SMAR 2017 – Fourth Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures

SMAR 2017

Review of Methods for Reinforced Concrete Column Retrofit

Alexander Sichko[1], Halil Sezen[2]

[1,2] The Ohio State University, Columbus, USA

ABSTRACT: When a reinforced concrete (RC) structure is deemed structurally deficient, strengthening or rebuilding are required. Outside of fiber-reinforced polymers (FRP), RC jacketing and external steel elements are two common retrofit methods for columns. Selected studies are reviewed and information surrounding key design considerations identified and presented. The emerging variation of RC jacketing using high-performance concrete (HPC) is highlighted. Additionally, a new slip coefficient is discussed to model the level of composite action between the concrete jacket and original column.

1 INTRODUCTION

Reinforced concrete columns are critical elements in many structures as local member failure may lead to partial or complete collapse of the structure. If a column is structurally deficient due to damage, which may be caused by an earthquake, from design or construction error, or from reinforcement corrosion, retrofit can be a suitable option to bring it back into service. There are many methods available to retrofit the column, each with relative performance and practical strengths and weaknesses. Concrete jacketing and external steel elements are two widely used and studied methods which can work to improve strength, stiffness, displacement ductility, energy dissipation, and failure mode.

FRP retrofit is outside the paper's scope considering the numerous resources available. This paper seeks to advance the available knowledge on RC jacketing and external steel elements by highlighting key design parameters and their influence on the retrofit performance. Additionally, the emerging RC jacketing variation of using HPC or similar materials, is covered in some depth along with presentation of a new modeling parameter to better predict the composite behavior of an RC jacketed section.

2 RETROFIT METHODS FOR COLUMNS

Engineers are likely to encounter columns with lap splices, existing loads and/or corrosion. Combined with retrofit specific considerations, including interface between old and new concrete, steel jacket arrangement, and anchorage, there are a number of parameters which can impact performance. Figure 1 contains generalized illustrations for concrete jacketing and external steel elements.

2.1 Concrete Jacketing

Concrete jacketing is a popular method of retrofit as it follows the same design and construction procedures of RC columns and the jacket can provide protection from both environmental effects and fire. The jacket can increase the axial and flexural strength through increasing confinement and providing additional steel reinforcement. As the majority of retrofit columns are load bearing at the time of retrofit, it is important to note that pre-loading of the original section has been shown to have negligible impact (Julio et al. 2005, Julio and Branco 2008, Vandoros and Dritsos 2006a).

As several studies like Julio et al. (2003) have provided excellent synthesis on important design parameters, eight representative studies were selected to evaluate the emerging area of high-performance concrete jackets and to investigate the current state of research on the interface condition between old and new concrete. A new model to predict composite behavior of various interface conditions is also introduced. Table 1 contains a summary of the critical parameters for the eight selected studies.

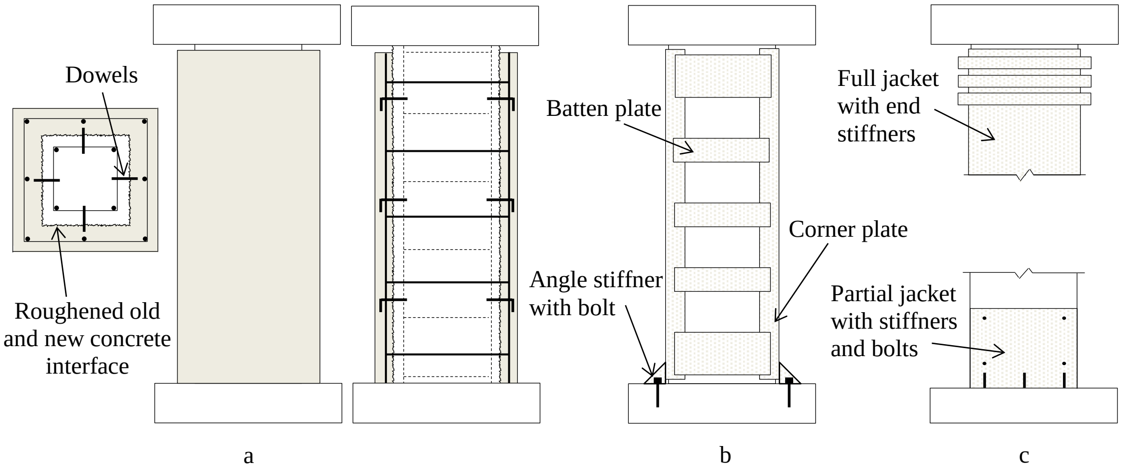


Figure 1. Strengthening scheme examples: a) concrete jacketing, b) steel cage, c) steel jacketing

