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External FRP confinement of concrete columns using shape modification technology

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ABSTRACT: Fiber Reinforced Polymer (FRP) composites are effective for strengthening circular concrete columns. However, the effectiveness of FRP confinement for square and rectangular columns is greatly reduced due to loss of the membrane effect. Shape modification is a possible approach for eliminating the effects of column corners and flat sides, thereby restoring the membrane effect and improving the compressive behavior of FRP-confined square and rectangular concrete columns. A shape modification technology using chemical posttentioning achieved by using expansive cement concrete is studied. Shape modification by using expansive cement concrete and prefabricated FRP composite shells can change the FRP confinement from "passive" to "active", and thus increase the axial strength as well as the ductility of square and rectangular columns compared to the original columns with the same number of FRP composite layers. Parametric studies regarding the optimal geometry of the shape-modified cross-section are presented utilizing the analytical model.

1 INTRODUCTION

Externally bonded Fiber Reinforced Polymer (FRP) composite jackets can provide effective confinement for circular concrete columns (Nanni and Bradford 1995, Karbhari and Gao 1997). FRP confinement is much less effective in increasing the axial compressive strength of square and rectangular columns compared to circular ones (Rochette and Labossière 2000, Pessiki et al. 2001). A fundamental reason for this is that FRP composite jackets are more effective for circular sections as opposed to square or rectangular sections that have stress concentration at the corners and ineffective confinement at the flat sides. In addition, steel ties limit the rounding of the corner radius in existing square or rectangular column cross-sections. Lower confinement effectiveness for square and rectangular columns results in softening behavior and the FRP composite ruptures prematurely; therefore, the inherent high tensile strength of FRP composite materials cannot be fully utilized. One approach for improving the effectiveness of FRP jackets for rectangular columns is to perform shape-modification of the column cross-section into an elliptical, oval, or circular cross-section. One method is to change the rectangular/square section directly to an ellipse/oval/circle and then wrap the section with FRP composite jackets. Tests performed by Seible and Priestley (1993) established that elliptical jackets provide excellent enhancement of the flexural performance for inadequately confined rectangular columns. Teng and Lam (2002) investigated the compressive behavior of carbon FRP-confined elliptical columns; they showed that FRP confinement effectiveness depends on the elliptical shape, and that substantial strength gains could be achieved.

Another method for performing shape-modification is to use prefabricated (non-bonded) FRP composite shells with expansive cement concrete. 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 cross-section to achieve shape modification. Expansive cement consists of a Portland cement and a calcium-sulfoaluminate anhydrite component; the hydration of the latter component causes expansion. The mechanism of expansive cement concrete can be used with FRP composite shells for confinement. When expansive cement concrete is applied to prefabricated FRP shells, expansion of the cement grout is restrained by the FRP shell, thus creating a post-tensioning effect which confines the expansive cement concrete and the original concrete core. An experimental study was performed to investigate the effect of FRP confinement for columns using shape modification. A finite element model for describing the axial stress versus axial strain relationship for shape-modified concrete columns is developed. Practical and efficient implementation of shape modification technology is discussed.

2 EXPERIMENTAL PROGRAM

2.1 *Experimental program*

The experiments involved FRP-jacketed specimens bonded for the total column height, as well as shape-modified specimens confined with FRP composites. Shape modification was performed using two methods: (1) non-shrink cement concrete and subsequent application of a bonded FRP jacket, and (2) prefabricated FRP composite shells with chemical post-tensioning. A Carbon Fiber Reinforced Polymer (CFRP) system was used. A subset of the experimental results is utilized for three groups of specimens: S, R2 and R3; "S" denotes square specimens, "R2" and "R3" denotes rectangular specimens with an aspect ratio of 2:1 and 3:1, respectively. All specimens were 914 mm high; no steel reinforcement was used inside the concrete. Each group included an unconfined (baseline) specimen, a specimen with square or rectangular cross-section confined by bonded CFRP jackets, a shape-modified specimen using prefabricated CFRP shells with expansive cement concrete, and a shape-modified specimen using non-shrink concrete wrapped with CFRP composite jackets. All FRP-confined specimens had an FRP jacket applied for the full column height. *Sikawrap Hex 103C* was used as the CFRP composite material for this experimental study.

Table 1 lists details of the specimens. The specimens are identified using a three-code base: (1) shape of the column (square or rectangular) and aspect ratio of rectangular cross-section (2:1 or 3:1); (2) type of FRP composite (CFRP) and the number of layers, in this case two; and (3) type of material used to achieve shape modification, i.e. expansive cement concrete (E) or non-shrink cement concrete (F); the specimen with the original square or rectangular geometry is denoted as (0). Regular concrete was used to cast the original square or rectangular specimens; expansive cement concrete or non-shrink cement concrete was used to perform shape modification. The unconfined concrete strength for shape-modified column specimens, as shown in Table 1 is obtained by taking the mean strength over the entire modified cross-section. Table 2 lists the mix design for expansive cement concrete.

