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SEISMIC RETROFIT OF BRIDGE COLUMNS USING FIBER REINFORCED POLYMER COMPOSITE SHELLS AND SHAPE MODIFICATION

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ABSTRACT :

Fiber Reinforced Polymer (FRP) composites can provide effective confinement to circular concrete columns for the purpose of seismic retrofit of bridges. However, the retrofit effectiveness of FRP confinement for square and rectangular columns is greatly reduced due to the flat sides and sharp corners. 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. An effective method for performing shape modification with FRP composites 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 column with a square or rectangular cross-section to achieve shape modification. The restraint of the expansion caused by hydration of the component of expansive cement induces the active confinement pressure. Large-scale experimental results have shown that shape-modification using expansive cement concrete can achieve a higher axial compressive strength and ductility for modified square and rectangular columns compared to the original columns with the same number of FRP composite layers. An analytical model was developed to determine the stress-strain behavior of shape-modified columns with expansive cement concrete. In addition, a parametric study for the practical use of shape modification is carried out.

KEYWORDS: Axial stress, Axial strain, Confinement, Ductility, Expansive cement concrete, Fiber reinforced polymers (FRP), Seismic retrofit.

1. INTRODUCTION

Shear failures of bridge columns due to insufficient transverse reinforcement have occurred extensively in past earthquakes. Ductility in bridge columns is normally provided by column plastic hinges with adequate confinement (Priestley et al. 1996). 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 and ductility of square and rectangular columns compared to circular ones (Rochette and Labossière 2000). The reason for this is that FRP composite jackets are more effective for circular sections as opposed to square or rectangular sections that have stress concentrations 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 columns. 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 can not 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 aspects for efficient implementation of shape modification technology are discussed.

2. EXPERIMENTAL PROGRAM

2.1. Experimental Program

The experiments in this research 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; the FRP shell was constructed as two half-cylinders that were spliced with an FRP layer after they were cured. 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 CFRP composite shells were made prior to casting of expansive cement concrete. Strain gauges were used to measure hoop expansion of the CFRP composite shells during curing of the expansive cement concrete. The CFRP hoop strain reached 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. Once the non-shrink cement concrete was cured, the formwork was removed and bonded CFRP jackets were wrapped on the modified cross-section. SikaGrout 212 was selected to make non-shrink cement concrete fill; the mix ratio by weight was designed as: (SikaGrout 212: Water: Fine aggregate) = (2:0.5:1). The CFRP composite material used was SikaWrap Hex 103C which is a high strength, unidirectional carbon fiber fabric with epoxy resin. The material properties of the CFRP composite from tensile coupon tests were: tensile strength = 1220 MPa, tensile modulus = 87 GPa, and ply thickness = 1.0 mm; the ultimate tensile strain was 1.4%.

Table 1. Details of column specimens with CFRP 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.

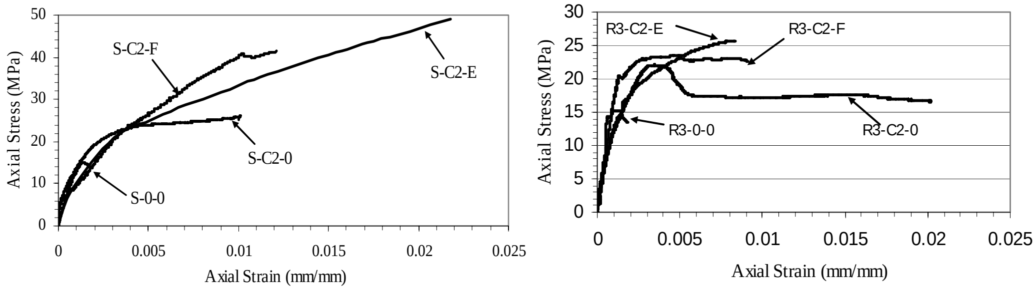
Table 2. Mix design per m^3 for expansive cement concrete

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
and fracture of the CFRP 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 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 CFRP 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; vertical cracks were observed in the expansive cement concrete. At the end of the test, cracks were observed in the expansive cement concrete, but the original concrete cross-section was protected; 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.

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.



(a) (b)

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

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 higher aspect ratio R3-C2-E and R3-C2-F as the section becomes a flatter ellipse. Detailed experimental results are described elsewhere (Yan 2005).