2.1.1 Synthesis

One of the emerging variations of concrete jacketing is the use of HPC jackets. Both the compressive and tensile strengths of the jacket are increased by adding fibrous materials in the jacket concrete. This generally brings about several benefits relative to normal concrete: reduction in jacket size, reduction or elimination of need for additional reinforcement, and savings in labor without sacrificing composite section performance (Rabehi et al. 2014, Koo and Hong 2016, Meda et al. 2009). As the research is still in early stage, more work is needed to corroborate and further the understanding of many important parameters including initial damage, interface condition, fibrous material properties, percentage of fibrous material added, and original column details.

As the section size enlargement when utilizing concrete jacketing increases dead-load and may be prohibitive from a functional standpoint, the ability to reduce the jacket thickness is desirable. Jackets of 5 cm or less, ranging from 10% - 17% of the original column thickness, were shown to have strength increases of 70% - 133% as the jacket thickness increased, regardless of reinforcement corrosion level (Meda et al. 2015, Koo and Hong 2016). Normal concrete jacket thicknesses are often 30% or more of the original column thickness (Meda et al. 2009), so the reduction represents a significant reduction in materials, dead load, and section size.

One of the advantages of an HPC jacket is the potential to avoid providing additional steel reinforcement due to enhanced tensile properties of jacket. With no additional steel, 71% and 128% strength increases were realized for an increase in cross-sectional area of 44% and 77%, respectively (Koo and Hong 2016). Given the common use of retrofit in seismic regions, displacement ductility requirements may require additional steel. Relative to the original section,

Table 1. Concrete jacketing study summary

<table>
<tr><th>Reference</th><th>Main Parameters</th><th>Retrofit Method</th><th>Main Findings</th><th>Strength</th><th>Displacement Ductility</th><th>Stiffness</th><th>Failure Mode</th></tr>
<tr><td rowspan="2">Bousias et al. (2007)</td><td rowspan="2">Interface preparation</td><td rowspan="2">Full jacket - roughened, dowels, or both applied to interface</td><td rowspan="2">No clear dependency between interface and performance parameters</td><td colspan="3">Relative to monolithic column</td><td rowspan="2">Various</td></tr>
<tr><td>Slight increase</td><td>Similar</td><td>Slight decrease</td></tr>
<tr><td rowspan="2">Ilki et al. (2008)</td><td rowspan="2">Panel thickness, column splice</td><td rowspan="2">Partial jacket - surface roughened, HPC panels epoxy bonded in plastic regions</td><td rowspan="2">Thicker panels superior for continuously reinforced column, thinner panel superior for lap-spliced column; initial damage insignificant</td><td colspan="3">Relative to original column</td><td rowspan="2">Not reported</td></tr>
<tr><td>Increased</td><td>Increased</td><td>Increased</td></tr>
<tr><td rowspan="2">Julio and Branco (2008)</td><td rowspan="2">Interface preparation, preloading</td><td rowspan="2">Full jacket - sandblasting or sandblasting and dowels</td><td rowspan="2">Interface condition and preloading have negligible impact on strength</td><td colspan="3">Relative to monolithic column</td><td rowspan="2">Not reported</td></tr>
<tr><td>Equivalent</td><td>Not reported</td><td>Not reported</td></tr>
<tr><td rowspan="2">Koo and Hong (2016)</td><td rowspan="2">Jacket thickness, stirrups</td><td rowspan="2">Full jacket - surface sandblasted, 13mm fiber, high temp cure</td><td rowspan="2">Jacket thickness improves strength and ductility; stirrups have significant impact on drift</td><td colspan="3">Relative to original column</td><td rowspan="2">Mixed</td></tr>
<tr><td>Increased</td><td>Increased</td><td>Increased</td></tr>
<tr><td rowspan="2">Meda et al. (2015)</td><td rowspan="2">Rebar corrosion</td><td rowspan="2">Full jacket - sandblasting, high performance fiber reinforced concrete (HPFRC) jacket without steel reinforcement</td><td rowspan="2">HPFRC jacket effective in improving performance of column with 20% corrosion</td><td colspan="3">Relative to uncoroded column</td><td rowspan="2">None</td></tr>
<tr><td>Increased</td><td>Not reported</td><td>Increased</td></tr>
<tr><td rowspan="4">Rabehi et al. (2014)</td><td rowspan="4">Concrete type</td><td rowspan="4">Full jacket - loaded to 70% ultimate strength, column cleaned and loose concrete removed, 2.5% steel fiber</td><td rowspan="4">Ultra high performance fiber reinforced concrete jacket superior to ordinary concrete for strength; ordinary concrete better for ductility</td><td colspan="3">Relative to original column</td><td rowspan="4">Rupture</td></tr>
<tr><td>Increased</td><td>Increased</td><td>Increased</td></tr>
<tr><td colspan="3">Relative to normal concrete jacket</td></tr>
<tr><td>Increased</td><td>Decreased</td><td>Increased</td></tr>
<tr><td rowspan="2">Vandoros and Dritsos (2006a)</td><td rowspan="2">Preloading</td><td rowspan="2">Full jacket - column preloaded to a 0.4 normalized axial load ratio, stirrup ends welded shut</td><td rowspan="2">Preloaded increased strength and deformation capacity, and lowered stiffness</td><td colspan="3">Relative to column with no preloading</td><td rowspan="2">Interface bond failure</td></tr>
<tr><td>Increased</td><td>Increased</td><td>Decreased</td></tr>
<tr><td rowspan="2">Vandoros and Dritsos (2006b)</td><td rowspan="2">Interface preparation</td><td rowspan="2">Full jacket - roughened, dowels, or both applied to interface</td><td rowspan="2">Roughened and dowels produced nearly equivalent behavior to monolithic section; others were noticeably worse</td><td colspan="3">Relative to monolithic column</td><td rowspan="2">Bar buckling</td></tr>
<tr><td>Equivalent</td><td>Equivalent</td><td>Similar</td></tr>
</table>