For shape-modified specimens, prefabricated FRP composite shells were made prior to casting of expansive cement concrete. Strain gauges were used to measure the hoop expansion of the FRP composite shells during the curing of the expansive cement concrete. The FRP hoop strain approached asymptotically a constant value after 60 days. Circular jackets achieved the highest expansion while R3 elliptical jackets had the smallest expansion. As an alternative, shrinkage compensated cement concrete was used to modify the rectangular/square sections to elliptical/circular sections. Once the non-shrink cement concrete was cured, the formwork was removed and bonded FRP jackets were wrapped on the modified cross-section. SikaGrout 212 was selected to make the non-shrink cement concrete fill. The mix ratio by weight was designed as follows: (SikaGrout 212: Water: Fine aggregate) = (2: 0.5:1). The compressive strength of non-shrink cement concrete after 28 days was 15 MPa. The CFRP composite material used was SikaWrap Hex 103C which is a high strength, unidirectional carbon fiber fabric with epoxy resin. The material properties were determined from tensile coupon tests per ASTM D3039 (ASTM 2001). The properties of the CFRP composite system were: tensile strength = 1220 MPa, tensile modulus = 87 GPa, and ply thickness = 1.0 mm; the ultimate tensile strain was 1.4%. All specimens were subjected to a monotonic uniaxial load until failure.

Table 1. Details of column specimens with FRP composite jackets

Specimen	a×b(1) (mm)	B×D(2) (mm)	f_{co}' (3) (MPa)	Aspect ratio
S-0-0	279×279	-	15.2	1:1
S-C2-0	279×279	-	15.2	1:1
R2-0-0	203×381	-	14.8	2:1
R2-C2-0	203×381	-	14.8	2:1
R3-0-0	152×457	-	14.6	3:1
R3-C2-0	152×457	-	14.6	3:1
S-C2-F	279×279	406×406	15.2	1:1
R2-C2-F	203×381	635×387	15.2	1.6:1
R3-C2-F	152×457	746×381	15.2	2.0:1
S-C2-E	279×279	406×406	13.3	1:1
R2-C2-E	203×381	648×368	13.1	1.8:1
R3-C2-E	152×457	775×279	13.1	2.8:1

(1) a, b= length of short and long side of cross-section before shape modification; (2) B, D=length of major and minor axis after shape modification; (3) f_{co}'= unconfined concrete compressive strength.

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

Property		Weight (Kg)	Volume (m^3)
Cement	Type K expansive cement	224	0.07
	Komponent	106	0.03
Water	volume/weight	239	0.24
Rock	ASTM C-33 (SSD) 10 mm pea gravel	332	0.13
Sand	ASTM C-33 (SSD)	1369	0.53

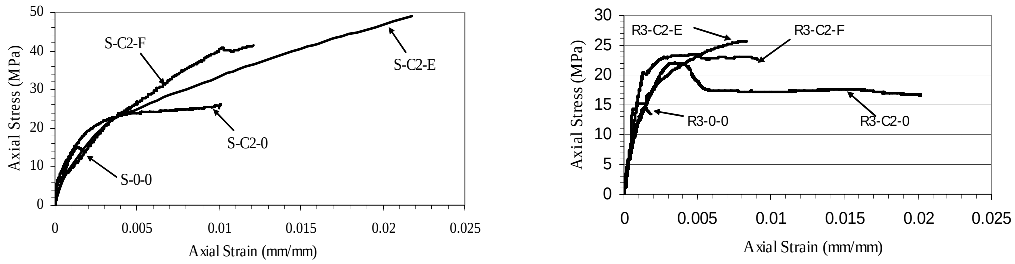
2.2 *Failure modes*

For FRP-confined square/rectangular columns without shape modification, failure started with concrete crushing followed by fracture of the FRP composite jacket at a corner. Failure was brittle due to stress concentration at the corners and inefficient confinement of the flat sides, which eliminate membrane action of the FRP jacket and result in ineffective confinement except at the four corners. For bond-jacketed specimens with non-shrink cement concrete, failure was similar to FRP-confined specimens without shape modification. Because of restoration of the membrane effect and the increased confinement, specimens failed more explosively with larger strain energy absorption. Failure modes varied with aspect ratio; shape-modified square columns in Group S had the highest capacity and most catastrophic damage, while shape-modified rectangular specimens in Group R3 had the smallest capacity and lightest damage. Failure of shape-modified specimens with non-bonded FRP shells and expansive cement concrete was fracture of the FRP shell and cracking of the expansive cement concrete. Fracture of the FRP shell extended over the column height, demonstrating extensive participation of the FRP shell in confinement; shear and compression cracks were observed in the expansive cement concrete. These specimens achieved a higher compressive strain compared to FRP-bonded specimens. Specimens with a smaller aspect ratio reached a higher axial strength. In addition, specimens with a larger aspect ratio failed less explosively than specimens with a smaller aspect ratio.