3. ANALYTICAL MODEL FOR AXIAL STRESS VERUS AXIAL STRAIN RELATIONSHIP

A plasticity approach based on the five parameter Willam and Warnke (1975) model was used to obtain the axial strength of FRP-confined concrete. For FRP-confined concrete with hardening behavior, as shown in Fig. 2(a) the axial strength $f_{cc}^{'}$ is given as:

$$f_{cc}^{'} = \left(-4.322 + 4.721\sqrt{1 + 4.193\frac{f_{lu}}{f_{co}^{'}}} - 2\frac{f_{lu}}{f_{co}^{'}} \right) f_{co}^{'}; \quad \frac{f_{lu}}{f_{co}^{'}} \geq 0.2 \tag{1}$$

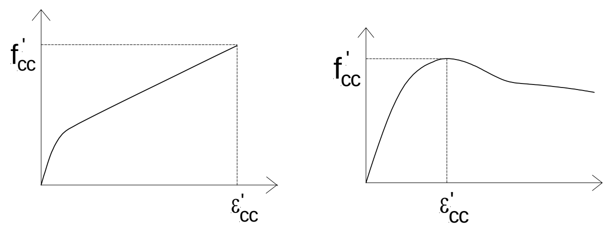
where $f_{lu} / f_{co}^{'}$ is the effective confinement ratio, or the maximum confining pressure provided by the FRP jacket or post-tensioned FRP shell relative to the average unconfined concrete strength $f_{co}^{'}$. The maximum confining pressure, f_{lu} is obtained when the FRP jacket strain ε_j reaches its ultimate strain, ε_{ju} as follows:

$$f_{lu} = \frac{1}{2} k \rho_{FRP} E_j \varepsilon_{fu} \tag{2}$$

where ε_{fu} is the ultimate FRP tensile strain, E_j is the modulus of elasticity of the FRP laminate, ρ_{FRP} is the volumetric ratio of the FRP jacket defined as the ratio of the product of the circumference times the thickness of the jacket t_j to the area enclosed by the jacket; k is the confinement effectiveness coefficient given as:

$$k = k_s k_p k_\varepsilon \tag{3}$$

where k_s is the shape factor which relates the effectively confined concrete area to the total cross-sectional area, k_p is the post-tensioning factor which accounts for the contribution of the post-tensioning effect caused by dilation of the expansive cement concrete, and k_ε is the jacket efficiency factor which accounts for the fact that the ultimate FRP hoop stress at failure was always lower than the tensile strength of the FRP laminate. The jacket efficiency factor is related to the friction between concrete and FRP laminate, as well as the FRP jacket bond type and cross-sectional geometry. In addition, the strain distribution over the circumference of a circular jacket is consistent and uniform, while a large non-uniformity of strain was observed in non-circular jackets. The jacket efficiency factor is defined as the ratio of FRP tensile hoop strain at rupture in the column tests, ε_{ju}, to the ultimate tensile strain from FRP tensile coupon tests, ε_{fu}, or $k_{\varepsilon} = \varepsilon_{ju} / \varepsilon_{fu}$. A detailed description of the confinement effectiveness coefficient and its contributing factors can be found elsewhere (Yan 2005).



(a) (b)

Figure 2 Definition of stress and strain parameters: (a) hardening behavior; (b) softening behavior

The effective confinement ratio is related to the axial strength because it includes shape, jacket efficiency, and post-tensioning effects, which influence confinement stiffness. For $f_{lu} / f_{co}^{'} \geq 0.2$, the experimental data suggests that hardening behavior similar to that shown in Fig. 2(a) is likely. For the range $f_{lu} / f_{co}^{'} < 0.2$, softening behavior is likely to result as shown in Fig. 2(b), and the axial strength $f_{cc}^{'}$ is given as:

$$f_{cc}^{'} = \max\left(\left(\frac{-4.322 + 4.721\sqrt{1 + 4.193\dfrac{f_{lu}}{f_{co}^{'}}} - 2\dfrac{f_{lu}}{f_{co}^{'}}}{0.0768\ln\left(\dfrac{f_{lu}}{f_{co}^{'}}\right) + 1.122}\right) f_{co}^{'},\ f_{co}^{'}\right);\quad \frac{f_{lu}}{f_{co}^{'}} < 0.2 \tag{4}$$

The axial strain $\varepsilon_{cc}^{'}$ in the FRP-confined concrete is given by one of three expressions, depending on the type of confinement (bonded versus post-tensioned FRP jackets) and confinement effectiveness (hardening versus softening behavior). Thus, for concrete confined with externally bonded FRP jackets and hardening behavior (i.e. $f_{lu} / f_{co}^{'} \geq 0.2$), the axial strain $\varepsilon_{cc}^{'}$ is given as:

$$\varepsilon_{cc}^{'} = \frac{f_{cc}^{'}(1 + 2\beta k_{\varepsilon}\varepsilon_{fu})}{E_0};\quad \beta = 190\left(\frac{f_{lu}}{f_{co}^{'}}\right)^{-0.8} \tag{5}$$

where β is a constant associated with the elastic modulus degradation theory (Pantazopoulou and Mills 1995), expressed empirically in Eqn. (5) as a function of the jacket effective confinement ratio; and E_0 = initial elastic modulus of FRP-confined concrete.

