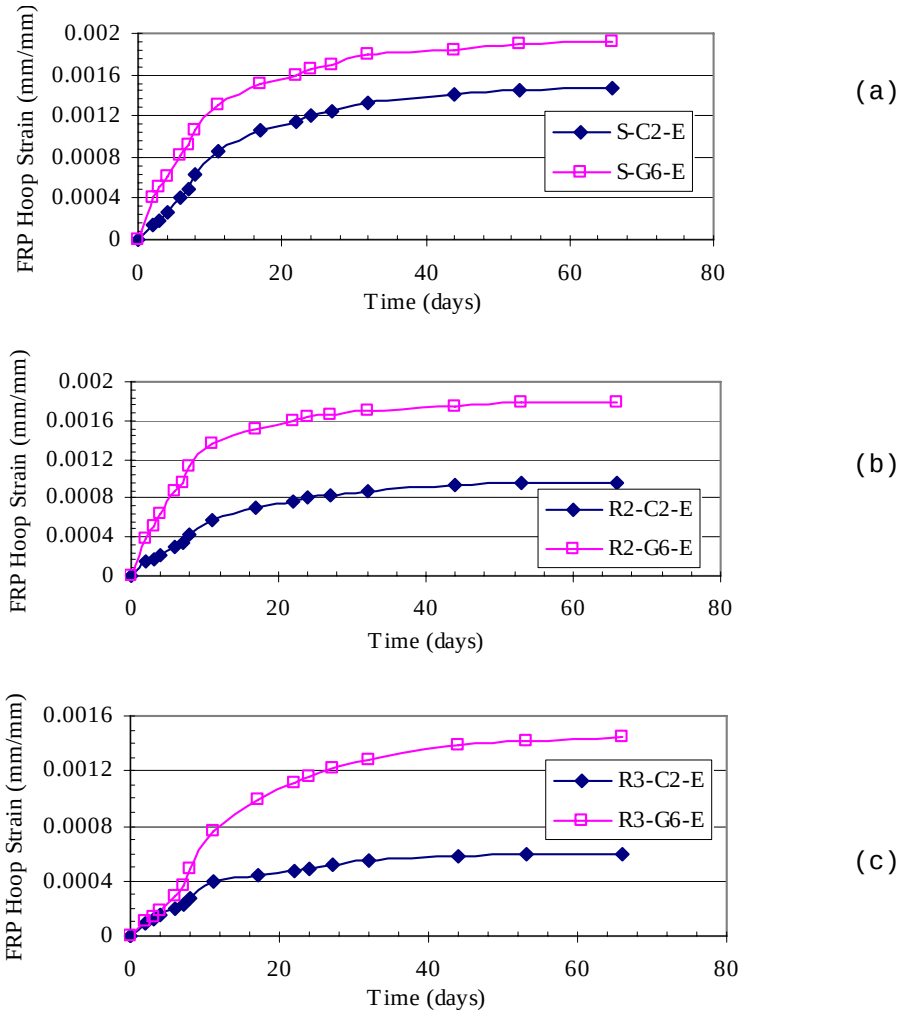
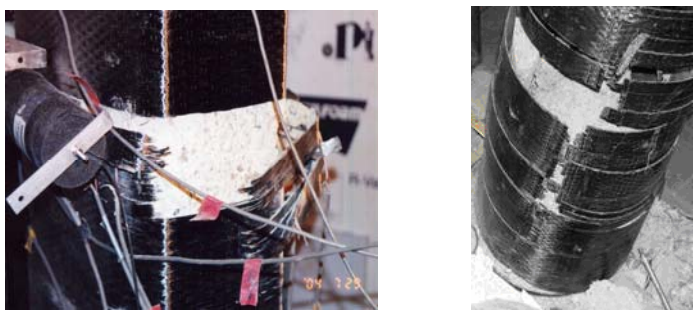


Figure 1–Expansion history for FRP shells with expansive cement concrete: (a) Square S; (b) Rectangular R2; (c) Rectangular R3



(a) (b)

Figure 2–Typical failure modes for FRP-confined specimens: (a) without shape modification; (b) with shape modification.

