Retrofit of Reinforced Concrete Columns

HONORS THESIS

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ABSTRACT

Many reinforced concrete structures are deficient in stiffness, ductility, and strength capacity compared to current standards. When a powerful event, such as an earthquake, occurs, un-strengthened and inadequate concrete members may fail and produce catastrophic results. In order to counteract this problem, many different retrofit and repair methods have been studied, implemented and have produced a variety of results. This research is focused on comparing dozens of retrofit and repair methods for reinforced concrete columns in order to analyze the efficacy of these methods. The primary methods compared are reinforced concrete jacketing and a variety of steel confinement methods. The steel confinement methods include steel jackets, steel cages, precambered steel plates, and pre-stressed steel sections. A variety of constraints are compared across the methods including the loading, interface mechanisms, connection methods, size and orientation of the jacket. Each retrofit method functions differently under each constraint, and the benefits and downsides of each were discussed and compared.

ACKNOWLEDGEMENTS

I would like to thank Professor Halil Sezen for helping me through this process. His advice and guidance through my research as well as career decisions has been useful, and has been greatly appreciated. I would also like to thank Professor Michael Hagenberger for serving on my defense panel and providing support and guidance in classes and for my future career. I would also like to thank Alexander Sichko for his continued work on the project. Thank you also to the College of Engineering at the Ohio State University for their funding, enabling further support to work on this project. Finally, I would like to thank all my friends and family for their support throughout the process of completing my thesis and defense.

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CHAPTER 1: INTRODUCTION

1.1 Overview

With the number of structurally deficient structures and structures vulnerable to high impact events such as natural disasters or blasts, understanding how to retrofit existing structures is important. While the relevancy of structural retrofit has increased more recently, research into the retrofit of reinforced concrete structures has been performed for years. However, with the amount of information available, little work has been done comparing the efficacy of different methods or under different scenarios, since many studies are focused on structure-specific retrofit.

Given the structural retrofit needs of columns, relative to other structural elements such as beams, walls or slabs, retrofit of columns is of particular importance. Additionally, retrofitting structures that may be vulnerable can improve their resiliency and potentially increase the lifespan of both the column and the structure.

1.2 Scope

This research was focused on understanding and comparing the efficacy of reinforced concrete jacketing and steel retrofit methods. The steel retrofit methods encompass steel jacketing, steel caging, precambered steel plating, and external prestressing. Reinforced concrete jacketing, steel jacketing, steel caging, precambered steel plating, and external pre-stressing are discussed in Chapters 2, 3.1, 3.2, 4, and 5, respectively. Other and newer retrofit methods are briefly discussed in Chapter 6, however, they are not the focus of this research. Additionally, the structural performance is a primary consideration of this research; however, the practicality of the methods are considered.

1.3 Objectives

With this research being focused on understanding and comparing different methods and different constraints within each method, there are two main foci. Within each given method, studies compare performance under a variety of different scenarios and constraints. As such, it is important to generalize performance for each method to understand how the method functions, in order to applied broadly. In order to understand the unique performance characteristics for each method, the methods are compared.

1.4 Methods

While completing the objectives, a process was involved to compare the methods. First, the articles to be studied were identified. Then one-page documents, presented in the appendices, were created to summarize the significance, parameters, results, and effectiveness of the method(s) within each article. Using that information, parameters were determined based on each paper to understand effects across a variety of studies and constraints. Using these tables, articles concerned with each parameter were compared to understand how the retrofit method functions under those conditions. General findings were then summarized to present overall conclusions. Finally, these findings were compiled within each method and compared across different methods to understand how the methods relate to each other.

CHAPTER 2: REINFORCED CONCRETE JACKETING RETROFIT METHOD

Reinforced concrete jacketing is a traditional and one of the most common methods to retrofit and/or repair reinforced concrete columns. The additional cross-section area helps the column transfer more load while providing additional confinement. Reinforced concrete jackets can have multiple interface mechanisms to facilitate the transfer of loads from the original column to the jacket, or be designed with none. Testing a variety of loading cases, including preloading, unloading, temporarily shoring, and/or testing different directions of loading can

Table 2.1: Reinforced concrete jacket studies and topics evaluated

Study	Interface	Loading	Cross-Section	Reinforcement		
				Type	Stirrup Spacing	Long. Reinf
Achillopoulou et al. (2013a)	X	X				
Achillopoulou et al. (2013b)	X	X				
Achillopoulou et al. (2014)	X	X			X	
Bett et al. (1988)						
Bousias et al. (2004)				X		
Bousias et al. (2007a)	X					
Bousias et al. (2007b)		X				
Chang et al. (2014)	X		X			
da Porto et al. (2012)						
Ersoy et al. (1993)		X				
Julio et al. (2003)	X				X	
Julio et al. (2008)	X					
Kaliyaperumal et al. (2009)						
Lampropoulos et al. (2008)	X		X			
Mourad et al. (2012)		X				
Pellegrino et al. (2009)	X		X			
Rodriguez et al. (1994)		X				X
Sengtottian et al. (2013)		X				X
Sezen et al. (2011)		X		X		
Takeuti et al. (2008)		X	X	X		
Takiguchi et al. (2001)				X		
Vandoros et al. (2006a)	X					
Vandoros et al. (2006b)		X				
Vandoros et al. (2008)	X					

show how the jackets perform under different scenarios. The size, shape, and aspect ratio of the cross-section is useful in determining what size jacket to provide. Additionally, analysis of different reinforcement types, spacing, and provisions can further determine design details.

2.1 Effect of Interface between Jacket and Original Column

Researchers have analyzed several different mechanisms for facilitating load transfer from columns to reinforced concrete jackets. Such methods include welded U-bars, dowels, roughened surface, or even no treatment. Comparing these can demonstrate how efficient the interface mechanisms are, which option or options may be best, and whether providing any is necessary.

Bousias et al. (2007a) tested six columns with shotcrete jackets and different connection means to the original column under lateral loading. The retrofit was simple, similar to the one shown in Figure 2.1. The options were welded U-bars, dowels, roughened surface, roughened surface and dowels, no treatment, and a monolithic column. The benefits of dowels and surface roughening were cancelled out when both were applied to a column together.

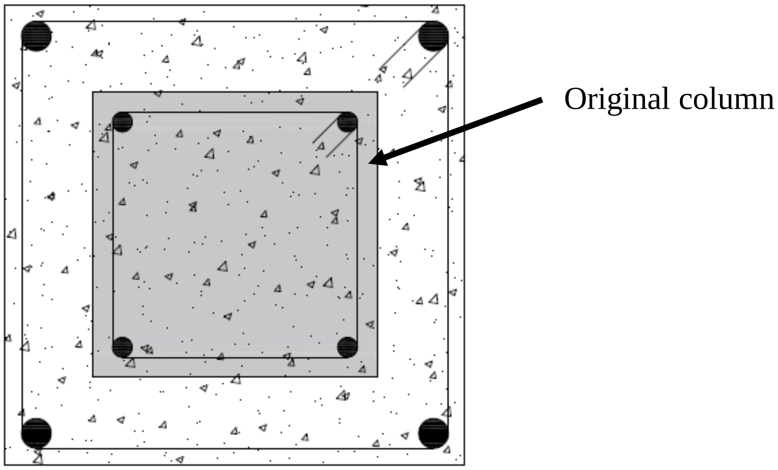


Figure 2.1: Standard cross-section of reinforced concrete jacket

Achillopoulou et al. (2013b) examined how bending welded steel bars in reinforced concrete jackets affects the force transfer mechanisms in columns previously damaged and subsequently repaired under axial loading. Jackets were tested with different concrete strengths, transverse reinforcement ratios, confinement ratios, presence of resin or polymer sheets to minimize friction, and two axial load patterns to simulate realistic loading. The column had the basic cross-section shown in Figure 2.1, with some specimens provided with dowels, as shown in Figure 2.2. This experiment found that dowels impact the maximum load minimally, but increases slip resistance. However, earlier failure may occur from damaged areas spreading from dowels.

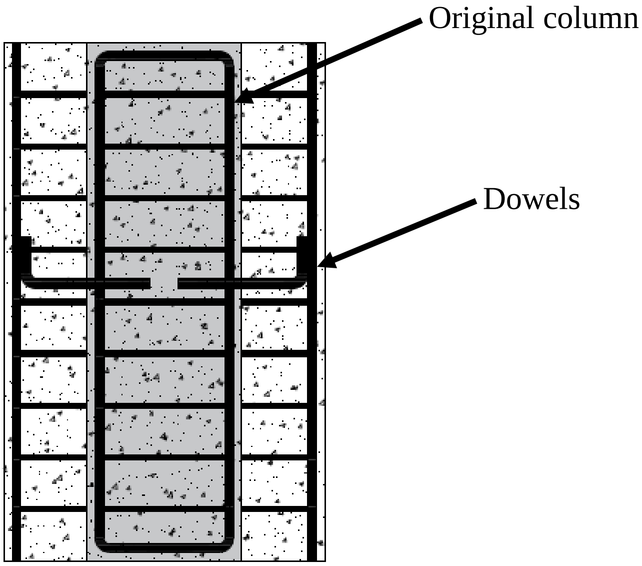


Figure 2.2: Profile of dowels anchored to original column and reinforced concrete jacket

Similar to Achillopoulou et al. (2013b), Achillopoulou et al. (2013a) tested six axially loaded square reinforced concrete columns with different transverse reinforcement ratios and confinement ratios that were previously damaged and repaired. Some of the columns had the basic retrofit cross-section shown in Figure 2.1, some had welded bars as shown in Figures 2.3 and 2.4, and others had dowel bars like those shown in Figures 2.2 and 2.6. It was found that larger diameter welded bars buckle earlier and carry less load, but they all still transferred loads to the new concrete due to confinement effects. Buckling from larger welds to smaller reinforcement bars resulted in smaller maximum loads and less stiffness. Nevertheless, the dowels increased the load transfer capacity of the columns.

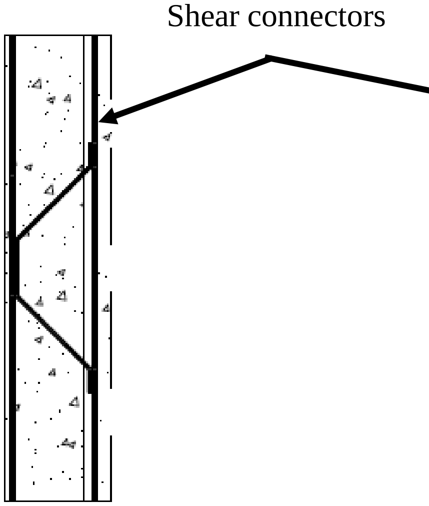


Figure 2.3: Profile of shear connectors between original column and jacket reinforcement

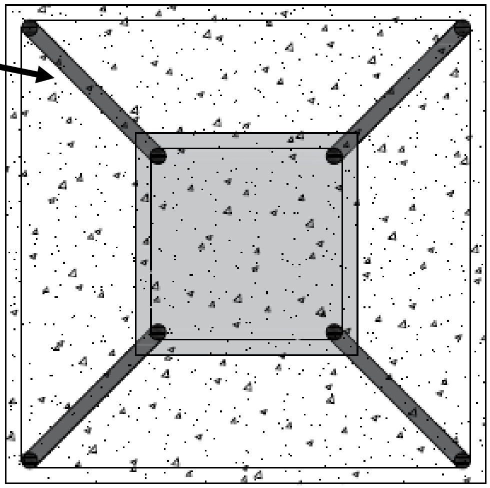


Figure 2.4: Cross-section of shear connectors between original column and jacket reinforcement

Due to the presence of construction deficiencies in as-built columns, Achillopoulou et al. (2014) examined how such occurrences and different anchors affect the column's ability to transfer loads to a reinforced concrete jacket under axial loading. Some of the columns had the basic retrofit cross-section shown in Figure 2.1, some had welded bars as shown in Figures 2.3 and 2.4, and others had dowel bars like those shown in Figures 2.2 and 2.6. A total of 16 ½-scale columns were tested with varying initial construction damage, stirrups spacing, kind of interface reinforcement, and load patterns. Once the columns surpassed a certain level of damage, repaired columns could not attain a certain strain capacity. Welded bars caused buckling of longitudinal bars and lost secant stiffness, but increased the initial column stiffness. Dowels effectively increased the maximum load on the damaged columns, however, a plastic region was created around the connection bar—causing failure and high displacement.

Chang et al. (2014) tested using reinforced concrete jackets or wing walls in order to strengthen columns under lateral loading. The columns with the reinforced concrete jackets had cross-sections similar to the one shown in Figure 2.1, with dowels like in Figures 2.2 and 2.6. One of the jacketed columns used transverse adhesive anchors, while one of the wing-walled columns had two rows of transverse adhesive anchors and the other had one row. Under lateral cyclic loading, standard hooks were proven to perform better than post-installed anchors due to the number of variables in post-installment. Since the concrete cover ruptured in the footing of one of the jacketed columns, the effectiveness of transverse adhesive anchors could not be verified.

Julio et al. (2008) evaluated the use of different interface treatments on reinforced concrete jacketed columns under lateral loading. The seven column-footings had the following details: non-adherent jacket, monolithic jacket, jacket without surface preparation, jacket with sand blasting, jacket with sand blasting and steel connectors, jacket after sand blasting and axial force, and a non-strengthened column. As such, most of the columns had similar cross-sections to Figure 2.1. The three columns with surface preparation obtained similar results to the jacketed column without any interface treatment. As a result, it was found that columns with bending moment/shear force ratio's greater than 1.0 and jacket thickness less than 17.5% column width do not need surface treatment to achieve monolithic behavior. Additionally, strength degradation was not apparent in the experiment.

In the literature review performed in Julio et al. (2003), a variety of results relating to interface surface treatment have been compiled. Sand-blasting is the most efficient at roughening the surface, since pneumatic hammering causes micro-cracking of the substrate. The moisture level of the substrate may be critical in ensuring a good bond; excessive humidity can close pores and prevent absorption of the repair material. Epoxy resin as a bonding agent on sand-blasted surfaces decreases the shear and tensile strength of the interface. Steel connectors crossing the interface had no significant effect on the debonding force, but increased the longitudinal shear strength. Therefore, improving interface surface roughness or the usage of bonding agents is not necessary.

While evaluating using a partial reinforced concrete jacket with the jacket on just the compressive side of a column, Lampropoulos et al. (2008) tested the use of shear connectors between the old and new reinforcement under lateral loading. The jacketed columns looked like Figure 2.1, while the ones with a concrete layer resembled Figure 2.5. Figure 2.3 shows what the columns with shear connectors look like. The preloading effect decreases the monolithic coefficients for strength if shear connectors are present. Layered columns without shear connectors may have significantly lower strength than a comparable monolithic column.