For concrete confined with externally bonded FRP jackets and softening behavior (i.e. $f_{lu} / f_{co}^{'} < 0.2$), the axial strain $\varepsilon_{cc}^{'}$ corresponding to $f_{cc}^{'}$ is given as:

$$\varepsilon_{cc}^{'} = \frac{f_{cc}^{'}}{E_0 - \beta f_{cc}^{'}} \tag{6}$$

For circular and elliptical columns with post-tensioned FRP shells, the axial strain $\varepsilon_{cc}^{'}$ corresponding to $f_{cc}^{'}$ is given as:

$$\varepsilon_{cc}' = \frac{2k_{\varepsilon}\varepsilon_{fu}}{1-\gamma};\quad \gamma = 0.26 + 0.428\left(\frac{f_{lu}}{f_{co}'}\right) \tag{7}$$

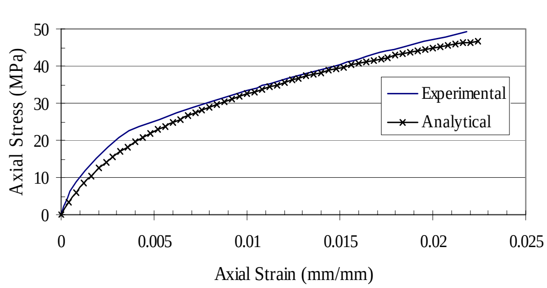
where k_{ε} = jacket efficiency factor, obtained empirically as 0.4 for circular and 0.3 for elliptical post-tensioned specimens; and γ is a constant relating the volumetric strain to axial strain, expressed empirically in Eqn. (7) as a function of the effective confinement ratio.

An incremental approach using Eqs. (1-7) can be applied to obtain the complete stress-strain behavior of FRP-confined concrete which can be implemented using a spreadsheet or computer program. Figure 3 shows selected comparisons between the analytical model and experimental results for square and rectangular R2 specimens. The analytical results agree reasonably well with the experiments. Additional comparisons of analytical, including finite element analyses, to experimental results can be found elsewhere (Yan 2005).

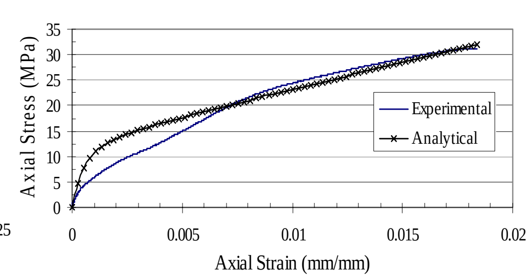
For typical columns, seismic retrofit is achieved by confining only a short length of the bridge column, typically extending over the plastic hinge length at the base and (if applicable) at the top of the column (Pantelides et al. 1999, 2007); it is assumed that the plastic hinge length is 0.5 times the column section depth. The equations provided which use empirical data from the present tests as well as other large-scale tests are believed to be applicable for columns that exist in typical bridges. However, typically a small gap (51 mm) is left between the bottom (top) of the column and the FRP shell and thus the expansive grout should carry only a small axial load after placement. The gap is left at the bottom (top) of the columns to allow independent movement at the joints and to prevent bearing of the FRP jacket on the footing's top surface (cap beam soffit) (Pantelides et al. 1999).

4. OPTIMAL SHAPE MODIFICATION PARAMETRIC STUDY

To investigate the most "effective" shape of rectangular/square concrete columns, a parametric study was performed to find the optimal cross-section for applying shape modification based on several considerations including strength and strain level, cost, and construction. An original concrete column having a height of 914 mm with a cross-section of 152mm x 457mm 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 and aspect ratios, as shown in Fig. 4. In this context, an "oval" shape means a shape that is approximately circular, whereas an "elliptical" shape implies that the cross-section is approximately a rectangle with rounded corners. All shape-modified columns are to be constructed using non-bonded CFRP composite jackets and expansive cement concrete. The compressive strength for unconfined rectangular concrete and expansive cement concrete was assumed as 15 MPa and 10 MPa, respectively, that are typical of the compressive strengths of the materials used in the experimental study.