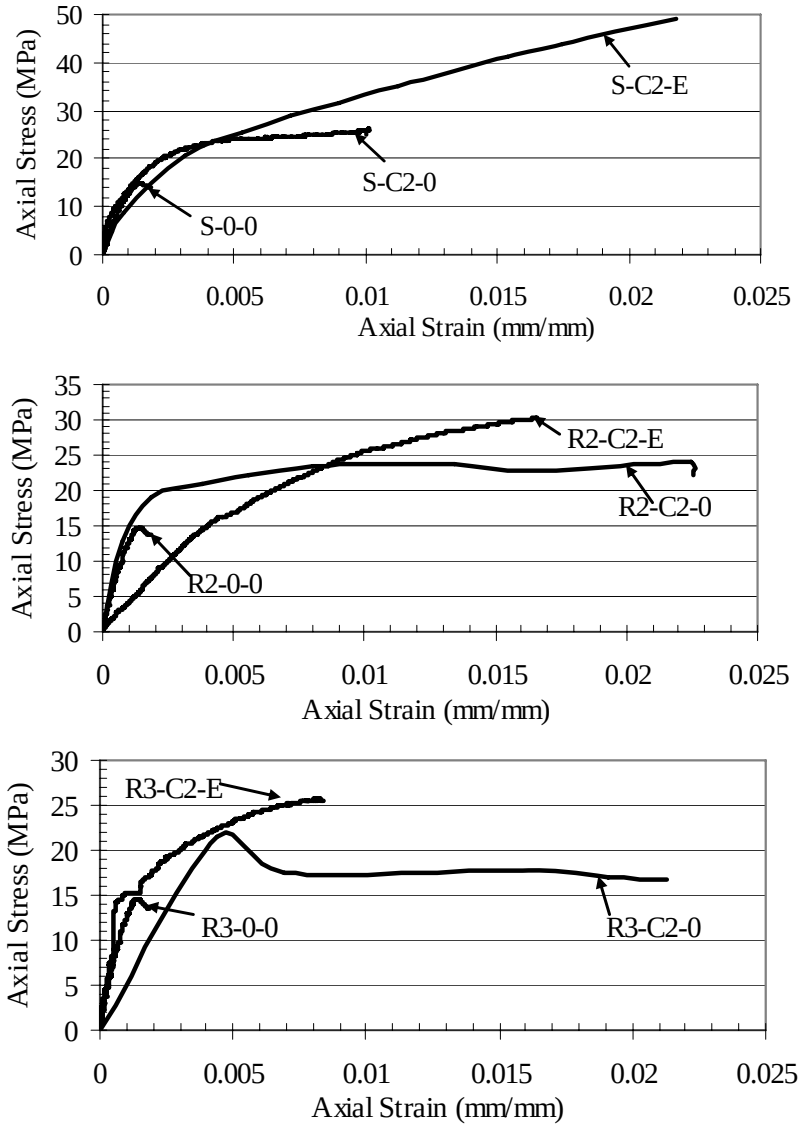


Figure 3. Axial stress-strain curves for CFRP-confined columns:
(a) Square S; (b) Rectangular R2; (c) Rectangular R3

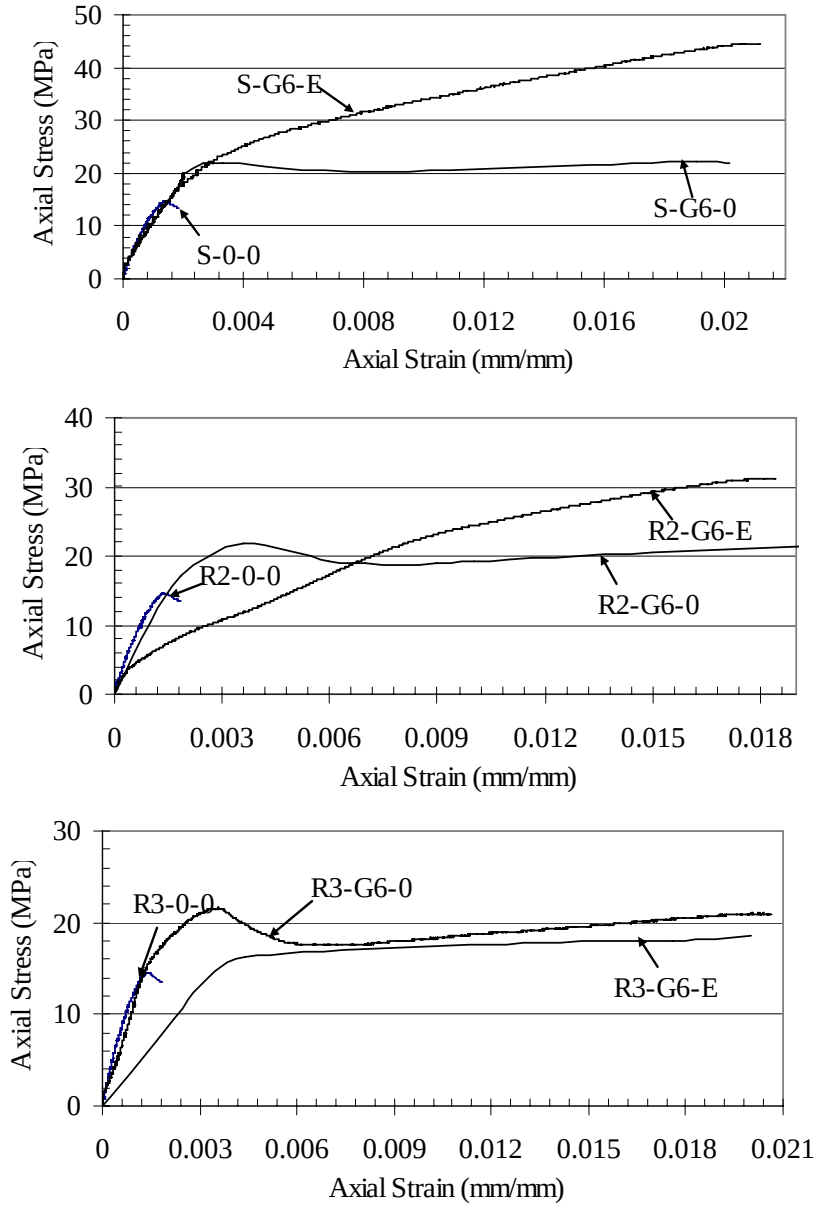


Figure 4. Axial stress-strain curves for GFRP-confined columns:
(a) Square S; (b) Rectangular R2; (c) Rectangular R3