a 50% increase in ductility can be expected without additional steel (Rabehi et al. 2014, Koo and Hong 2016). If stirrup reinforcement is included, for a jacket of sufficient thickness, the strength gains are minimal but the maximum drift ratio is nearly quadrupled and is nine times larger than the original column (Koo and Hong 2016). The need to include additional steel reinforcement will depend on the existing column capacity, required capacity, and the fiber details. The effects of jacket thickness and additional steel can be seen below in Figure 2.

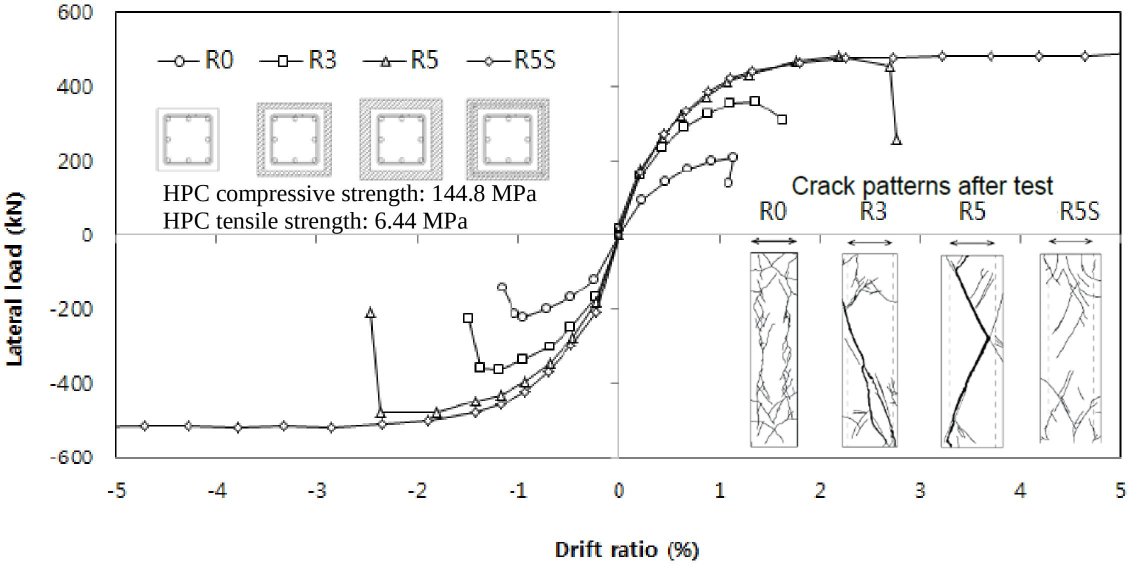
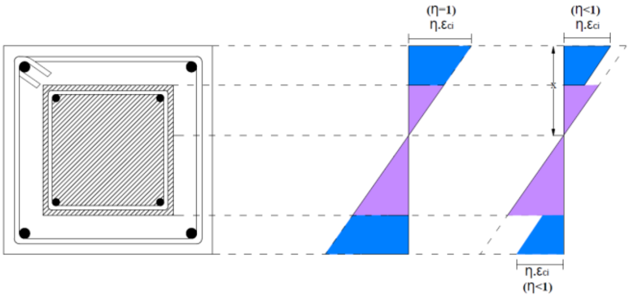