(a)



(b)

Figure 3 Comparisons between analytical results and experiments:(a) S-C2-E; (b) R2-G6-E

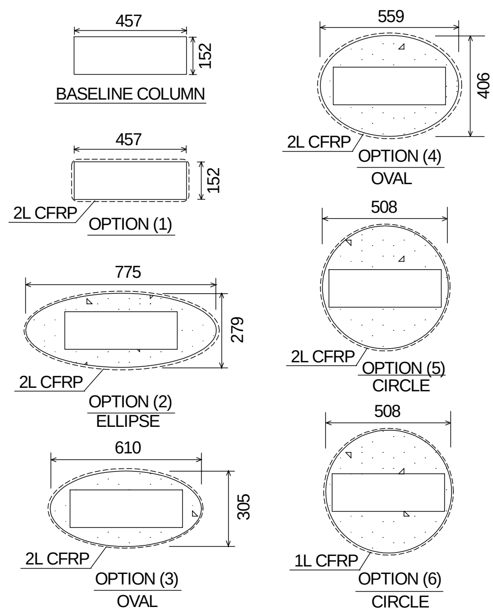


Figure 4 Strengthening Options 1-6

Based on Eqs. (1-7), stress-strain curves for all shape-modified columns are developed in Fig. 5. The stress-strain relationship for a column confined with a bonded CFRP jacket without shape modification (Option 1), shows softening with increased axial strain but little increase in axial strength. All shape-modified columns show an improvement in compressive strength. Options 3 and 4 with the oval shape show better performance than Option 2 with the elliptical section; Option 6 with a single CFRP layer is also superior to Option 2. Option 5, which has a circular section after shape modification, shows the highest increase in axial strength and axial strain, and Option 2 shows the lowest increase. Option 5 requires a large cross-section for shape modification, which would result in increased cost and a larger foundation. Table 3 shows comparisons of the increases in volume, FRP surface area, axial strength, and axial strain, between shape modification options and Option 1. A negative sign implies a decrease. The increase of the column cross-section and FRP jacket area is related to cost and construction feasibility; the effectiveness of shape modification can be evaluated by the level of increase in $f_{cc}^{'}$ and $\varepsilon_{cc}^{'}$. 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.

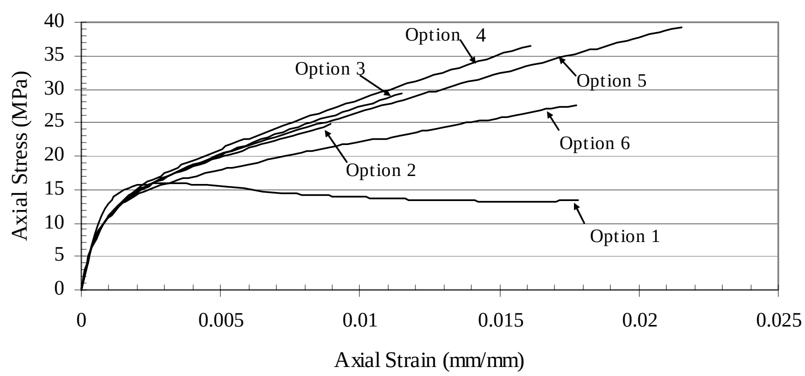


Figure 11 Predicted stress-strain relationships for Options 1-6

Table 4. Comparisons of Options 2-6 with Option 1

Option	Increase of volume	Increase of the total area of FRP jacket	f_{cc}'/f_{co}'	$\varepsilon_{cc}'/\varepsilon_{co}'$
(2)	144%	44%	1.6	3.6
(3)	109%	21%	1.9	4.6
(4)	156%	25%	2.4	6.4
(5)	191%	31%	2.6	8.6
(6)	191%	-33%	1.8	7.1

5. CONCLUSIONS

Shape modification using expansive cement concrete and prefabricated FRP composite shells can achieve significant axial strength and ductility for square and rectangular columns through effective confinement, and is suitable for seismic retrofit. A higher axial strength and ultimate strain was achieved for a shape-modified column with expansive cement concrete and a fewer number of FRP layers was required compared to a rectangular column with bonded FRP jackets. The non-bonded FRP jacket can be used as a stay-in-place formwork, which would save construction time and the additional significant expense of formwork.

The optimal column cross-sectional shape for FRP confinement is circular. For columns with a rectangular cross-section, especially those with a large aspect ratio, change to a circular cross-section requires a higher cost and significant enlargement of the foundation. Therefore, for strengthening rectangular columns by shape modification, the influence of volume increase, increase in surface area, foundation enlargement, and FRP material cost need to be considered to obtain an optimal solution.

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