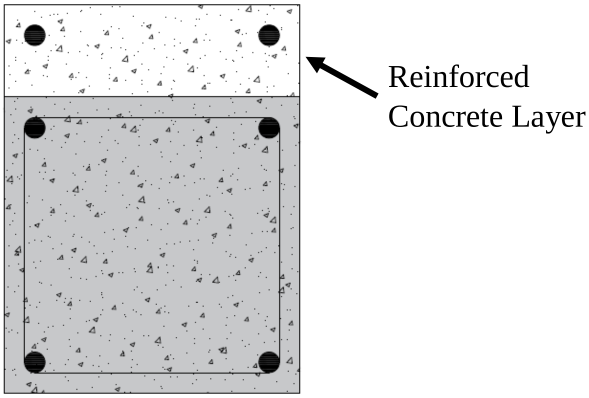


Figure 2.5: Profile of column with a reinforced concrete layer without shear connectors

Vandoros et al. (2006a) tested a variety of interface treatments to retrofit ½ height, full scale laterally loaded columns according to old Greek Codes with shotcrete jackets. The connection techniques were roughening the surface, embedding steel dowels, and a combination of both. These three strengthened columns, one unstrengthened column, and one as-built monolithic specimen were tested with constant axial load and a horizontal cyclic load at the top of the unjacketed part of the column. The columns followed the basic jacketing arrangement in Figure 2.1, while the dowels looked like those in Figure 2.6. Interface treatment options proved to influence failure mechanisms and crack patterns. Roughening the surface and providing dowels performed best, but all strengthened columns dissipated energy better. While strengths and stiffnesses of the strengthened specimens were slightly lower than for the monolithic specimen, drift ratios and energy dissipation rates were higher during all loading stages—due to the additional friction from surface preparation. Due to the similar performance during all loading stages, monolithic behavior can be assumed if both dowels and surface roughening are provided.

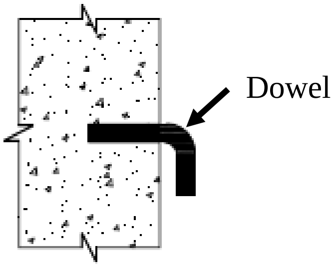


Figure 2.6: Detail view of dowels before jacket installation

Vandoros et al. (2008) evaluated a couple more options for interface treatment of reinforced concrete jacketed ½ height full-size concrete columns representing 1950s Greek ground floor columns tested with lateral loading. The methods evaluated were welded jacket stirrup ends, dowels and jacket stirrup end welding, and bent down steel connector bars welded to the original longitudinal and jacket bars. Figure 2.3 shows what the bend down steel connectors look like, while most of the columns followed the basic cross-section in Figure 2.1. Consistent with other experiment results, columns with no treatment showed significant strength and stiffness increases. Further, it was found that the column with no treatment had similar capacity to the treated columns; however, significant capacity differences became apparent in the maximum loading stage. Welded jacket stirrup ends prevented longitudinal bars from buckling in the jacket. The column with dowels and welded stirrup ends performed closest to the monolithic column, but also had higher concrete strength used. Welding stirrup ends together can improved the strength of poured concrete jackets instead of using shotcrete jackets.

When Pellegrino et al. (2009) evaluated how different layer thicknesses of a partial polymer-modified cementitious mortar jacket rehabilitate columns under axial loading. The columns with the repair layers are shown in Figures 2.7 and 2.8. The layers (15 mm and 50 mm) for each of the columns tested debonded before failure, demonstrating the importance of a durable interface mechanism. Previously, the surface had been roughened, cleaned, and wetted to improve bonding. Debonding resulted in premature failure of the thinner layer at about 67% of the ultimate load.

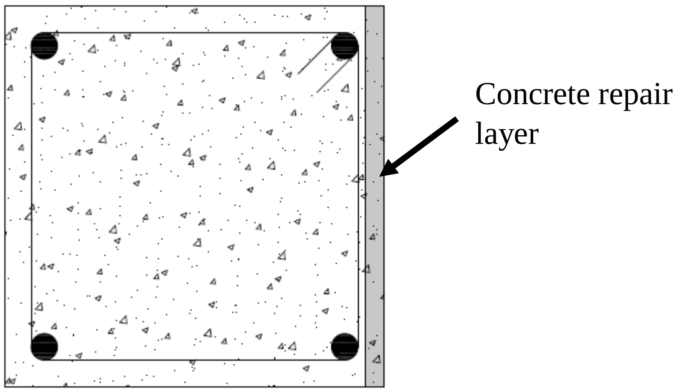


Figure 2.7: Cross-section of small repair layer to damaged column

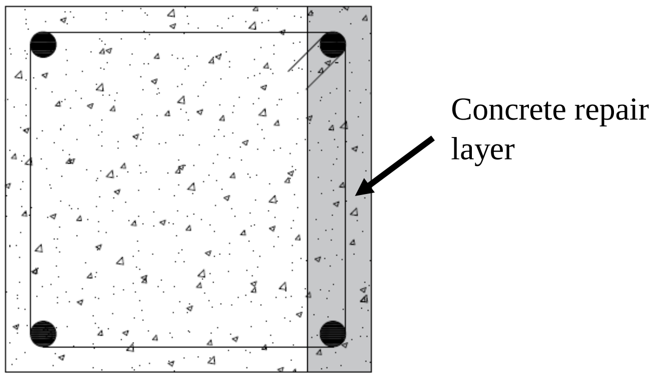


Figure 2.8: Cross-section of large repair layer encompassing reinforcement to damaged column

Table 2.2: Summary of effects of interface

Achillopoulou et al. (2013a)	Larger diameter welded bars buckle earlier and carry less load, but they transferred loads to the new concrete due to confinement effects. Buckling from larger welds to smaller reinforcement bars resulted in smaller maximum loads and less stiffness. Dowels increased the load transfer capacity of the columns.
Achillopoulou et al. (2013b)	Dowels impact the maximum load minimally, but increases slip resistance. Earlier failure may occur from damaged areas spreading from dowels.
Achillopoulou et al. (2014)	Welded bars caused buckling of longitudinal bars and lost secant stiffness, but increased the initial column stiffness. Dowels effectively increased the

	maximum load on the damaged columns, however, a plastic region was created around the connection bar—causing failure and high displacement.
Bousias et al. (2007a)	The benefits of dowels and surface roughening were cancelled out when both were applied to a column together.
Chang et al. (2014)	Standard hooks were proven to perform better than post-installed anchors due to the number of variables in post-installment.
Julio et al. (2003)	Sand-blasting is the most efficient at roughening the surface, since pneumatic hammering causes micro-cracking of the substrate. Moisture level of the substrate may be critical in ensuring a good bond; excessive humidity can close pores and prevent absorption of the repair material. Epoxy resin as a bonding agent on sand-blasted surfaces decreases the shear and tensile strength of the interface. Steel connectors crossing the interface had no significant effect on the debonding force, but increased the longitudinal shear strength. Therefore, improving interface surface roughness or the usage of bonding agents is not necessary.
Julio et al. (2008)	Columns do not need surface treatment to achieve monolithic behavior.
Lampropoulos et al. (2008)	Layered columns without shear connectors may have significantly lower strength than a comparable monolithic column.
Pellegrino et al. (2009)	A durable interface mechanism is important for columns with RC layers. Surface had been roughened, cleaned, and wetted to improve bonding. Debonding resulted in premature failure of the thinner jacket.
Vandoros et al. (2006a)	Roughening the surface and providing dowels performs best. Similar performance during all loading stages, monolithic behavior can be assumed if both dowels and surface roughening are provided.
Vandoros et al. (2008)	Columns with no treatment showed significant strength and stiffness increases with similar capacity to the treated columns; however, significant capacity differences became apparent in the maximum loading stage. Welded jacket stirrup ends prevented longitudinal bars from buckling in the jacket. The column with dowels and welded stirrup ends performed closest

	to the monolithic column. Welding stirrup ends together can improve the strength of poured concrete jackets instead of using shotcrete jackets.

There are conflicting accounts, but most studies find that interface preparation is important in improving column capacity. Dowels or shear connectors generally perform best, and can essentially achieve monolithic behavior; however, site specific constraints must be analyzed, such as the appropriate size of the bar and the potential for a plastic hinge.

2.2 Effect of Loading

Comparing preloading, unloading, loading, and shoring options amongst different reinforced concrete jacketed columns can further illuminate how to best construct columns or improve jacket performance. Preloading and unloading consider the influence of constructing the jackets while under loading. Further, some columns had shoring provided as the jacket was constructed to try to increase the amount of load transferred to the jacket. Some columns were tested under different loading conditions, such as with the load applied across different cross-sections, or only the original column or jacket.

Achillopoulou et al. (2013b) evaluated how differing axial load patterns may affect the structural capacity of the reinforced concrete jacket around a column. In the two load patterns tested, the column was the only part loaded on the top. At the bottom of the column, only the jacket transferred load in pattern A, while the whole cross-section was designed to transfer load in pattern B. The column had the basic cross-section shown in Figure 2.1, and the loading conditions are shown in Figure 2.9. Despite only the jacket absorbing the load at the bottom of the column in pattern A, load transferred similarly under both scenarios.

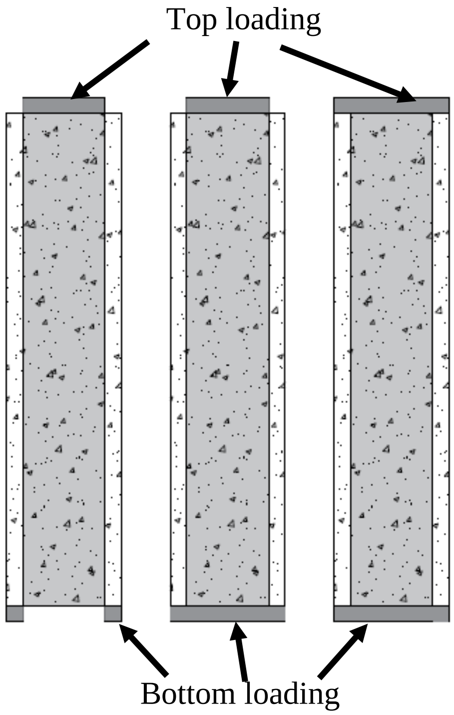


Figure 2.9: Loading conditions A, B, and D.

Having overloaded and then retrofitted columns, Achillopoulou et al. (2013a) found that the axial loading capacity of the column had decreased. The column had the basic cross-section shown in Figure 2.1, and the loading conditions are shown in Figure 2.9.

Similar to Achillopoulou et al. (2013b), Achillopoulou et al. (2014) tested the effects of different axial load patterns. Load pattern B loaded just the original column on the top, while D loaded the full cross-section. For both patterns, the support area on the bottom covered the whole cross-section. The columns had the basic cross-section shown in Figure 2.1, and the loading conditions are shown in Figure 2.9. Loading the whole cross-section directly at the top, as in pattern D, enables the capacity to initiate quickly, resulting in higher maximum load values as well as higher load values across the axial strain spectrum. Meanwhile, the confinement effects are not activated until load is distributed across the jacket, as demonstrated in pattern B.

Rodriguez et al. (1994) evaluated a variety of factors on the structural capacity of columns, including axially preloading and laterally testing columns. Two of the four columns were loaded to a damage level and repaired before being strengthened by reinforced concrete jackets. Some of the columns followed the basic jacketing section shown in Figure 2.1, while others had more reinforcement provided, as shown in Figures 2.10. Following testing, Rodriguez et al. found that the previous damage did not have a major effect on the jacket's seismic performance.

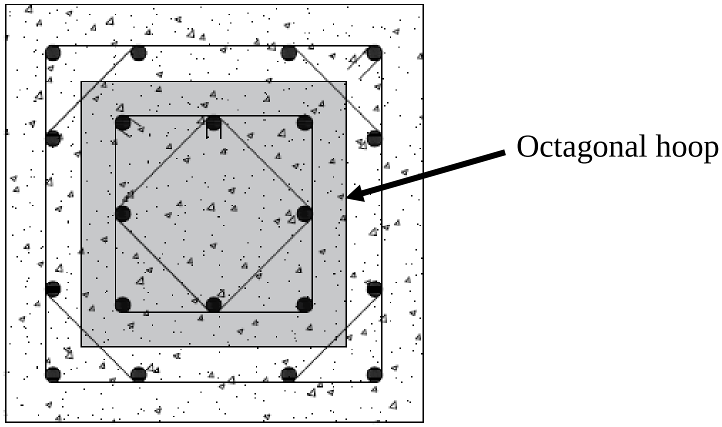


Figure 2.10: Reinforced concrete jacket with octagonal hoops.

Ersoy et al. (1993) experimented on the effects that load history, preloading level, and whether the columns was unloaded before jacketing on two series of five columns each. Series 1 was concerned with uniaxially loaded columns, while series two considered combined axial load and bending scenarios. The tested columns had a cross-section similar to the basic retrofit section in Figure 2.1. While unloading the column is preferable, creating the strengthening jacket while the column was loaded functioned similarly to the columns that were unloaded under uniaxial loading. However, if the column is damaged to a level requiring repair, unloading may have a more significant effect on the capacity of the column under uniaxial loading. Both the strengthening and repair jackets for series two reached or neared the capacity of the reference column. The repaired columns under combined loading attained less rigidity than the monolithic columns, while strengthened columns reached similar levels to the monolithic columns. Strength was not influenced significantly by monotonic or cyclic loading history, but rigidity was—cyclically loaded column had 40% less rigidity than the monotonically loaded column.

Sengottian et al. (2013) tested loading six circular columns to different axial load levels before retrofitting them. These levels were determined by testing them to a percentage of ultimate load. The column and the jacket are shown in Figure 2.11. It was found that loading to a higher level results in a more ductile response in the jacket after retrofitting.

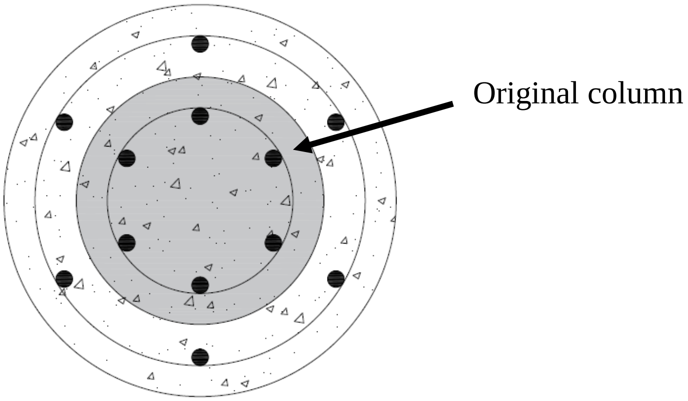


Figure 2.11: Reinforced concrete jacket retrofit of circular columns with circular jackets

Takeuti et al. (2008) evaluated a series of square and circular reinforced concrete columns. Half of the columns in each series of six were preloaded. Figures 2.1 and 2.11 resemble what typical cross-sections in the square jacketed, circular original, and circular jacketed columns, respectively, in this study. Following jacketing and axial testing, the preloaded and non-preloaded columns behaved similarly before reaching the predicted capacity of the primary column. Circular columns emphasized this effect due to better confinement in circular columns. However, it was found that strains in the steel reinforcement are different between the jacket and the column core. This is likely dependent on how much the columns are preloaded. Consistent with the results from Sengottian et al. (2013), it was found that preloading often resulted in higher ductility in the columns than for those not preloaded. Further, the difference in ductility was more apparent in the square cross-sections, likely due to the lower efficiency of square ties in confinement. Higher damage levels and lower efficiency of the square confinement ties may be causes of this. Additionally, it was found that capacity of jacketed preloaded columns did not suffer as a result of preloading. Columns that were not preloaded demonstrated similar stresses to the primary column. This effect is persistent throughout loading for circular columns, but only continues until peak load for square columns—likely due to confinement pressures. On the other hand, differences in strain between the jacket and the column core were apparent in preloaded columns. This is logical, since the preloading was only applied to the primary column.