Figure 2. Specimens with no jacket (R0), 15mm (10% of column thickness) HPC jacket (R3), 30mm (16.7% of column thickness) HPC jacket (R5), 30mm HPC jacket and stirrups (R5S) (Koo and Hong 2016)

A variant of the HPC jacketing method is to use pre-cast panels. Ilki et al. (2008) demonstrated that regardless of the initial damage, 15 and 30 mm panels produced equivalent strength gains, but the 30 mm panels were far superior at enhancing ductility and energy dissipation for columns with continuous reinforcement. However, the opposite was found for lap spliced columns with 15 mm panels superior. The strength gains averaged 20% which considering the panels were 10% or less of the section width and only located in plastic regions demonstrates alignment with the other studies with thicker full-height jackets. To ensure composite action, the column surface was roughened and epoxy used to bond the panels to the column.

The degree of composite action between two concrete sections poured at different times has been the subject of much debate and research. It is well established that interface condition and shrinkage are influential in bond strength (Santos and Julio 2014). However, there is a lack of consensus when it comes to both the impact and necessity when applied to column jacketing. Across a variety of test and specimen parameters, nearly monolithic behavior has been observed (Bousias et al. 2007, Julio and Branco 2008, Julio et al. 2005). In direct contrast, Vandoros and Dritsos (2006b, 2006c) found a significant decrease in performance in the absence of special considerations being employed along the interface with only the combination of dowels and surface roughening achieving monolithic behavior.

While the necessity of interface preparation is debated, the fact that roughening and/or dowels produce more monolithic behavior is agreed upon even if the relative performance gain amounts differ across studies. To further the understanding of interface condition impact, in a forthcoming paper the authors present a model developed by Caglar et al. (2017). Using a fiber cross section analysis, a new slip coefficient η, is introduced to represent the overall interface condition between old and new concrete. As the value of the coefficient decreases from 1.0, full composite action, the strain diagram for column will develop a discontinuity and reduce the member performance, as illustrated in Figure 3.



a b

Figure 3. Jacketed column cross section with strain diagrams a) no slip and b) slip

A total of 12 experimental columns of differing interface conditions were compared across various coefficient values to determine which value best matches the observed performance. Figure 4 contains two of the plots generated using OpenSees to do such comparison.

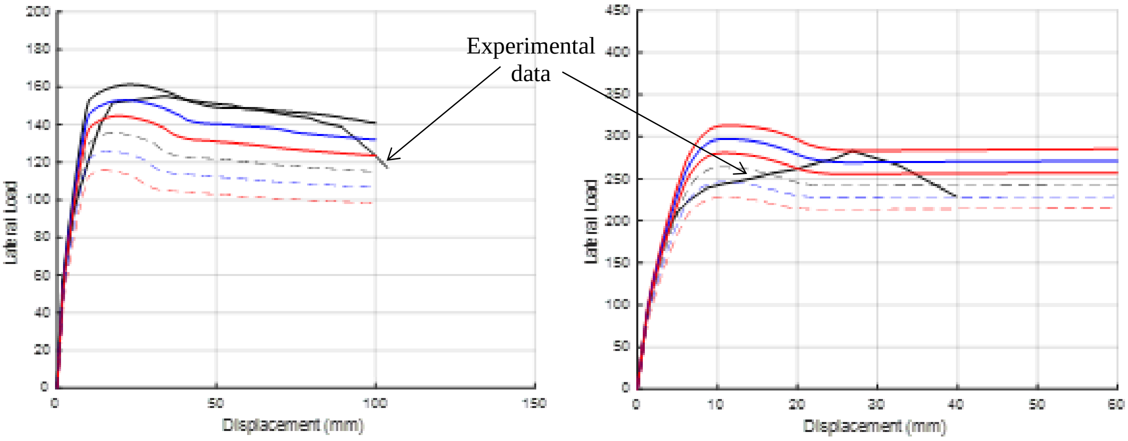


Figure 4. Experimental data for two columns overlaid with various slip coefficient values