2.3 *Stress-strain response*

Figures 1 (a) and (b) show the axial stress versus axial strain response for square and rectangular R3 groups, including baseline and confined specimens with CFRP jackets. CFRP-confined square specimen S-C2-0 showed a limited hardening behavior and CFRP-confined rectangular specimen 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 with aspect ratio.

For shape-modified specimens, the stress-strain curves show ascending branches without softening behavior. The level of improvement depends on the aspect ratio of the original cross-section. Improvement is significant for shape-modified square columns S-C2-E and S-C2-F since their modified shape was circular; the improvement was smaller for rectangular columns with the higher aspect ratio R3-C2-E and R3-C2-F as the section becomes a flatter ellipse.



(a) (b)

Figure 1. Stress-strain relationships: (a) square S-specimens; (b) rectangular R3-specimens.

3 FINITE ELEMENT ANALYSIS

3.1 *Drucker-Prager model*

The Finite Element Analysis Method (FEM) can be used to develop a stress-strain relationship for either bonded FRP-confined concrete columns or shape-modified concrete columns confined with FRP shells and expansive cement concrete. The FEM analysis was carried out based on the Drucker-Prager isotropic elasto-plastic model (Karabinis and Kiousis 1994) which assumes an elasto-plastic material response with an associative or non-associative flow rule. The yield function of the Drucker-Prager model is a linear relationship between the hydrostatic and deviatoric components of the stress tensor, expressed as:

$$\rho = c + 3\sin\phi \cdot \sigma_a \tag{1}$$

where ρ = deviatoric stress component; σ_a = hydrostatic stress component, also known as the mean normal stress; c = cohesion value of concrete; and ϕ = angle of internal friction of concrete. The yield surface of the Drucker-Prager model is a circular cone where σ_a and ρ correspond to the cartesian X and Y axis respectively; c corresponds to the intercept with the ρ axis; and $\tan\phi$ is the slope of the straight line. The values of ϕ and c proposed by Rochette and Labossière (1996) were used:

$$\phi = \sin^{-1}\frac{3}{1 + 0.0016 f_{co}'} \tag{2}$$

$$c = \left(f_{co}' - 1256\right)\frac{3 - \sin\phi}{6\cos\phi} \tag{3}$$

3.2 *Model implementation*

The ANSYS program was used for performing the FEM analysis. SOLID65, which is an eight-node brick element with three degrees of freedom at each node, was used to model the concrete elements. SHELL41 is a four-noded element having membrane (in-plane) stiffness with negligible out-of-plane stiffness that is well-suited for modeling FRP composite materials. The material properties c and ϕ for concrete were obtained from the Drucker-Prager model using Eqs. (2) and (3). The FRP composite was considered as an orthotropic linear material with different elastic moduli in different directions.

Due to the symmetry of the cross-section, only one-quarter of the cross-section was modeled. For the shape-modified columns with expansive cement concrete, tetrahedral concrete elements were used to model the expansive cement grout and the original square or rectangular concrete column was modeled by hexahedral concrete elements, as shown in Fig. 2. To model the post-tensioning effect of the expansive cement concrete on the FRP jackets, an equivalent thermal gradient was applied on the SHELL41 elements to match the observed initial hoop strain in the experiments, prior to application of the axial load. The loading process was divided into steps in which an incremental axial displacement was applied at the top surface of each column; all nodes on the top face were linked so that a uniform axial compressive displacement could be exerted. Every increment was iterated until convergence was met for force and displacement criteria. Calculations were terminated when the FRP composite jacket hoop strain reached its ultimate limit, ε_{ju}. Figure 3 shows the predicted axial stress-strain curves for square and rectangular concrete columns shape-modified with non-bonded CFRP shells and expansive cement concrete.

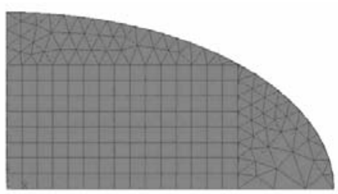


Figure 2. FEM model with FRP shell and expansive cement concrete.