Vandoros et al. (2006b) tested columns under lateral loading comparing the effect that preloading has on columns by testing four columns: one jacketed with preloading, one jacketed without preloading, a monolithic specimen, and an original column. These columns followed the typical jacketed column specimen shown in Figure 2.1. The preloaded column had higher strengths, displacements, and retained stiffness during the entire loading cycle than the column not preloaded. Lower jacket stresses helped the preloaded column dissipate energy during testing.

Mourad et al. (2012) evaluated the effect axial preloading has on concrete columns by testing two columns at each of 4 different levels of their ultimate load. Columns were jacketed using a ferrocement mortar jacket of 20 mm and welded wire mesh. The strengthened columns preloaded to their ultimate load exhibited progressive failure due to the predamage from losing capacity. The columns jacketed in this experiment and preloaded to levels of 0%, 60%, 80%, and 100% increased their capacity by approximately 33%, 28%, 15%, and 0%, respectively.

Bousias et al. (2007b) analyzed how previous damage on reinforced concrete columns with varying lap-splice lengths affects their capacity following jacketing and cyclic seismic loading. The basic jacketing cross-section shown in Figure 2.1 resembles these specimens. Columns were tested to their ultimate deformation, then jacketed. Jacketing helped improve both the yield moment and deformation capacity in the previously damaged columns. As a result, it was found that previous damage did not significantly impact the behavior of the jacketed columns. During testing, the jackets exhibited substantial bond splitting and spalling by the corner bars; although the deformation and lateral force capacity appeared to not have been affected.

Sezen et al. (2011) evaluated a variety of axial strengthening options for circular reinforced concrete columns while changing if the new jacket was directly loaded. The circular reinforced concrete column and jackets were similar to those shown in Figure 2.11. In every scenario tested, the jackets directly loaded resulted in a higher capacity. Therefore, the jackets should be extended to the top and bottom face of the column, so load is applied across the entire new cross-section.

Table 2.3: Summary of effects of loading

Achillopoulou et al. (2013a)	It was found that the loading capacity of the column had decreased after overloading and retrofitting columns
Achillopoulou et al. (2013b)	Load transferred similarly when only the jacket was directly loaded versus the whole cross-section.

Achillopoulou et al. (2014)	Loading the whole cross section directly at the top enables the capacity to initiate quickly, resulting in higher maximum load values as well as higher load values across the axial strain spectrum. Meanwhile, the confinement effects are not activated until load is distributed across the jacket.
Bousias et al. (2007b)	Previous damage did not significantly impact the behavior of the jacketed columns. During testing, the jackets exhibited substantial bond splitting and spalling by the corner bars; although the deformation and lateral force capacity appeared to not have been affected.
Ersoy et al. (1993)	While unloading the column is preferable, creating the strengthening jacket while the column was loaded functioned similarly to the columns that were unloaded under uniaxial loading. However, if the column is damaged to a level requiring repair, unloading may be more influential on the capacity of the column under uniaxial loading. The repaired columns under combined loading attained less rigidity than the monolithic columns, while strengthened columns reached similar levels to the monolithic columns. Strength was not influenced significantly by monotonic or cyclic loading history, but rigidity was—cyclically loaded column had 40% less rigidity than the monotonically loaded column.
Mourad et al. (2012)	The strengthened columns preloaded to their ultimate load exhibited progressive failure due to the predamage from losing capacity. The columns jacketed in this experiment and preloaded to levels of 0%, 60%, 80%, and 100% increased their capacity by approximately 33%, 28%, 15%, and 0%, respectively.
Rodriguez et al. (1994)	Previous damage did not have a major effect on the jacket's seismic performance.
Sengtottian et al. (2013)	Loading to a higher level results in a more ductile response in the jacket after retrofitting.
Sezen et al. (2011)	Jackets directly loaded resulted in a higher capacity.

Takeuti et al. (2008)	Preloaded and non-preloaded columns behaved similarly before reaching the predicted capacity of the primary column. Circular columns emphasized this effect due to better confinement in circular columns. However, strains in the steel reinforcement were different between the jacket and the column core. Differences in strain between the jacket and the column core were apparent in preloaded columns. Preloading often resulted in higher ductility in the columns than for those not preloaded. Further, the difference in ductility was more apparent in the square cross-sections, due to the lower efficiency of square ties in confinement. Columns that were not preloaded demonstrated similar stresses to the primary column. This effect is persistent throughout loading for circular columns, but only continues until peak load for square columns—due to confinement pressures.
Vandoros et al. (2006b)	The preloaded column had higher strengths, displacements, and retained stiffness during the entire loading cycle than the column not preloaded. Lower jacket stresses helped the preloaded column dissipate energy during testing.

Directly or indirectly loading the jacket results in similar performance. Loading the whole cross-section at the top enables capacity to initiate quicker, resulting in higher strength. The extent of previous damage is important in determining the capacity. Unloading the column is preferable, but may not be necessary. Rigidity and not strength was influenced by previous loading history. Circular jacketed columns behaved more similarly to the primary column due to better confinement than with rectangular columns and their jackets for both preloaded and non-preloaded columns.

2.3 Effect of Cross-Section

Evaluating how different cross-sections affect column performance is important in evaluating retrofit efficacy. Different cross-sections, such as square/rectangular, circular, wing-walls, and layers, produce different results. These shapes produce different results, and each may be desirable for retrofit based on the constraints and desired performance at the column to be retrofitted.

Chang et al. (2014) compared lateral strengthening columns with RC jackets or wing walls. Two columns are tested with each method, as well as an unretrofitted column according to pre-1999 design standards. The columns with the reinforced concrete jackets had cross-sections similar to the one shown in Figure 2.1. RC jackets had improved flexural and shear strength, resulting in better energy dissipation and ductility versus the wing walled columns, since jackets have a flexural not shear failure mode. However, wing-walled columns still had improvement in flexural and shear strength, but, unlike the jacketed columns, energy dissipation and ductility could not improve due to the shear and flexural failure.

Lampropoulos et al. (2008) tested using a full reinforced concrete jacket with applying on layer of reinforced concrete to the compressive side of a column under lateral loading. The jacketed columns looked like Figure 2.1, while the ones with a concrete layer resembled Figure 2.5.

Takeuti et al. (2008) tested using high strength reinforced concrete jackets on both square and circular cross sections under axial loading. Figures 2.1 and 2.11 resemble what typical cross-sections in the square jacketed, circular original, and circular jacketed columns, respectively, in this study. It was found that preloading may reduce the columns deformability, but does not negatively impact the column’s capacity. Since square cross-sections have less confinement, such effects are more apparent. Circular columns had a particularly strong relationship in relating the transverse reinforcement to ductility, due to uniform confinement.

Pellegrino et al. (2009) evaluated how different layer thicknesses of a partial polymer-modified cementitious mortar jacket rehabilitate columns loaded to 1/3 of their ultimate axial load. Six square columns were tested monotonically axially with 0 mm, 15 mm, and 50 mm thick layers on one side of the column. The columns with the repair layers are shown in Figures 2.7 and 2.8. Since the layers debonded before ultimate failure, the ultimate capacity could be higher than the testing if the bonding mechanisms are improved. The thinner jacket layers debonded earlier, at about 67% of the ultimate load. As a result, layer thickness is integral to column capacity.

Table 2.4: Summary of effects cross-section

Chang et al. (2014)	RC jackets had improved flexural and shear strength, resulting in better energy dissipation and ductility versus the wing walled columns, since jackets have a flexural not shear failure mode. However, wing-walled columns still had improvement in flexural and shear strength, but, unlike the jacketed columns, energy dissipation and ductility could not improve due to the shear and flexural failure.
Pellegrino et al. (2009)	Since the RC layers debonded before ultimate failure, the ultimate capacity could be higher than the testing if the bonding mechanisms are improved. RC layer thickness is integral to column capacity, since thinner layers debonded earlier.
Takeuti et al. (2008)	Preloading may reduce the columns deformability, but does not negatively impact the column’s capacity. Since square cross-sections have less confinement, such effects are more apparent. Circular columns had a particularly strong relationship in relating the transverse reinforcement to ductility, due to uniform confinement. Circular jacketed columns behaved more similarly to the primary column due to better confinement than with rectangular columns and their jackets for both preloaded and non-preloaded columns.

Jackets perform better in energy dissipation and ductility than wing-walled columns. Bonding mechanisms are more important with RC columns with RC layers due to debonding and confinement. Circular columns are better at relating the transverse reinforcement to ductility, due to uniform confinement. Circular jacketed columns behaved more similarly to the primary column due to better confinement than with rectangular columns and their jackets for both preloaded and non-preloaded columns.

2.4 Effect of Reinforcement

Reinforcement is an important variable to evaluate because original columns may have been designed with different rebar details and different rebar types or arrangements may be preferable to implement based on their performance.

2.4.1 Effect of Type of Reinforcement

This section compares the type of reinforcement used both within the reinforced concrete column and jacket. Options for reinforcement type include smooth bars, ribbed bars, welded wire fabric (WWF), and spiral rebar.

Bousias et al. (2004) compared how smooth and ribbed bars performed under lateral loading. The retrofitted columns looked like those in Figures 2.1 and 2.12. Columns with ribbed bars lap-spliced at the base have reduced cyclic deformation capacity and energy dissipation.

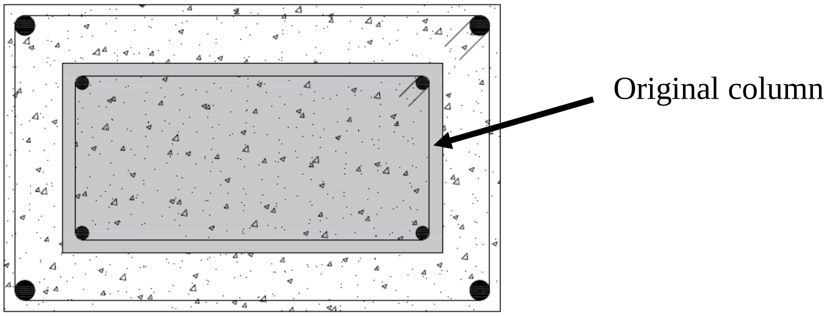


Figure 2.12: Reinforced concrete jacket of rectangular columns

Sezen et al. (2012) evaluated a variety of strengthening options for circular reinforced concrete columns with axial loading. Such options included using spiral rebar and welded wire fabric in reinforced concrete jackets. The circular reinforced concrete column and jackets were similar to those shown in Figure 2.11. Both the WWF and the rebar-reinforced concrete jackets experienced concrete spalling at around maximum axial capacity of the base column. These two methods also had similar stiffnesses before cracking. The WWF method only increased deformation capacity slightly, but provided moderate stiffness and strength increases. The capacity increase (140%) obtained by the WWF columns resulted in a brittle failure after peak capacity. Meanwhile, the spiral rebar method resulted in a capacity increase close to 350%.

Takeuti et al. (2008) compared square and circular axially loaded columns strengthened with high strength reinforced concrete jackets with either steel reinforcement in the jacket or welded wire mesh. Figures 2.1 and 2.11 resemble what typical cross-sections in the square jacketed, circular original, and circular jacketed columns, respectively, in this study. It was found that ductility is directly impacted by the jacket transverse reinforcement, particularly in circular columns with uniform confinement. Additionally, the welded wire mesh reinforcement proved to be effective at increasing capacity and resulted in similar ultimate strength, even when small diameter wires were used.

Takiguchi and Abdullah (2001) focused on varying the number of layers of wire mesh (two, three, four, and six layers) in ferrocement jackets cyclically laterally loaded with constant axial force. Figure 2.13 show what the original column and circular jacket look like. Ductility increased as the number of wire mesh layers increased. Even when only three layers of wire mesh were provided, the ductility improved significantly. The columns with four and six layers of wire mesh demonstrated ductile responses until a drift ratio of 10%.

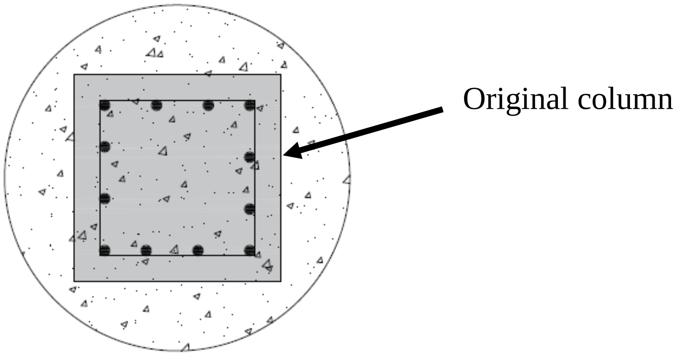


Figure 2.13: Circular concrete jackets on square reinforced concrete columns

Table 2.5: Summary of effect of type of reinforcement

Bousias et al. (2004)	Columns with ribbed bars lap-spliced at the base have reduced cyclic deformation capacity and energy dissipation than those with smooth bars
Sezen et al. (2011)	Both the WWF and the rebar-reinforced concrete jackets experienced concrete spalling at around maximum axial capacity of the base column. These two methods also had similar stiffnesses before cracking. The WWF method only increased deformation capacity slightly, but provided moderate stiffness and strength increases. The capacity increase (140%) obtained by the WWF columns

	resulted in a brittle failure after peak capacity. Meanwhile, the spiral rebar method resulted in a capacity increase close to 350%.
Takeuti et al. (2008)	Ductility is directly impacted by the jacket transverse reinforcement, particularly in circular columns with uniform confinement. Additionally, the welded wire mesh reinforcement proved to be effective at increasing capacity and resulted in similar ultimate strength, even when small diameter wires were used.
Takiguchi and Abdullah (2001)	Ductility increased as the number of wire mesh layers increased. Even when only three layers of wire mesh were provided, the ductility improved significantly. The columns with four and six layers of wire mesh demonstrated ductile responses until a drift ratio of 10%.

Ribbed bars have less cyclic deformation capacity and energy dissipation than smooth bars. Spiral rebar increased capacity most versus WWF and horizontal transverse reinforcement. Ductility is directly impacted by jacket transverse reinforcement, and increases with the number of wire mesh layers.

2.4.2 Effect of Stirrups

Stirrups have been designed from codes at different times and with different spacings. As such, several studies have evaluated how such differences affect reinforced concrete jacketed column performance.

Achillopoulou et al. (2014) evaluated how the spacing of stirrups affects jacketed reinforced concrete column axial performance. The columns had the basic cross-section shown in Figure 2.1. Columns were constructed with stirrups designed without high ductility requirements to standards from old codes, as well as confinement depicted modern codes. The different stirrup reinforcement ratios were only in the column cores; the jackets did not have varying stirrup reinforcement. In all the tests, both stirrup reinforcement ratios resulted in capacity being exceeded by 50% in dissipating energy until the peak point.

Julio et al. (2003), on the other hand, discussed the effects caused by varying the spacing of added stirrups in the reinforced concrete jackets. It was found that using more transverse reinforcement can result in monolithic performance of jacketed reinforced concrete columns. From testing, half the spacing of stirrups in the original column is recommended.

Table 2.6: Summary of effect of stirrups

Achillopoulou et al. (2014)	In all the tests, both stirrup reinforcement ratios resulted in capacity being exceeded by 50% in dissipating energy until the peak point.
Julio et al. (2003)	More transverse reinforcement can result in monolithic performance of jacketed reinforced concrete columns. Half the spacing of stirrups in the original column is recommended.

Amount of stirrup reinforcement may be influential at increasing capacity. Performance may also vary more after the peak point with different stirrup reinforcement ratios.