Aggregation of all 12 test specimens resulted in the following suggested values for the slip coefficient, contained in Table 2. This coefficient can roughly be translated as the degree of slip relative to an equivalent monolithic section, i.e. slip coefficient for monolithic section is 1.0.

Table 2. Proposed slip coefficients for the boundary between concrete jacket and original column

Specimen	No treatment	Roughness	Dowel	Roughness & Dowel
Suggested Value	0.75	0.80	0.85	0.90

2.2 External Steel Elements

Similar to concrete jacketing, external steel elements work to improve column performance by way of increasing original column confinement and providing additional steel reinforcement that may increase shear strength. However, unlike concrete jacketing, there is no effective increase in section size to directly contribute to axial capacity increase. From a practical standpoint, steel jacketing causes minimal interruption into existing space, is relatively simple and quicker to install, and can be low cost. The eight selected research studies in Table 3 focus on two main parameters governing the design: plate configuration and anchorage.

Table 2. External steel elements study summary

Reference	Main Parameters Studied	Retrofit Method	Main Findings	Strength	Displacement Ductility	Stiffness	Failure Mode
Aboutaha et al. (1996)	Bolt pattern, column width, jacket length, concrete strength	Jacket around base - inadequate lap slices, non-shrink grout filled voids, adhesive anchor bolts	Jacket height should be at least 1.5x lap splice length; bolts at top and bottom are most significant; for smaller columns bolts are not necessary	Relative to original column			Delayed
				Increased	Increased	Increased	
Belal et al. (2014)	Plate configuration, shape, size	Full and discontinuous jacket - plates, channels, and angles welded	Angles and C-shapes require different number of batten plates; brittle failure mode became more ductile	Relative to original column			Delayed
				Increased	Increased	Increased	
He et al. (2016)	Preloading, eccentric load, retrofit thickness	Full jacket - circular steel jacket applied to square column	Existing load had negligible impact; increase of jacket thickness reduces impact of existing eccentric load	Relative to original column			Not reported
				Increased	Not reported	Increased	
Lai and Ho (2015)	Column strength, preloading, jacket spacing	Steel strips - strips tightened with no prestressing	Pre-loading and jacket spacing have minimal impact; higher compressive strength reduced strength gains	Relative to original column			Local buckling
				Increased	Increased	Not reported	
Li et al. (2009)	Rebar corrosion, axial load	Discontinuous jacket - angles and batten plates, CFRP wrap	Corrosion reduces strength and makes ductility increases more pronounced; CFRP wrap over steel jacket best	Relative to original column			Not reported
				Increased	Increased	Not reported	
Lin et al. (2010)	Jacket cross-section shape	Full jacket - normal weight concrete filled void between jacket and column	Octagonal and elliptical steel jacket similarly effective preventing lap-splice failure and improving performance	Relative to original column			Delayed
				Increased	Increased	Increased	
Nagaprasad et al. (2009)	End batten size	Steel cage - battens welded to corner steel angles, bolts secured to footing	Greater strength with taller end batten and enhanced plastic rotational capacity	Relative to original column			Not reported
				Increased	Increased	Increased	
Uy (2001)	Plate shape, height, number, and anchorage	Full height steel plates - bonded to two or four sides, stiffeners on ends	Gluing and bolting effective at increasing strength and stiffness; eliminated buckling in slender columns	Relative to original column			Buckling and crushing
				Increased	Not reported	Increased	
Xiao and Wu (2003)	Stiffener configuration	Full jacket and stiffeners - thin plates welded, stiffeners installed at ends	End stiffeners effective in encouraging plastic hinge development	Relative to original column			None
				Increased	Increased	Increased	