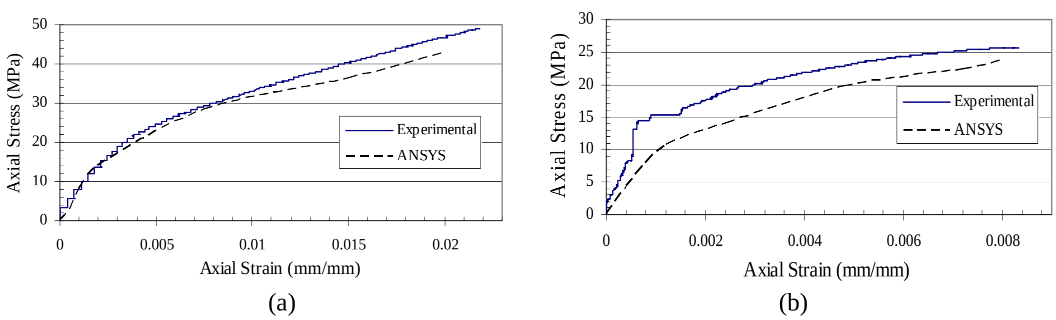


Figure 3. Comparisons between FEM model results and experiments: (a) S-C2-E; (b) R3-C2-E.

To investigate the most “effective” shape of shape-modified rectangular concrete columns, a parametric study was performed to find the optimal cross-sectional shape for applying shape modification based on several considerations including strength and strain level, cost, and construction feasibility. An original concrete column having a height of 914 mm with a cross-section of 152 mm x 457 mm was considered. Option (1) for strengthening is to apply two layers of bonded CFRP composite without shape modification. Options (2) through (6) are to perform shape modification with different geometries, number of CFRP layers, and aspect ratios, as shown in Fig. 4(a). All shape-modified columns are to be constructed using non-bonded CFRP composite jackets and expansive cement concrete. The stress-strain relationships for all shape-modified columns are developed in Fig. 4(b). Several options are available from the construction feasibility and cost point of view, and if a large increase in axial strength and axial strain capacity is required Option 5 should be considered. Option 5 may require significant enlargement of the foundation; Option 4 with an oval cross-section is the optimal amongst the remaining options.

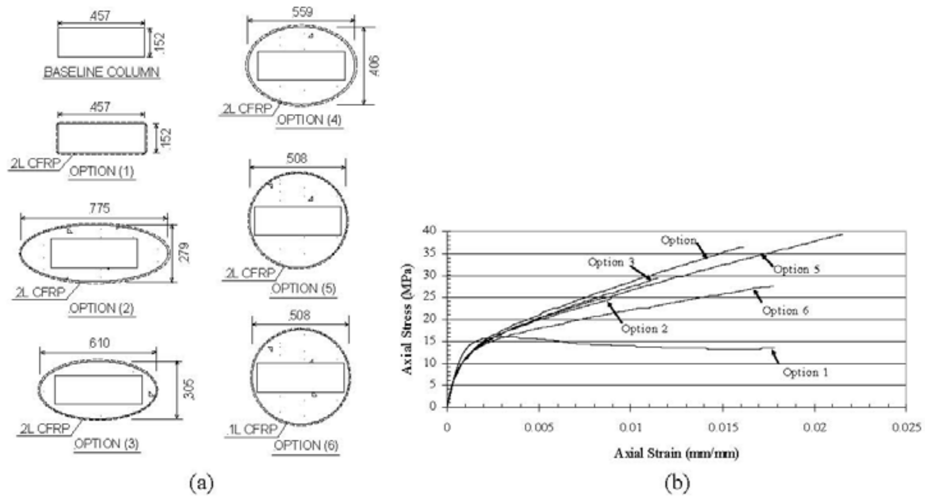


Figure 4. Parametric study of strengthening: (a) Options 1-6; (b) stress-strain curves.

4 CONCLUSIONS

Shape modification using expansive cement concrete and prefabricated FRP shells changes confinement from passive to active, and achieves a higher axial compressive strength and strain for modified square and rectangular columns compared to the original columns with the same number of FRP layers. The difference in cost between expansive and Portland cement is small compared to the total cost of the retrofit. From the practical point of view, the non-bonded FRP jacket can be used as a stay-in-place form, which would save construction time and the significant expense of formwork. A finite element model using ANSYS was developed to describe the stress-strain behavior of shape-modified columns with expansive cement concrete, which shows good agreement with the experimental results. To achieve the “optimal” cross-sectional shape for strengthening rectangular columns by using shape modification technology, a parametric study involving the influence of volume and surface area, foundation enlargement, and material cost must be considered.

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