2.4.3 Effect of Longitudinal Reinforcement

The studies in this section evaluate how providing different numbers of longitudinal bars or having different details impacts retrofitted column capacity. Rodriguez et al. (1994) evaluated how using different numbers of bars in jackets on reinforced concrete columns impacts their lateral performance. Some of the columns followed the basic jacketing section shown in Figure 2.1, while others had more reinforcement provided, as shown in Figures 2.10. Since the columns were tested laterally with a constant small axial load, the increased reinforcement was unnecessary due to ACI's conservative recommendations.

Similar to Rodriguez et al. (1994), Julio et al. (2003) discussed the difficulties in having a continuous reinforced concrete column and jacket cross a slab. It was discussed how welded wire fabric in mortar provides benefits versus tensile reinforcement by increasing shear strength and ductility.

Sengottian et al. (2013) tested columns with axial loading and either two or six longitudinal bars. The column and the jacket are shown in Figure 2.11. While the columns with only two bars failed earlier, the difference was relatively small (68% - 74% versus 82% - 94% capacity increase). Further, as the preloading from the column increased from 50%- 60% - 70% of ultimate force, the difference between the jacketed column ultimate capacities with two or six longitudinal bars decreased. Additionally, as shown, all columns were successful and increasing the column strength.

Table 2.7: Summary of effect of longitudinal reinforcement

Rodriguez et al. (1994)	Since the columns were tested laterally with a constant small axial load, the increased reinforcement was unnecessary due to ACI's conservative recommendations.
Sengtottian et al. (2013)	The difference between using two or six bars in the jacket resulted in a relatively small difference. Further, as the preloading from the column increased from 50%- 60% - 70% of ultimate force, the difference between the jacketed column ultimate capacities with two or six longitudinal bars decreased.

ACI's recommendations for longitudinal reinforcement are conservative and additional reinforcement may not be necessary. Increasing the amount of longitudinal reinforcement may not have a significant impact on the jacket capacity.

CHAPTER 3: STEEL CONFINEMENT RETROFIT METHODS

Table 3.1: Summary of steel jacket studies and their parameters

Study	Plastic Hinge	Interface	Connection	Jacket sizing	Cross-Section	Loading
Aboutaha et al. (2016)	X					
Chai et al. (1991)	X					
Choi et al. (2008)			X	X		
Choi et al. (2010)		X				
ElGawady et al. (2010)						
Eunsoo et al. (2008)			X			
Lee et al. (2012)						
Li et al. (2005)				X		
Lin et al. (2010)	X				X	
Priestley et al. (1994)				X	X	
Saiid et al. (2004)						
Aboutaha et al. (1999)						X
Xiao et al. (2003)	X					
Fakharifar et al. (2016)						
Belal et al. (2015)				X	X	
Uy (2002)		X			X	
Sezen et al. (2011)						

3.1 Steel Jacketing Retrofit Method

Steel jackets are another common retrofit method for columns, and are used frequently. In their most basic form, a steel jacket can be comprised of only wrapping steel plates around a column. Under different scenarios, steel jackets may also include adhesives between the jacket and the column, concrete or grout to fill in gaps between a larger jacket and the column, anchor bolts to facilitate the connections, and end stiffeners to move the plastic-hinge. Some of the primary considerations for these methods are the plastic-hinge behavior, interface preparation, connections within the jacket, sizing of the jacket, the cross-section or shape used, and various loading cases, which are shown in Table 3.1.

3.1.1 Behavior in Plastic-Hinge Region

Plastic-hinge behavior where lateral forces cause structures to rotate near the ends of columns is an important consideration, particularly under seismic loading. As such, preventing such behavior is important in retrofitting reinforced concrete columns. To do this, studies have been completed on how standard jackets, jackets with end stiffeners or capitals, or additional anchoring can mitigate against plastic-hinge behavior.

Aboutaha et al. (1996) evaluated using steel plates under lateral loading in the potential plastic hinge regions of columns with different cross-sections, concrete strengths, jacket heights, adhesive anchor bolt arrangement, and the vertical spacing of bolts. A sample cross-section with four anchor bolts is shown in Figure 3.1. As the spacing of the bolts decreased, the hysteresis loop pinched resulting in a degradation of lateral force as drift ratio increased. Despite having the lowest concrete strength, fewest number of bolt, and largest spacing, the specimen that had a long jacket and additional angles at the corners performed best. This demonstrates the importance of a longer steel jacket and having additional confinement. Therefore, smaller jackets can even be retrofitted without anchor bolts. Additionally, the number of anchor bolts was determined based on the strength of the concrete—columns made from higher strength concrete require less anchor bolts than those made from lower strength.

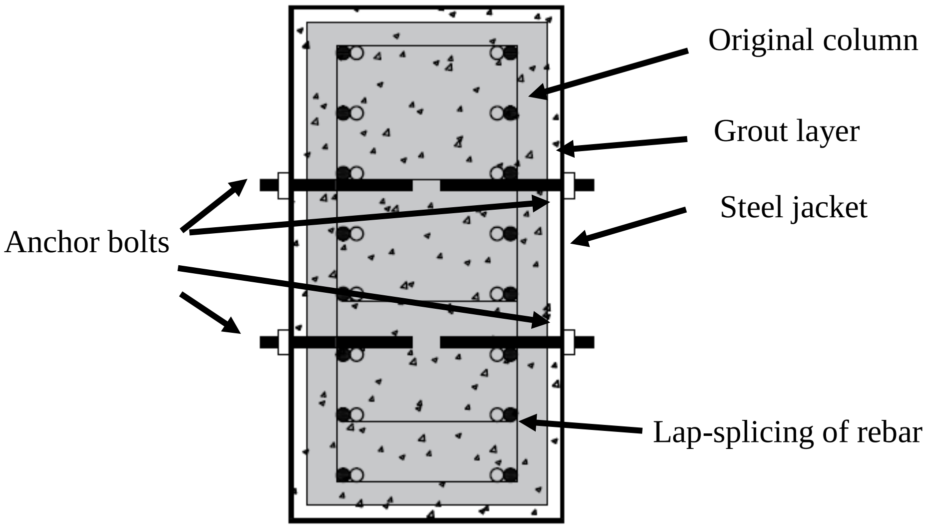


Figure 3.1: Steel jacket retrofit with anchor bolts

Chai et al. (1991) tested columns with steel jackets in the plastic hinge region under lateral loading with a constant axial load. Figure 3.2 shows the cross-section of the columns tested with the steel jacket. The main variables tested were: provision of lap-splices or continuous reinforcement, use of a strong or weak footing, partial or full retrofit. Lapping starter bars in the plastic hinge region proved to fail prematurely; the use of continuous reinforcement instead, decreases the likely strength degradation after this point.

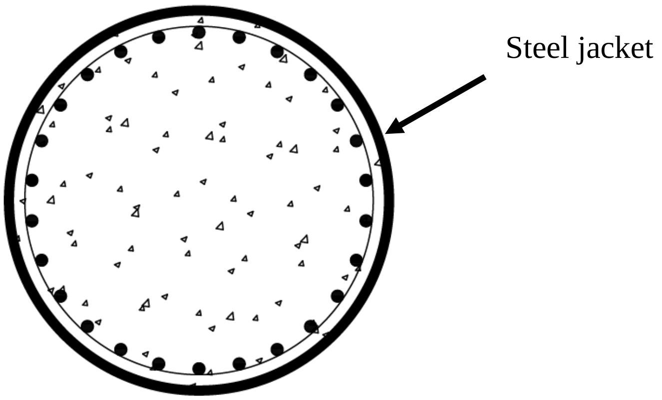


Figure 3.2: Steel jacket retrofit on circular reinforced concrete columns

Lin et al. (2010) investigated using octagonal or elliptical steel jackets, as shown in Figure 3.3 on rectangular lap-splice deficient reinforced concrete columns under lateral loading. While both jackets were successful at improving strength and ductility capacities and preventing non-ductile splice failures, the octagonal greatly prevented lap-splice failure while enhancing ductility.

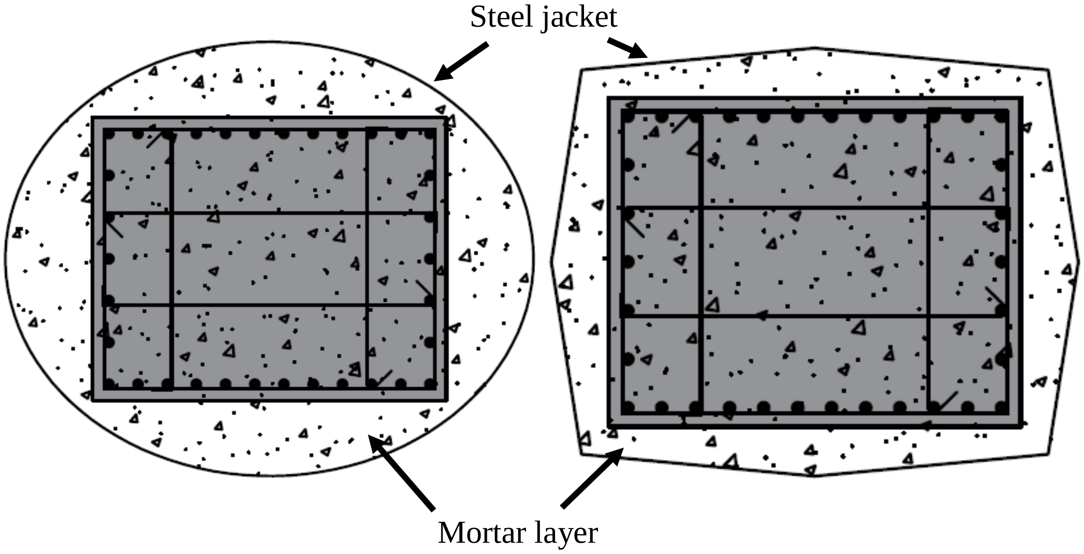


Figure 3.3: Elliptical (a) and octagonal (b) steel jacket retrofit with concrete infill

In addition to using a steel jacket, Xiao et al. (2003) provided end stiffeners in the potential plastic hinge regions under lateral cyclic loading. Different types of stiffeners were evaluated: thick plate, angle, and square pipe, as shown in Figure 3.4 with the standard column cross-section shown in Figure 3.5. All the stiffeners enabled the column to reach satisfactory ductility, while the column without stiffeners did not reach a sufficient ductility. Angle stiffeners may be the most viable, since they are more readily available and are easy to weld. While the thick plate and angle stiffeners yielded, strain was relatively small throughout the testing process demonstrating the conservativeness of the design approach.

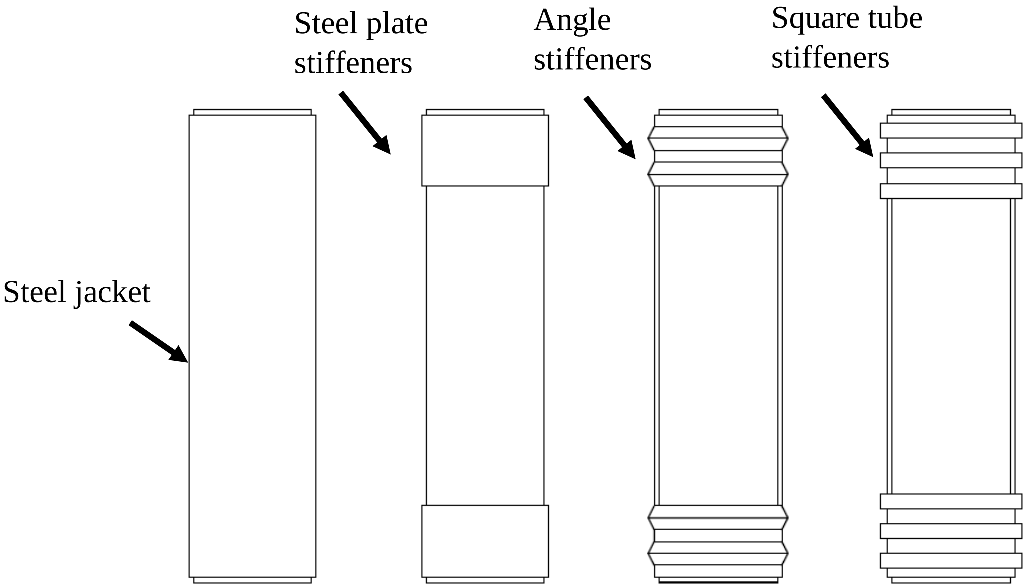


Figure 3.4: Steel jackets provided with no stiffeners; steel plate stiffeners; angle stiffeners; and square tube stiffeners.

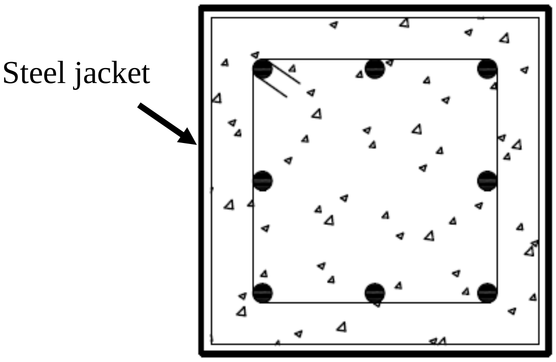


Figure 3.5: Standard steel jacket retrofit of square reinforced concrete columns

Table 3.2: Summary of effect of plastic-hinge on retrofit performance

Aboutaha et al. (2016)	Providing a longer steel jacket and having additional confinement in the plastic-hinge region can result in higher strength. Smaller jackets can even be retrofitted without anchor bolts. Columns made from higher

	strength concrete require less anchor bolts than those made from lower strength.
Chai et al. (1991)	Lapping starter bars in the plastic hinge region failed prematurely. Providing continuous reinforcement instead decreases the likely strength degradation after this point.
Lin et al. (2010)	While both octagonal and elliptical jackets were successful at improving strength and ductility capacities and preventing non-ductile splice failures, the octagonal greatly prevented lap-splice failure while enhancing ductility.
Xiao et al. (2003)	All the stiffeners enabled the columns to reach satisfactory ductility versus those without stiffeners. Angle stiffeners may be the most viable, since they are more readily available and are easy to weld. While the thick plate and angle stiffeners yielded, strain was relatively small throughout the testing process demonstrating the conservativeness of the design approach.

Longer steel jackets and additional confinement with anchor bolts can result in higher column capacity. Continuous reinforcement in the plastic-hinge region is important at minimizing strength degradation. Using an octagonal jacket instead of an elliptical jacket can prevent lap-splice failure better and enhance ductility. Stiffeners helped columns improve ductility. Angle stiffeners may be the most practical due to availability and constructability.

3.1.2 Interface

Researchers have evaluated how influential providing additional interface preparation is n column performance. Options evaluated include no preparation, adhesives, and bolts.

Choi et al. (2008) evaluated how useful adhesives are in steel jackets by testing steel jackets on circular reinforced concrete columns, such as the one shown in Figure 3.6, loaded axially with and without adhesives applied. The main variables were the strengths, lateral confining pressure, thickness of the jacket, adhesive presence, and welding quality. Adhesives decreased the compressive strength of the retrofitted specimens since the adhesive reduced the confining effect, and the jackets already provided sufficient lateral pressure.