2.2.1 Synthesis

Plate configuration concerns the most efficient use of cross-sectional steel area. In this light, Belal et al. (2014) found the ideal configuration to be dependent on the corner plates (Figure 1b). When using angles, three batten plates as compared to six produced an additional 10% gain in strength, and 45% overall. This is advantageous as it reduces the amount of labor. However, using C-shapes resulted in the opposite finding. The fully jacketed section, using thin-plates, produced the lowest strength increase of 19%; however, full jacketing with suitable thickness can significantly increase strength, ductility, and stiffness (Sezen and Miller 2011). Overall, plate thickness needs to be carefully considered as performance decreases past a certain thickness threshold (He et al. 2016, Sezen and Miller 2011). Similar to Belal et al. (2014), for circular columns, Lai and Ho (2015) found that three steel strips produced strength gains in excess of six strips. Especially in seismic retrofits, ensuring plastic hinging is a top priority. To do so, end stiffeners (Figure 1c) or thicker batten plates, recommended to be at least 1.5 times the width of the intermediate batten plates (Figure 1b), can be used (Xiao and Wu 2003 and Nagaprasad et al. 2009).

A second design consideration is bonding of retrofit to the column. Significant performance gains were found by Belal et al. (2014) and Nagaprasad et al. (2009) without grouting for steel caging. If plates are used, as in Figure 1c, bolts and/or adhesive may be needed. Square columns with tested by Uy (2001) produced a 32% increase in strength with bolts and adhesive compared to 16% with bolts only. A rectangular section experienced premature buckling of the bolted and glued section leading to an 11% increase in strength versus 20% for bolted. The author speculates steel plate imperfections may have caused this, indicating plate quality should be ensured before bonding. Bolts and adhesive together may not always produce such performance gains, especially on thinner columns (Aboutaha et al. 1996). Additionally, placing bolts between the top and bottom rows produced minor performance gains further simplifying the retrofit (Aboutaha et al. 1996).

Columns in use are likely to have lap splices, existing axial loads, and/or reinforcement corrosion. Increasing the jacket height from 1.3 to 1.5 times the lap splice length significantly improved the ductility while maintaining the 50% increase in strength (Aboutaha et al. 1996). Expanding to a full jacket produced a greater than 60% increase in strength with improved ductility (Lin et al. 2010). Concerning existing axial loads, a less than 5% reduction in strength was found when the columns were retrofitted while bearing 50% of their nominal strength (Lai and Ho 2015 and He et al. 2016). As for corrosion, utilizing a steel cage resulted in an inverse relationship with strength and ductility (Li et al. 2009). At approximately 10% corrosion loss, strength increased 67% and ductility increased 35% whereas at approximately 18% corrosion loss, strength increased 60% but ductility increased 85%. This is likely the result of reduced confinement from internal reinforcement resulting in reduced strength, but there was sufficient retrofit steel to further increase the ductility before failure. Subject to remaining within the outlined loading and corrosion parameters, it is reasonable to design retrofits assuming no loading and no corrosion.

3 CONCLUSIONS

In addition to both concrete jacketing and external steel elements proving to be suitable retrofit methods based on performance increases, there are a few other key conclusions. 1) HPC can be used to reduce jacket size and reduce or eliminate the need for additional steel reinforcement, 2) while full composite action may not be achieved subject to the interface condition between old and new concrete, depending on the application it may not be necessary and the discussed model can help to predict composite retrofit performance, 3) steel cage method with stiffeners or wider end battens without need for grout can be an effective method for seismic retrofit, and 4) existing loading on the original column was not found to significantly impact retrofit performance.

4 REFERENCES

Aboutaha, R.S., Engelhardt M.D., Jirsa J.O., and Kreger M.E. 1996. "Retrofit of concrete columns with inadequate lap splices by the use of rectangular steel jackets". *Earthquake Spectra.* 12 (4): 693-714.

Belal, M.F., Mohamed H.M., and Morad S.A. 2014. "Behavior of reinforced concrete columns strengthened by steel jacket". *HBRC Journal.* 11 (2): 201-212.

Bousias, S.N., Biskinis D., Fardis M.N., and Spathis A.L. 2007. "Strength, stiffness, and cyclic deformation capacity of concrete jacketed members". *ACI Structural Journal.* 104 (5): 521.

Caglar, N., Sezen H., Sichko A., Bicici E. 2017. Manuscript to be submitted for publication to ACI Structural Journal.