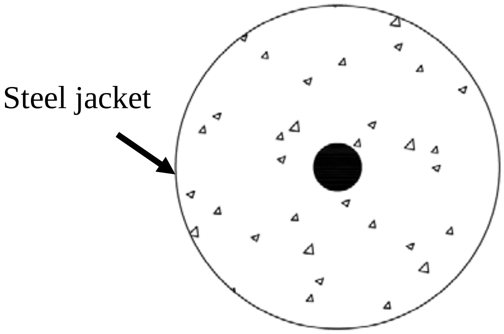
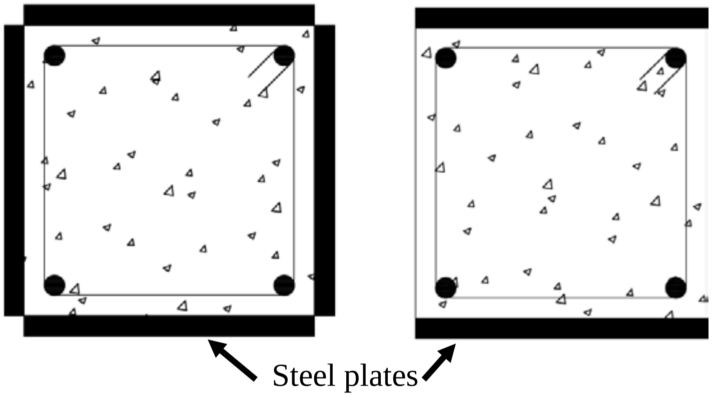


Figure 3.6: Steel jacket retrofit on column with one bar

Uy et al. (2002) tested the anchorage of steel plates to reinforced concrete square columns under axial loading by providing bolts or glue and bolts. A variety of different number of plate options were used, including those shown in Figure 3.7. Using both glue and bolts was the most effective and limiting local slip buckling to provide composite action between the column and the plate. Additionally, the glue and bolt technique may have applications in slender columns, such as those in elevated water tanks.



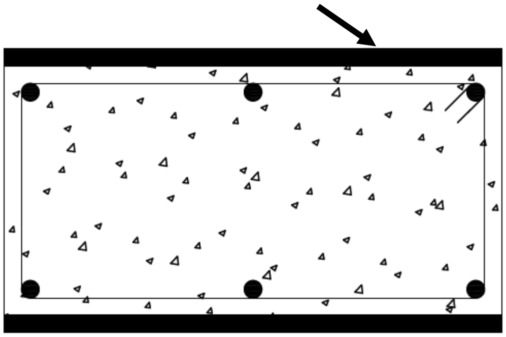


Figure 3.7: Partial and complete steel jackets provided on square and rectangular columns

Table 3.3: Summary of interface effect on retrofit

Choi et al. (2010)	Adhesives decreased the compressive strength of the retrofitted specimens since it reduced the confining effect and the jackets already provided sufficient lateral pressure.
Uy (2002)	Using both glue and bolts was the most effective at limiting local slip buckling to provide composite action between the column and the plate. The glue and bolt technique may have applications in slender columns, such as those in elevated water tanks.

Providing adhesives is unnecessary and unfavorable, since steel jackets laterally confine the column effectively. However, using both glue and bolts is effective for columns with individual plates jacketing the column.

3.1.3 Effect of Jacket Connections

Since steel jackets must be wrapped around a column or attached by some means, the connection is an important parameter. Researchers compared how welding one or two sections of a jacket, or providing external pressure effect column performance.

Using no grout or adhesive between a steel jacket and the circular reinforced concrete columns, Choi et al. (2010) evaluated the application of different techniques to confine the jacket under lateral loading. These option were: providing external pressure on the steel jacket using hoops, welding along the overlap between the cylindrical plates, and welding lateral bands across the plates. Improving the installation process and providing more external pressure may be required for these jackets, since there was not an increase in the flexural strength of the columns. Welding the strip bands were sufficient in protecting the weld line from fracture.

Choi et al. (2008) also investigated using a whole steel jacket or two split jackets and strip bands on axially loaded circular reinforced concrete columns, with the standard cross-section shown in Figure 3.6. The main variables were the strengths, lateral confining pressure, thickness of the jacket, adhesive presence, and welding quality. The whole jackets were more successful than the split jackets at producing full plastic deformation.

Table 3.4: Summary of effect of jacket-column connection on retrofit

Choi et al. (2010)	Improving the installation process and providing more external pressure may be required for these jackets, since there was not an increase in the flexural strength of the columns. Welding the strip bands were sufficient in protecting the weld line from fracture.
Eunsoo et al. (2008)	The whole jackets were more successful than the split jackets at producing full plastic deformation.

Whole jackets produce better full plastic deformation than split jackets.

3.1.4 Effect of Jacket sizing

Analyzing the thickness of the jacket is important in designing the jacket to efficiently meet the column’s structural requirements.

Choi et al. (2008) evaluated the use of different steel jacket thicknesses or multiple jackets on axially loaded circular reinforced concrete columns, as shown in Figure 3.6. The main variables were the strengths, lateral confining pressure, thickness of the jacket, adhesive presence, and welding quality. Jackets with two layers versus one layer of an equivalent overall thickness behave approximately the same. Additionally, jacket thickness and peak strength have a nearly linear relationship.

Li et al. (2005) tested reinforced concrete cylinders, like the one shown in Figure 3.8, with varying concrete strengths, jacket thicknesses, and type of lateral steel reinforcement under axial loading. Logically, thicker steel jackets provided more confinement, increasing the stress of the confined concrete.

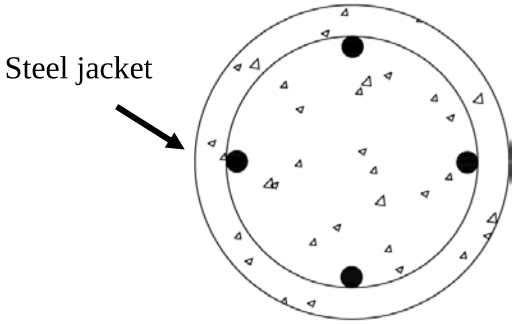


Figure 3.8: Standard steel jacket on circular reinforced concrete columns

Priestley et al. (1994) examined how different loading, aspect ratio's, reinforcing, jacket thickness, and jacket strength affect circular and rectangular reinforced concrete columns under lateral loading with a constant axial force. Cross-sections of these columns are shown in Figures 3.2 and 3.3a. The thinner jacket used on the circular columns could not confine the column sufficiently at large ductility factors, even though all the columns surpassed the shear requirements.

Using different steel jacket and cage cross-sections and spacings, Belal et al. (2015) investigated how steel jackets made from cross sections contribute to the strength of retrofitted reinforced concrete columns under axial loading. Columns with angles, channels, and plate cross sections of the same area were used with different sizes and numbers of batten plates resulting in the same cross-section area as well, as shown in Figure 3.9. Steel plates were found to be less effective due to the thinness of the plate, in relation to using steel cages made from angles or channels. More information about the results can be found in section 3.2.4.

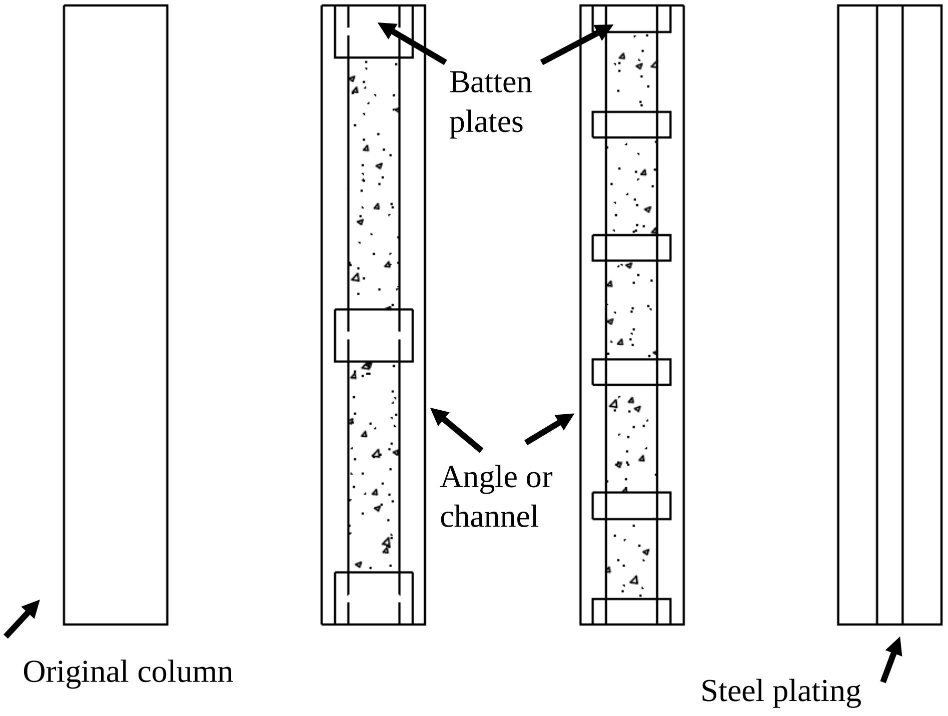


Figure 3.9: Original column; steel cage with 3 battens; steel cage with 6 battens; steel plating

Table 3.5: Summary of jacket sizing effect on retrofit performance

Choi et al. (2008)	Jackets with two layers versus one layer of an equivalent overall thickness behave approximately the same. Additionally, jacket thickness and peak strength have a nearly linear relationship.
Li et al. (2005)	Logically, thicker steel jackets provided more confinement, increasing the stress of the confined concrete.
Priestley et al. (1994)	The thinner jacket used on the circular columns could not confine the column sufficiently at large ductility factors, even though all the columns surpassed the shear requirements.
Belal et al. (2015)	Steel plates were less effective due to the thinness of the plate, in relation to using steel cages made from angles or channels. More information about the results can be found in section 3.2.4.

Two jacket layers versus one of equivalent size perform essentially the same, due to the degree of confinement. Jacket thickness and peak strength have a nearly linear relationship. Thin steel plates may have problems due to ductility or buckling.

3.1.5 Effect of Cross-Section

For columns without significant space constraints, the column may have flexibility with the cross-section shape. As such, the optimum column cross-section should be chosen. Studies have compared a variety of shapes of steel jackets including square, rectangular, elliptical, circular, or octagonal cross-sections for square or rectangular columns; and circular or elliptical jackets for circular columns.

Lin et al. (2010) investigated using octagonal or elliptical steel jackets, shown in Figure 3.3, on rectangular lap-splice deficient reinforced concrete columns under lateral loading. While both cross-section options were successful at improving strength and ductility capacities and preventing non-ductile splice failures, the octagonal greatly prevented lap-splice failure while enhancing ductility. The octagonal steel jacket also had better energy dissipation and lateral capacity further preventing seismic failures, although it used a thicker jacket. Additionally, octagonal jackets are more preferable from a constructability aspect, since they only require 8 bends, while the elliptical jacket requires continuous bending of the steel plate. In addition to improving strength, energy dissipation, and other aforementioned factors, octagonal jackets may also be preferable due to being lower cost, and taking up less space than elliptical jackets.

Priestley et al. (1994) evaluated elliptical and circular steel jackets on rectangular and circular reinforced concrete columns, respectively, under lateral loading with a constant axial load. These cross-sections are shown in Figures 3.2 and 3.3a. Loading, aspect ratios, reinforcing, jacket thickness, and jacket strength varied between the columns tested. Rectangular columns with elliptical steel jackets and circular columns with circular steel jackets increased the elastic stiffness by 64% and 30%, respectively. This demonstrates how the retrofitted columns will experience higher shear than non-retrofitted columns. Both were very effective at improving shear strength and flexural ductility of under-designed columns for shear.

Belal et al. (2015) also evaluated steel jackets of different shapes, thicknesses, and spacings. The results of this experiment are described above in 3.1.4: Jacket sizing

Uy (2002) tested different cross-sections and lengths of rectangular and square RC columns with steel plates on two or four sides under axial loading with different glue and bolting options, shown in Figure 3.7. The tall slender columns experienced the greatest increase in axial capacity after jacketing by 100%. Nevertheless, the steel jackets were effective for all columns tested.

Table 3.6: Summary of effect of retrofit cross-section performance

Lin et al. (2010)	While both cross-section options were successful at improving strength and ductility capacities and preventing non-ductile splice failures, the octagonal section greatly prevented lap-splice failure while enhancing ductility. The octagonal steel jacket also had better energy dissipation and lateral capacity further preventing seismic failures, although it used a thicker jacket. Additionally, octagonal jackets are more preferable from a constructability aspect, since they only require 8 bends, while the elliptical jacket requires continuous bending of the steel plate. Octagonal jackets may be preferable due to having a lower cost and taking up less space than elliptical jackets.
Priestley et al. (1994)	Rectangular columns with elliptical steel jackets increased the elastic stiffness by more than double the circular steel jackets. Both were very effective at improving shear strength and flexural ductility of under-designed columns for shear.
Belal et al. (2015)	The results of this experiment are described above in 3.1.4.
Uy (2002)	Tall slender columns experienced the greatest increase in axial capacity after jacketing by 100%. Nevertheless, the steel jackets were effective for all columns tested.

The use of an octagonal instead of an elliptical jacket for rectangular columns prevents lap-splice failure, enhances ductility, improves energy dissipation and lateral capacity, is easier to construct, has a lower cost, and takes up less space. Elliptical steel jackets were twice as effective at increasing elastic stiffness as circular jackets on rectangular columns. Both improved shear strength and flexural ductility sufficiently. Steel jackets are more effective at improving axial capacity for tall slender columns.

3.1.6 Effect of Loading

Evaluating the effect of different loadings on retrofitted columns is important in simulating realistic loading conditions. Therefore, preloading levels and loading columns in strong and weak direction were compared to understand the steel jacket's success.

Aboutaha et al. (1999) tested laterally loading partial and solid steel jacketed rectangular RC columns, like those shown in Figure 3.1, in either the weak or strong direction. The jackets were successful and strengthening the columns previously inadequate in shear under loading from both the weak and strong directions.

Table 3.7: Summary of loading results on retrofit

Aboutaha et al. (1999)	The jackets were successful at strengthening the columns previously inadequate in shear under loading from both the weak and strong directions.

The jackets can improve capacity in both strength and weak directions.

3.2 Steel Cage Retrofit Method

Similar to steel jacketing, the steel cage retrofit method consists of surrounding a column with steel plates. For the steel cage, individual plates are welded together to provide confinement, instead of a few plates that completely surround the column. Different cross-sections of steel may be used including plates, angles, and channels with varying numbers and thicknesses of the steel members. Steel cages have similar parameters to steel jackets, as shown in Table 3.2, which include the interface from the cage to the column, the sizing of jacket members, the cross-section of steel used, and different loading applied.

Table 3.8: Steel cage studies and parameters

Study	Interface	Cage sizing	Cross-section	Loading
Adam et al. (2009)	X	X		
Gimenez et al. (2009)				X
Li et al. (2009)				
Nagaprasad et al. (2009)				
Roca et al. (2011)				
Belal et al. (2015)			X	
Montuori et al. (2009)		X		

3.2.1 Effect of Interface between Steel Cage and Original Column

For the interface between the steel cage and the column, the effect of providing mortar and differing levels of friction were analyzed to understand their usefulness in steel cage retrofit.

Adam et al. (2009) evaluated how angle sizes, steel strength, concrete strength, strip sizes, steel strips at column ends, and the interface affect column performance under axial loading. The columns tested in this study resembled the ones in Figure 3.9. As expected, better friction between the steel cage and mortar resulted in greater load transmission, and strength as a result.

Table 3.9: Summary of effect of interface on steel cage retrofit

Adam et al. (2009)	Better friction between the steel cage and mortar can improve load transmission and column strength.

Better friction between the steel cage and mortar can improve load transmission and column strength.

3.2.3 Effect of Cage Sizing

Analyzing the thickness of the steel cage is important in designing the cage to efficiently meet the column's structural requirements.

Adam et al. (2009) evaluated how angle sizes, steel strength, concrete strength, strip sizes, steel strips at column ends, and the interface affect column performance under axial loading. The steel cage was composed of four angles on each corner of the column connected by strips of varying sizes and spacings, like the steel cages shown in Figure 3.9. As a result of a parametric study performed in tandem with the experimental tests, increasing the size of the angles of the cage increased confinement effectiveness, but decreased the effectiveness of load transfer between the cage and column. As for the strips, larger strips improved confinement and load transfer from how shear stress was transferred. Having closer spacing of strips near the ends can move the failure point towards the center of the column.

Montuori et al. (2009) investigated how axial capacity and ductility can be enhanced with steel cages by varying the longitudinal reinforcement, number of ties, eccentricity of load, and presence and spacing of hoops and battens under axial loading. These columns followed a standard steel jacketing cross-section, shown in Figure 3.5. By comparing the use of hoops or battens in the specimens, it was found that angles and battens provide different performance in confinement than hoops provide. The presence of angles at the corner and their confinement can also provide lateral restraint to prevent or hinder spalling and buckling of bars.

Table 3.10: Summary of effect of cage sizing results on steel cage retrofit

Adam et al. (2009)	Increasing the size of the angles of the cage increased confinement effectiveness, but decreased the effectiveness of load transfer between the cage and column. Larger strips improved confinement and load transfer from how shear stress was transferred. Closer spaced strips near the ends can move the failure point towards the center of the column.
Montuori et al. (2009)	Angles and battens provide different performance in confinement than hoops. The presence of angles at the corner and their confinement can also provide lateral restraint to prevent or hinder spalling and buckling of bars.

Larger angles increases confinement, but decreases load transfer. Larger strips can improve confinement and load transfer. Closer spacing near the ends can shift the failure point towards the column center. Angles can provide lateral restraint to prevent or hinder spalling and bar buckling.

3.2.4 Effect of Cross-Section

Since a variety of cross-sections are available for application in steel cages, understanding the performance of these is important. The most common cross-sections used are angles or channels at the corners, or plates across the column. Differing numbers or thicknesses of batten plates to connect the angles, channels, or plates also produce varying results on the structural performance of the columns.

Belal et al. (2015) tested the efficacy of different cross sections of steel jackets and cages on reinforced concrete columns under axial loading, as shown in Figure 3.9. Columns with angles, channels, and plate cross sections of the same area were used with different sizes and numbers of batten plates resulting in the same cross-section area as well. Angles and channels performed similarly, but steel plates resulted in less capacity for the column, due to the thinness of the plate. Batten plates had variable results based on which cross-section was used. Fastening more, thinner plates resulted in higher strength for the channels, but lower strength for angles. This may be due to the continuity of the channel, so more plates improve that continuity; while the angles benefited more from improved confinement stress from the thicker plates. Additionally, the columns with angles experienced less deformation than from the other steel jacket/cage cross-sections. Additional consideration should be provided when using C-sections with batten plates or plates only, since their thinner thicknesses may present buckling problems.

Table 3.11: Summary of effect of cross-section results on steel cage retrofit

Belal et al. (2015)	Angles and channels performed similarly, but steel plates resulted in less capacity for the column, due to the thinness of the plate. Batten plates had variable results based on which cross-section was used. Fastening more, thinner plates resulted in higher strength for the channels, but lower strength for angles. More plates improve continuity in channels; while the angles benefited more from improved confinement stress from the thicker plates. Additionally, the columns with angles experienced less deformation than from the other steel jacket/cage cross-sections. Additional consideration should be provided when using C-sections with batten plates or plates only, since their thinner thicknesses may present buckling problems.

Angles and channels performed similarly and were a better alternative to steel plates. Batten plate sizing is dependent upon the cross-section used. More plates is preferable for channels, but larger plates is preferable for angles. Angles can result in less deformation than other cross-section. Channels may have problems with buckling due to their thinness.

3.2.5 Effect of Loading

Evaluating the effect of different loadings on retrofitted columns is important in simulating realistic loading conditions. Therefore, preloading levels are important understand the steel jacket's success.

Gimenez et al. (2009) evaluated the use of different types of column connections at ends, as shown in Figure 3.10, and if unloading columns before strengthening on reinforced concrete (RC) columns under axial loading. Only a small difference in strength and performance was measured in the column that was unloaded versus the one that had 900 kN of preloading. When capitals were present, more loads were distributed to the cage when the columns was unloaded.

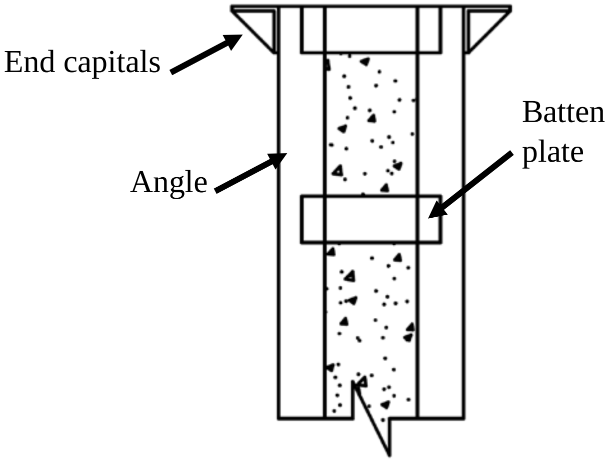


Figure 3.10: End capitals provided with steel cage retrofit method

Table 3.12: Summary of effect of loading results on steel cage retrofit

Gimenez et al. (2009)	Only a small difference in strength and performance was measured in the column that was unloaded versus the one that had preloading. When capitals were present, more loads were distributed to the cage when the columns was unloaded.

Unloading by removing existing column loads had a small effect on strength and performance of the column. Capitals provided at the ends helped more load distribution to the columns after unloading.

CHAPTER 4: PRE-CAMBERED STEEL PLATING RETROFIT METHOD

Precambered steel plates are a unique method of steel retrofit for columns. The process consists of placing a steel plate larger than the available space for the column and providing a spacer to camber the plate, as shown in Figure 4.1. Then the spacer is removed and the cambered plate is anchored to the column to alleviate column stress. Through this process, the main considerations are the thickness of the plate, the degree of initial precambering, the eccentricity of loading, and whether the columns are preloaded.

Table 4.1: Summary of precambered steel plate studies and parameters

Study	Thickness	Initial Precambering	Eccentricity	Preloading
Su et al. (2012)	X	X		X
Wang et al. (2012)	X	X	X	
Wang et al. (2013)	X	X	X	

4.1 Effect of Plate thickness

Analyzing the thickness of the precambered steel plates is important in designing the cage to efficiently meet the column’s structural requirements.

Su et al. (2012) evaluated how preloaded reinforced concrete columns can be strengthened by precambered steel jackets under axial loading. The columns varied in plate thickness, precambering, and preloading. The thicker plates delayed the development of mid-height cracks while enhancing the strength and deformability of columns. The thickness of the precambered steel plates increased the strength of the columns more than proportional—3.5 to 4 times higher strength for a plate twice as thick.

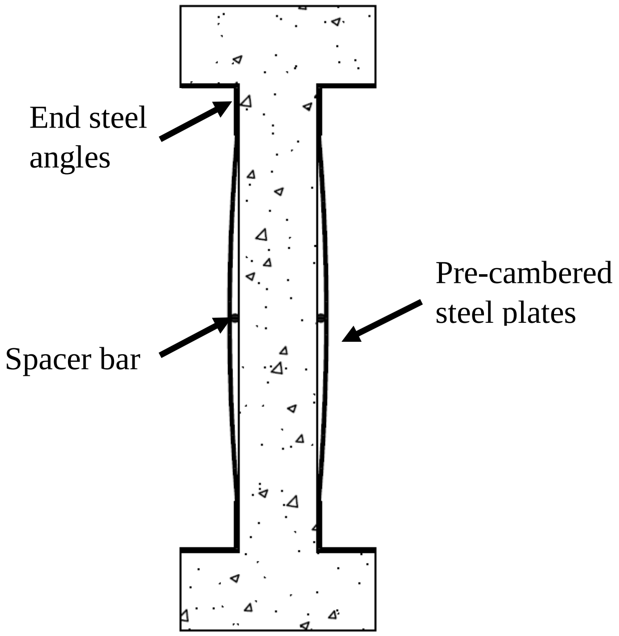


Figure 4.1: Pre-cambered steel before anchoring

Wang et al. (2012) tested precambered steel plates on reinforced concrete columns under axial loading with varying plate thicknesses, eccentricities, and initial precamber displacements. Thicker plates proved to increase the ultimate load capacity of columns and improve axial deformation capacity of columns significantly as a result of this study. As eccentricity and the preloading levels rose, the columns increased in strength due to thicker plates less.

Wang et al. (2013) investigated the effects precambered steel plates have on eccentrically preloaded reinforced concrete columns under axial loading. Plate thickness had a significant impact on the displacement ductility—larger plates produced better ductility. Thicker plates also improved the axial deformation capacity and ultimate load capacity.

Table 4.2: Summary of effect of plate thickness effect on retrofit

Su et al. (2012)	The thicker plates delayed the development of mid-height cracks while enhancing the strength and deformability of columns. The thickness of the precambered steel plates increased the strength of the columns more than proportional—3.5 to 4 times higher strength for a plate twice as thick.
Wang et al. (2012)	Thicker plates increased the ultimate load capacity of columns and improved axial deformation capacity of columns significantly. As eccentricity and the preloading levels rose, the increase in strength due to thicker plates was less significant.
Wang et al. (2013)	Larger plates produced better ductility. Thicker plates also improved the axial deformation capacity and ultimate load capacity.

Thicker plates enhances strength and deformability. Increasing plate thickness increases strength significantly more than proportionally.

4.2 Effect of Initial Precambering

Since the degree of precambering is a main design parameter, determining the optimum initial precambering is necessary in effectively designing the retrofit.

Su et al. (2012) evaluated how preloaded RC columns can be strengthened by precambered steel jackets under axial loading. The columns varied in plate thickness, precambering, and preloading. Controlling the precamber profile can alleviate stress-lagging effects. Increasing the precamber increases load sharing and results in higher ultimate load capacity, since plates continued to behave elastically despite concrete reaching peak capacity.

Wang et al. (2012) tested precambered steel plates on RC columns under axial loading with varying plate thicknesses, eccentricities, and initial precamber displacements. It was further confirmed that controlling the precamber profile can alleviate stress-lagging effects. Increasing initial precamber also resulted in more load sharing and higher ultimate load capacity from post-compressive stress.

Wang et al. (2013) investigated the effects precambered steel plates have on eccentrically preloaded RC columns under axial loading. This study proved again that stress lagging effects can be diminished if the precambered profile is controlled. Larger initial precambering also increased the ultimate load capacity. Displacement ductility was not significantly affected from the initial precamber.

Table 4.3: Summary of initial precambering effect on retrofit

Su et al. (2012)	Controlling the precamber profile can alleviate stress-lagging effects. Increasing the precamber increases load sharing and results in higher ultimate load capacity, since plates continued to behave elastically despite concrete reaching peak capacity.
Wang et al. (2012)	Controlling the precamber profile can alleviate stress-lagging effects. Increasing initial precamber also resulted in more load sharing and higher ultimate load capacity from post-compressive stress.
Wang et al. (2013)	Stress lagging effects can be diminished if the precambered profile is controlled. Larger initial precambering also increased the ultimate load capacity. Displacement ductility was not significantly affected from the initial precamber.

Controlling the precamber profile can alleviate stress-lagging effects, but has a minimal effect on displacement ductility. More precamber improves load sharing and higher capacity.

4.3 Effect of Eccentricity

In structures, columns are frequently eccentrically loaded with varying degrees of eccentricity. Therefore, the structural performance differences from columns with offset loading was compared for varying levels of eccentricity.

Wang et al. (2012) tested precambered steel plates on RC columns under axial loading with varying plate thicknesses, eccentricities, and initial precamber displacements. As expected, higher eccentricities produced smaller load capacities.

Wang et al. (2013) investigated the effects precambered steel plates have on eccentrically preloaded RC columns under axial loading. More eccentricity increased the midheight lateral displacement of the column, which increased the secondary moment and P-Delta effects. Therefore, eccentricity in influential in the bending-moment capacity of RC columns. Additionally, displacement ductility was not significantly affected from the eccentricity.

Table 4.4: Summary of eccentricity effect on retrofit

Wang et al. (2012)	Higher eccentricities produced smaller load capacities.
Wang et al. (2013)	More eccentricity increased the midheight lateral displacement of the column, which increased the secondary moment and P-Delta effects. Therefore, eccentricity in influential in the bending-moment capacity of RC columns. Displacement ductility was not significantly affected from the eccentricity.

Higher eccentricity results in less column capacity and increases mid-height displacement, but does not significantly affect displacement ductility.

4.4 Effect of Preloading

Often it is not possible to unload a column to install a retrofit method, so previous loading must be considered when designing the precambered steel plates.

Su et al. (2012) evaluated how preloaded RC columns can be strengthened by precambered steel jackets under axial loading. The columns varied in plate thickness, precambering, and preloading. Precambered steel plates did not experience load transfer of preloading, resulting in stress-lagging and premature failure. Further, higher preloading correlated to less plate strength utilization coefficients, meaning less ultimate load capacity.

Table 4.5: Summary of preloading effect on retrofit

Su et al. (2012)	Precambered steel plates did not experience load transfer of preloading, resulting in stress-lagging and premature failure. Higher preloading correlated to less plate strength utilization coefficients, meaning less ultimate load capacity.

More preloading results in less load transfer and less plate strength utilization.

CHAPTER 5: EXTERNAL PRE-STRESSED STEEL RETROFIT METHOD

Pre-stressing columns typically consists of wrapping steel hoops around a column and tightening them to reach a desired force. The standard profile used for pre-stressing columns is shown in Figure 5.1. The main parameters compared across studies are the spacing of the hoops, the cross-section or column shape used, and combining pre-stressed steel with other retrofit methods.

Table 5.1: Summary of pre-stressed steel retrofit parameters

Study	Spacing	Cross-section	Other methods
Saatcioglu et al. (2003)	X	X	
Fakharifar et al. (2016)			X
Ho et al. (2010)			
Lai et al. (2015)	X		X

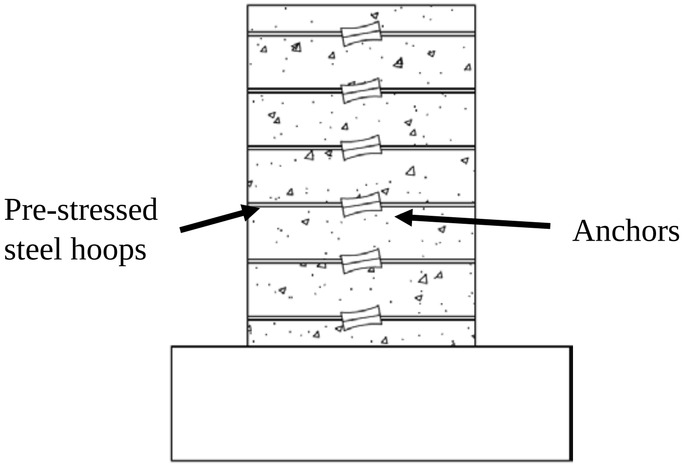


Figure 5.1: Standard profile of pre-stressed steel hoops

5.1 Effect of Spacing of Pre-stressing Hoops

Appropriately spacing pre-stressed hoops is important in providing sufficient confinement and meeting the structural demands of the columns while avoiding overdesigning the retrofit.