He, A., Cai J., Chen Q.J., Liu X., and Xu J. 2016. "Behaviour of steel-jacket retrofitted RC columns with preload effects". *Thin-Walled Structures.* 109: 25-39.

Ilki A., Demir C., Bedirhanoglu I., and Kumbasar N. 2008. "Seismic retrofit of brittle and low strength RC columns using fiber reinforced polymer and cementitious composites". *Advances in Structural Engineering.* 12 (3): 325-347.

Julio, E.N.B.S., Branco F., and Silva V.D. 2003. "Structural rehabilitation of columns with reinforced concrete jacketing". *Progress in Structural Engineering and Materials.* 5 (1): 29-37.

Julio, E.N.B.S., Branco F., and Silva V.D. 2005. "Reinforced concrete jacketing-interface influence on monotonic loading response". *ACI Structural Journal.* 102 (2): 252-257.

Julio, E.N.B.S., and Branco F. 2008. "Reinforced Concrete Jacketing -- Interface Influence on Cyclic Loading Response". *ACI Structural Journal.* 105 (4): 471.

Koo, I.Y., and Hong S.G. 2016. “Strengthening RC columns with ultra high performance concrete”. The 2016 Structures Congress. Jeju Island, Korea, August 28 – September 1, 2016

Lai, M.H., and Ho J.C.M. 2015. "Axial strengthening of thin-walled concrete-filled-steel-tube columns by circular steel jackets". *Thin-Walled Structures.* 97: 11-21.

Li, J., Gong J., and Wang L. 2009. "Seismic behavior of corrosion-damaged reinforced concrete columns strengthened using combined carbon fiber-reinforced polymer and steel jacket". *Construction and Building Materials.* 23 (7): 2653-2663.

Lin, M.L., Chen P.C., Tsai K.C., Yu Y.J., and Liu J.G. 2010. "Seismic steel jacketing of rectangular RC bridge columns for the mitigation of lap-splice failures". *Earthquake Engineering & Structural Dynamics.* 39 (15): 1687-1710.

Meda, A., Plizzari G.A., Rinaldi A., and Martinola G. 2009. "Strengthening of R/C existing columns with high performance fiber reinforced concrete jacket". 443-444.

Meda, A., Mostosi S., Rinaldi Z., and Riva P. 2015. "Corroded RC columns repair and strengthening with high performance fiber reinforced concrete jacket". *Materials and Structures.* 49 (5): 1967-1978.

Nagaprasad, P., Sahoo D.R., and Rai D.C. 2009. "Seismic strengthening of RC columns using external steel cage". *Earthquake Engineering & Structural Dynamics.* 38 (14): 1563-1586.

Rabehi, B., Ghernouti Y., Li A., and Boumchedda K. 2014. "Comparative behavior under compression of concrete columns repaired by fiber reinforced polymer (FRP) jacketing and ultra high-performance fiber reinforced concrete (UHPFRC)". *Journal of Adhesion Science and Technology.* 28 (22-23): 2327-2346.

Santos, P.M.D., and Julio E.N.B.S. 2014. "Interface shear transfer on composite concrete members". *ACI Structural Journal.* 111 (1): 113-121.

Sezen, H., and Miller E. 2011. "Experimental evluation of axial behavior of strengthened circular reinforced-concrete columns". *ASCE Journal of Bridge Engineering*. 16 (2): 238-247.

Uy, B. 2001. "Strength of reinforced concrete columns bonded with external steel plates". *Magazine of Concrete Research.* 54 (1): 61-76.

Vandoros, K.G., and Dritsos S.E. 2006a. "Axial preloading effects when reinforced concrete columns are strengthened by concrete jackets". *Progress in Structural Engineering and Materials.* 8 (3): 79-92.

Vandoros, K.G., and Dritsos S.E. 2006b. "Interface treatment in shotcrete jacketing of reinforced concrete columns to improve seismic performance". *Structural Engineering and Mechanics.* 23 (1): 43-61.

Vandoros, K.G., and Dritsos S.E. 2006c. "Concrete jacket construction detail effectiveness when strengthening RC columns". *Construction and Building Materials.* 22 (3): 264-276.

Xiao, Y., and Wu H. 2003. "Retrofit of reinforced concrete columns using partially stiffened steel jackets". *Journal of Structural Engineering.* 129 (6).