Saatcioglu et al. (2003) evaluated the application of pre-stressed steel hoops on square and circular columns under lateral loading. The spacing and initial pre-stressing were the main variables in the columns. Having wider spacing may provide insufficient deformability and significantly reduced the effectiveness of the method.

Lai et al. (2015) studied the effect adding pre-stressed steel hoops to concrete filled steel (CFST) columns on axial performance. The main variables analyzed were the number of steel jackets, concrete strength, pre-loading level, and jacket spacing. Providing steel jackets spaced closer together, the column can experience larger and more uniform confining stress, which delays buckling of the steel tube.

Table 5.2: Summary of effect of spacing of pre-stressing

Saatcioglu et al. (2003)	Wider spacing does not provide sufficient deformability and decreases the effectiveness of the method.
Lai et al. (2015)	Wider spacing decreased and had less uniform confinement, causing earlier buckling.

Providing closer spaced pre-stressed steel hoops is important at increasing the effectiveness of the method with less deformability, and more uniform confinement.

5.2 Effect of Cross-Section

While pre-stressed steel hoops are used most frequently on circular columns, the method can be applied to square or rectangular columns. Researchers analyzed how this is done and the efficacy of the method.

Saatcioglu et al. (2003) evaluated the application of pre-stressed steel hoops on square and circular columns under lateral loading with varying spacing and initial pre-stressing. In order to apply this method to square or rectangular columns, steel spreader frames and raiser disks must be provided to develop uniform lateral pressure.

Table 5.3: Summary of effect of cross-section

Saatcioglu et al. (2003)	Square or rectangular columns require additional equipment to attach and effectively distribute the stress from the pre-stressed steel hoops to the column.

Square or rectangular columns require additional equipment to attach and effectively distribute the stress from the pre-stressed steel hoops to the column.

5.3 Effect of Pre-stressing Combined with Other Methods

Since pre-stressed steel hoops are relatively small compared to other methods and focus on confinement, often another method is implemented along with pre-stressed hoops. Such additional methods including providing the pre-stressed steel hoops around a steel jacket and/or a concrete jacket.

Fakharifar et al. (2016) tested a combined retrofit method on severely damaged circular reinforced concrete columns under lateral loading. One column was designed to restore capacity with the steel jacket and pre-stressed hoops, while the other column was designed to improve its performance by adding a concrete jacket and anchoring it to the footing. These methods were effective at improving load transfer with anchoring the column to the footing, improving confinement both actively and passively, and remaining low in both cost and time relative to other methods.

Lai et al. (2015) studied the effect adding pre-stressed steel hoops to concrete filled steel (CFST) columns on axial performance. Preloading of the columns resulted in less improvement in strength due to stress-lagging. The combination of jacket and hop converted the end buckling failure mode to the rows between the steel hoops bulging.

Table 5.4: Summary of effect of pre-stressing combined with other methods

Fakharifar et al. (2016)	Providing hoops with a steel jacket was effective at restoring the capacity of a damaged column, while adding a concrete jacket and anchorage to the footing enabled improved capacity.
Lai et al. (2015)	CFST columns with pre-stressed steel hoops can mitigate against end buckling and improve axial performance.

Providing hoops with a steel jacket was effective at restoring the capacity of a damaged column, while adding a concrete jacket and anchorage to the footing enabled improved capacity. CFST columns with pre-stressed steel hoops can mitigate against end buckling and improve axial performance.

CHAPTER 6: OTHER RETROFIT METHODS

6.1 Fiber-Reinforced Polymer Retrofit Method

Fiber-reinforced polymers (FRP) are not within the scope of this research; however, a summary of their use is presented. Triantafillou (2001) described key behavior and design aspects for FRP. For flexural members, FRP resists tensile forces from its internal strain, which is a function of the failure mode, axial rigidity, and type of FRP as well as the strength of the column. Similar to its function with tensile forces, FRP's effectiveness in confinement depends on the jacket characteristics, but is less effective for rectangular columns, due to confining stress being transferred through the corners of the cross-section. FRP is particularly good at developing sufficient ductility enhancement for plastic hinge regions and at preventing lap-splice failure if sufficient lateral pressure is applied. In terms of practicality, FRP wrapping takes little time, and takes up a minimal amount of space.

6.2 Shape Memory Alloy Retrofit Method

Ozbulut et al. (2011) focused on the efficacy of shape memory alloys (SMAs) on reinforced concrete column retrofit. SMAs rely on alloys that can exist in multiple states based on stress and temperature. Once applied to a column, it can undergo high stress and have temporary deformation, but once heat is applied to it, the alloy will deform back to its original shape. As a result, SMAs have great energy dissipation and recovery capacity, but the high cost and limited amount research on them have prevented their implementation.

CHAPTER 7: CONCLUSIONS

Each retrofit method functions uniquely and their benefits are based on column specifics, but some generalizations on performance can be made. While intuitively, unloading may be preferable, the benefits are minimal for the confinement methods—reinforced concrete jacketing, steel jacketing and steel caging. Additionally, some studies had conflicting accounts, but generally loading the entire cross-section for reinforced concrete jackets is desirable by extending the reinforced concrete jacket the full height of the column, because it enables the capacity of the jacket to be used earlier. Meanwhile, the steel confinement methods should not extend the full height of the column to avoid placing the steel under excessive stress. Meanwhile, retrofitting circular columns, for all the methods including FRP, generally resulted in more monolithic behavior than for square or rectangular columns due to confinement.

Reinforced concrete jackets generally perform well under axial loading, particularly due to the large increase in area. However, they can also perform well under lateral loading. Shear connectors and dowels are more important for reinforced concrete jackets under lateral loading to improve force transfer from the column to the jacket.

For reinforced concrete jackets, the reinforcement provided is important, particularly in lateral loading. Ductility and strength is directly impacted by jacket transverse reinforcement, with spiral rebar performing the best versus WWF and horizontal transverse reinforcement. However, increasing longitudinal reinforcement past ACI’s recommendations is unnecessary and does not have a notable effect.

Cross-sections are another important consideration for retrofitting columns. For all the methods, it is important to choose the appropriate shape for the column retrofit. For concrete and steel jackets, it is highly preferable to provide a complete jacket around the entire column, rather than only on one or two sides. Not only does this increase the capacity, but it also mitigates against potential problems with the interface. Energy dissipation also improves with complete jackets for reinforced concrete jacketing. For steel jackets, octagonal jackets result in better performance than elliptical jackets on rectangular columns. For steel cages, angles with batten plates connecting them increased strength the most given the same amount of steel used compared to using channels or plates. This is because the angles could be slightly thicker and buckling in a major concern with steel jackets and cages.

Steel plate thickness functions differently for different methods. Increasing the thickness for steel jackets results in approximately a linear increase in peak strength, while increasing thickness for precambered steel plates results in a significantly larger increase—around four times higher strength.

Spacing of pre-stressed steel hoops installed on a column are very important for the increasing the existing column's strength with less deformability and more uniform confinement. Due to their limitations focused on confinement, the pre-stressed steel hoops are often provided with another method, such as steel or concrete jackets to further improve performance.

The summary tables below discuss the primary findings from each method and parameter. While these results are based on findings from a plethora of articles and studies, individual decisions for the optimum method should be made based on a case-by-case basis and being cognizant of the constraints of the site.

Table 7.1: Summary of reinforced concrete jacketing effects

Parameter	Result
Interface	Dowels or shear connectors generally transfer loads best.
Loading	Loading the whole cross-section at the top results in higher strength.
Cross-section	Circular jacketed columns behaved more monolithically due to better confinement.
Reinforcement	Ductility is directly impacted by jacket transverse reinforcement. Spiral rebar increased capacity the best versus horizontal rebar and WWF. Increasing the amount of longitudinal reinforcement may not have a significant impact on the jacket capacity.

Table 7.2: Summary of steel jacket effects

Parameter	Result
Plastic-Hinge	Providing continuous reinforcement, or longer steel jackets and additional confinement with anchor bolts can result in higher capacity in the plastic hinge regions.
Interface	Adhesives are undesirable, except for with partial steel jackets.
Connections	Whole jackets produce better full plastic deformation than split jackets.
Jacket sizing	Jacket thickness and peak strength have a nearly linear relationship. Thin steel plates may have problems due to ductility or buckling.
Cross-section	Octagonal versus elliptical steel jackets are preferable both structurally and practically for rectangular columns.
Loading	The jackets tested can improve capacity in both strength and weak directions.

Table 7.3: Summary of steel cage effects

Parameter	Result
Interface	Better friction between the steel cage and mortar can improve load transmission and column strength.
Cage Sizing	Larger angles increase confinement, but decreases load transfer. Larger strips can improve confinement and load transfer. Batten plate sizing is dependent upon the cross-section used.
Cross-Section	Angles and channels performed similarly and were a better alternative to steel plates.
Loading	Unloading had a small effect on strength and performance of the column.

Table 7.4: Summary of precamber effects

Parameter	Result
Plate Thickness	Increasing plate thickness increases strength significantly more than proportionally, and also increases ductility.
Initial Precambering	Controlling the precamber profile can alleviate stress-lagging effects
Eccentricity	More eccentricity in loading results in less column capacity and increases mid-height displacement, but does not significantly affect displacement ductility.
Preloading	More preloading results in less load transfer and less plate strength utilization.

Table 7.5: Summary of pre-stressing effects

Parameter	Result
Spacing	Closer spaced pre-stressed steel hoops are important at increasing the effectiveness of the method with less deformability and more uniform confinement.
Cross-Section	Square or rectangular columns require additional equipment to attach and effectively distribute the stress from the pre-stressed steel hoops to the column.
Method Combination	Providing hoops with a steel jacket was effective at restoring the capacity of a damaged column. Adding a concrete jacket and anchorage to the footing improved capacity.

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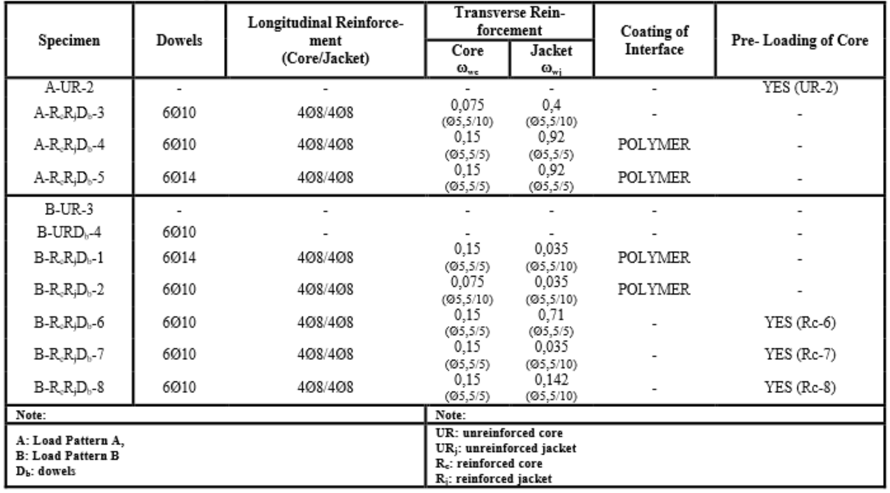
Appendix A: Reinforced Concrete Jacketing One-Pagers

Achillopoulou, D. V., Pardalakis, T. A., and Karabinis, A. I. (June 12, 2013b). Study of the Behavior of RC Columns Strengthened with RC Jackets Containing Dowels and Different Confinement Ratios. 4th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering.

Significance:
Achillopoulou et al. examined the force transfer mechanism of bent down welded steel bars in 6 square columns. Different concrete strengths, transverse reinforcement ratios, and confinement ratios were used. Two axial load patterns are used to simulate real loads and analyze the P-delta effects, energy absorbed, and ductility achieved. Five columns were coated with a resin without solvents for better adhesion, while four columns were coated with synthetic polymer sheets to minimize friction.

Loading/beam Images:

Specimen Details

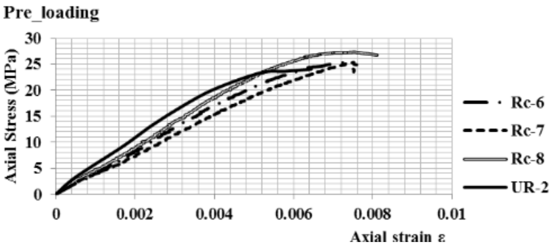


Specimen	Dowels	Longitudinal Reinforcement (Core/Jacket)	Transverse Reinforcement		Coating of Interface	Pre- Loading of Core
			Core ω_{wc}	Jacket ω_{wj}		
A-UR-2	-	-	-	-	-	YES (UR-2)
A-R$_c$R$_j$D$_b$-3	6Ø10	4Ø8/4Ø8	0,075 (Ø5,5/10)	0,4 (Ø5,5/10)	-	-
A-R$_c$R$_j$D$_b$-4	6Ø10	4Ø8/4Ø8	0,15 (Ø5,5/5)	0,92 (Ø5,5/5)	POLYMER	-
A-R$_c$R$_j$D$_b$-5	6Ø14	4Ø8/4Ø8	0,15 (Ø5,5/5)	0,92 (Ø5,5/5)	POLYMER	-
B-UR-3	-	-	-	-	-	-
B-URD$_b$-4	6Ø10	-	-	-	-	-
B-R$_c$R$_j$D$_b$-1	6Ø14	4Ø8/4Ø8	0,15 (Ø5,5/5)	0,035 (Ø5,5/10)	POLYMER	-
B-R$_c$R$_j$D$_b$-2	6Ø10	4Ø8/4Ø8	0,075 (Ø5,5/10)	0,035 (Ø5,5/10)	POLYMER	-
B-R$_c$R$_j$D$_b$-6	6Ø10	4Ø8/4Ø8	0,15 (Ø5,5/5)	0,71 (Ø5,5/5)	-	YES (Rc-6)
B-R$_c$R$_j$D$_b$-7	6Ø10	4Ø8/4Ø8	0,15 (Ø5,5/5)	0,035 (Ø5,5/10)	-	YES (Rc-7)
B-R$_c$R$_j$D$_b$-8	6Ø10	4Ø8/4Ø8	0,15 (Ø5,5/5)	0,142 (Ø5,5/10)	-	YES (Rc-8)

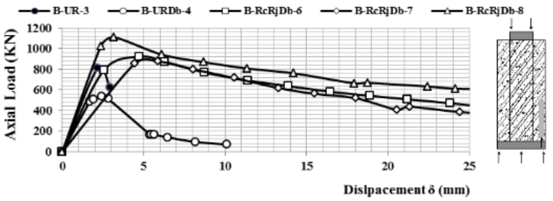
Note:
A: Load Pattern A,
B: Load Pattern B
D$_b$: dowels

Note:
UR: unreinforced core
UR$_j$: unreinforced jacket
R$_c$: reinforced core
R$_j$: reinforced jacket

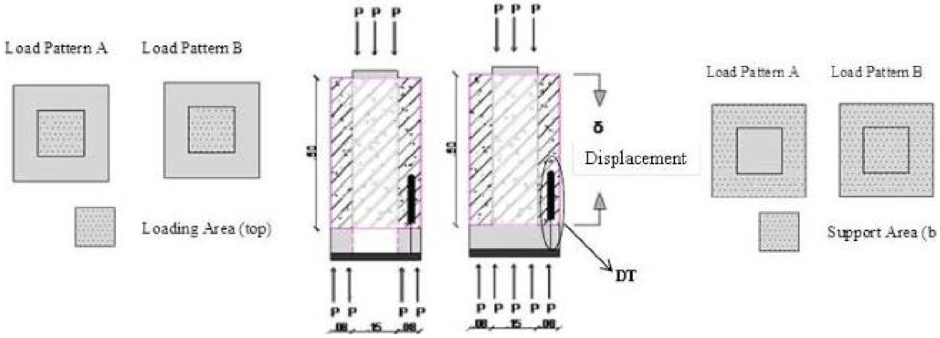
Axial Stress-Strain for Pre-loading



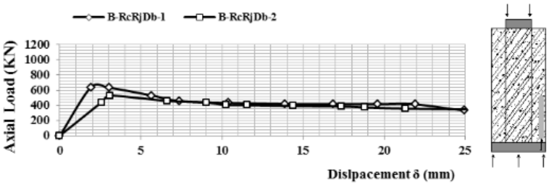
Displacement vs Axial Load for Load B



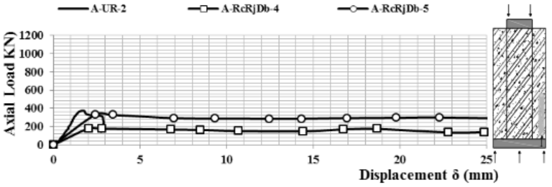
Load Pattern Shapes



Dowel Action



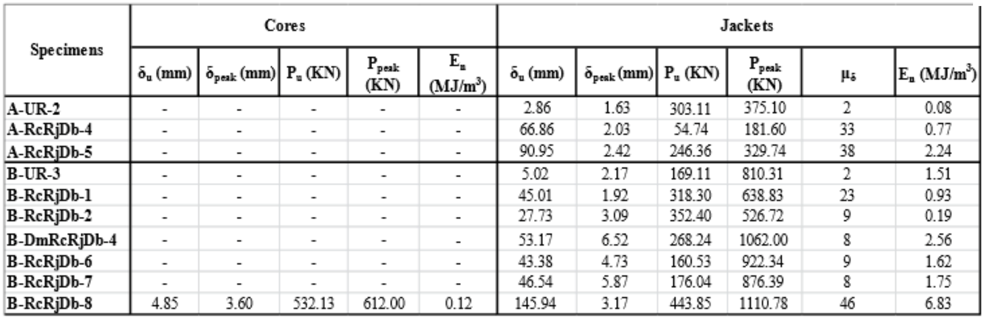
Displacement vs Axial Load for Load A



Load Pattern A is used to estimate the effect of load transfer from the core to the jacket through having the bottom of the column supported on the bottom only by the jacket area.

Results:

Experimental Results



Specimens	Cores					Jackets					
	δ_u (mm)	δ_{peak} (mm)	P_u (KN)	P_{peak} (KN)	E_u (MJ/m^3)	δ_u (mm)	δ_{peak} (mm)	P_u (KN)	P_{peak} (KN)	μ_δ	E_u (MJ/m^3)
A-UR-2	-	-	-	-	-	2.86	1.63	303.11	375.10	2	0.08
A-RcRjDb-4	-	-	-	-	-	66.86	2.03	54.74	181.60	33	0.77
A-RcRjDb-5	-	-	-	-	-	90.95	2.42	246.36	329.74	38	2.24
B-UR-3	-	-	-	-	-	5.02	2.17	169.11	810.31	2	1.51
B-RcRjDb-1	-	-	-	-	-	45.01	1.92	318.30	638.83	23	0.93
B-RcRjDb-2	-	-	-	-	-	27.73	3.09	352.40	526.72	9	0.19
B-DmRcRjDb-4	-	-	-	-	-	53.17	6.52	268.24	1062.00	8	2.56
B-RcRjDb-6	-	-	-	-	-	43.38	4.73	160.53	922.34	9	1.62
B-RcRjDb-7	-	-	-	-	-	46.54	5.87	176.04	876.39	8	1.75
B-RcRjDb-8	4.85	3.60	532.13	612.00	0.12	145.94	3.17	443.85	1110.78	46	6.83

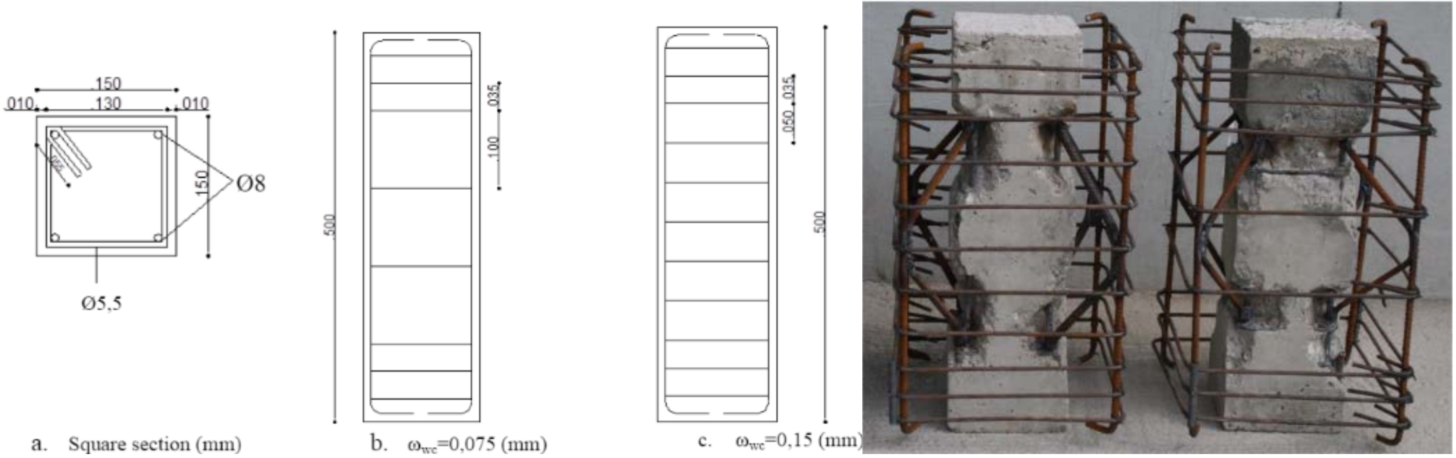
Effectiveness of the Method:
Initial damages affect the column behavior and capacity of shear mechanism. Load transferred to the jacket in similar ways for both load patterns. Initial damages did not affect the ability of the retrofitted column to act monolithic. Jacket transverse reinforcement and the dowel action performed differently for the different load patterns. The presence of dowels impacts the maximum load minimally, but increases slip resistance. Earlier failure occurs as a result of damaged areas spreading from dowels. The column with the densest stirrups achieved the highest axial load capacity increase.

Achillopoulou, D. V., Pardalakis, T. A., and Karabinis, A. I. (June 12, 2013a). Investigation of Force Transfer Mechanisms in Retrofitted RC Columns with RC Jackets Containing Welded Bars Subjected to Axial Compression. 4th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering

Significance:
Six square columns were tested with different transverse reinforcement ratios and confinement ratios. Columns were repaired after maximum load with high strength concrete. An axial loading pattern is simulated on half-scale columns.

Loading and Images:

Section and Transverse Reinforcement of Original Columns



a. Square section (mm) b. ω_{wc}=0,075 (mm) c. ω_{wc}=0,15 (mm)

Specimen Details

Specimen	Dowels	Bend down bars	Longitudinal Reinforcement (Core/Jacket)	Transverse Rein-forcement		Pre- Loading of Core
				Core ω_{wc}	Jacket ω_{wj}	
B-R$_c$R$_j$D$_w$ -9	-	4Ø8	4Ø8/4Ø8	0,15 (Ø5,5/50)	0,035 (Ø5,5/100)	Repeated (Rc-9)
B-R$_c$R$_j$D$_w$-10	-	4Ø10	4Ø8/4Ø8	0,075 (Ø5,5/100)	0,035 (Ø5,5/100)	-
B-R$_c$R$_j$D$_w$-11	-	4Ø10	4Ø8/4Ø8	0,15 (Ø5,5/50)	0,071 (Ø5,5/50)	-
B-R$_c$R$_j$D$_w$-12	-	4Ø10	4Ø8/4Ø8	0,075 (Ø5,5/100)	0,035 (Ø5,5/100)	YES (Rc-6)
B-R$_c$R$_j$D$_w$-13	-	4Ø8	4Ø8/4Ø8	0,15 (Ø5,5/50)	0,035 (Ø5,5/100)	YES (Rc-7)
B-R$_c$R$_j$D$_b$D$_w$-14	6Ø10	4Ø10	4Ø8/4Ø8	0,15 (Ø5,5/50)	0,071 (Ø5,5/50)	YES (Rc-8)
Note:						
A: Load Pattern A, **B: Load Pattern B** **D$_b$: dowels** **D$_w$: bend down bars (welded)**				**UR: unreinforced core** **UR$_j$: unreinforced jacket** **R$_c$: reinforced core** **R$_j$: reinforced jacket**		

Results:

Test Results

Specimens	Cores					Jackets					
	δ_u (mm)	δ_{peak} (mm)	P_u (KN)	P_{peak} (KN)	E_n (MJ/m^3)	δ_u (mm)	δ_{peak} (mm)	P_u (KN)	P_{peak} (KN)	μ_δ	E_n (MJ/m^3)
B-RcRjDw-9	4.65	4.25	537.08	599.18	0.10	87.98	1.58	207.95	1127.72	56	2.96
B-RcRjDw-10	-	-	-	-	-	121.76	2.09	236.00	793.21	58	3.66
B-RcRjDw-11	-	-	-	-	-	54.14	2.48	235.50	1055.75	22	2.26
B-RcRjDw-12	-	-	-	-	-	48.20	2.15	271.54	1016.86	22	1.70
B-RcRjDw-13	-	-	-	-	-	108.84	2.63	537.65	1158.68	41	3.44
B-RcRjDbDw-14	4.82	3.59	568	613.4	0.18	131.56	2.41	126.54	1053.48	55	5.34

Effectiveness of the Method:
Welded bars of larger diameter buckle earlier and bear less load, but all transfer loads to new concrete due to confinement. The buckling from larger welds to smaller reinforcement bars results in smaller maximum loads and less stiffness. Dowel action increases jacketed column capacity to transfer load.

Achillopoulou D., Pardalakis T., and Karabinis A. (December 01, 2014). Interface Capacity of Repaired Concrete Columns Strengthened with RC Jackets. Transactions of the Všb: Technical University of Ostrava, Civil Engineering Series, 14, 2, 129-145

Significance:
Achilloppoulou et al. examined how initial construction deficiencies and different anchors affect the ability to transfer loads at the interface of the RC jacket and the column. Sixteen 1:2 scale columns were tested with such deficiencies. Realistic loads are simulated and applied directly to the column, which transfers load to the jacket. The variables were initial construction damage, stirrup spacing, interface reinforcement type, and load pattern influence.

Loading/beam Images:

Specimen Characteristics

				Connectors		
Specimens	Construction damages	ω_{wc}	ω_{wj}	Dowels	Welded bend down bars	Load Pattern
$B\text{-}D_mR_cR_j\text{-}3$	√	0.15	0.035	-	-	*B*
$B\text{-}R_cR_jD_b\text{-}7$	-	0.15	0.035	6Φ10	-	*B*
$B\text{-}R_cR_jD_w\text{-}9$	-	0.15	0.035	-	4Φ8	*B*
$B\text{-}D_mR_cR_jD_b\text{-}4$	√	0.15	0.142	6Φ10	-	*B*
$B\text{-}R_cR_jD_b\text{-}8$	-	0.15	0.142	6Φ10	-	*B*
$D\text{-}D_mR_cR_jD_b\text{-}5$	√	0.15	0.035	6Φ10	-	*D*
$D\text{-}R_cR_jD_b\text{-}6$	-	0.15	0.035	6Φ10	-	*D*
$D\text{-}R_cR_jD_w\text{-}7$	-	0.15	0.035	-	4Φ8	*D*
Note:						
B/*D*: Load Pattern Shape		D_m: Construction Damages			D_b: Dowel bar	
R_c: Reinforced core		R_j: Reinforced jacket			D_w: Welded bar	

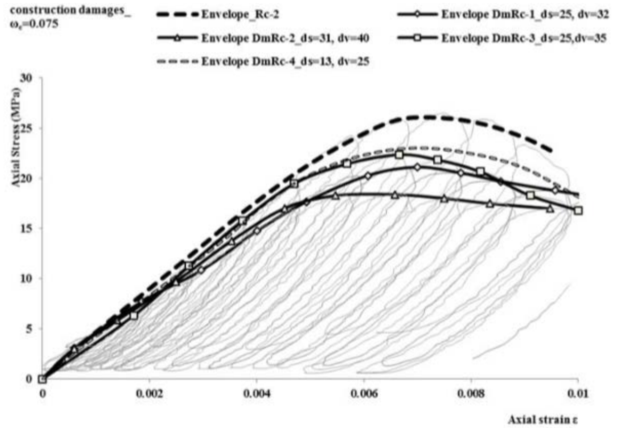
Damage Indices of Specimen Cores

Specimen	ω_{wc}	ω_{wj}	d_s (%)	d_v (%)
R_c-2	0.075	-	-	-
D_mR_c-1	0.075	25	10	32
D_mR_c-2	0.075	31	14	40
D_mR_c-3	0.075	25	14	35
D_mR_c-4	0.075	13	14	25
R_c-1	0.15	-	-	-
D_mR_c-1	0.15	25	20	40
D_mR_c-3	0.15	13	24	34
D_mR_c-4	0.15	25	28	46
D_mR_c-5	0.15	37	26	54
D_mR_c-6	0.15	31	22	46
ω_{wc}= mechanical percentage of stirrups				

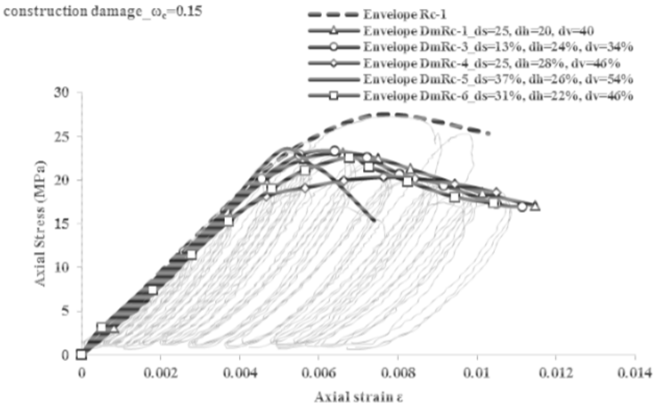
Load Pattern B is only loaded at the column at the top, whereas D loads the jacket as well. Both load the entire section on the bottom.

Results:

Construction Damage on Columns with Low Ductility



Construction Damage Effect on Columns with Sufficient Ductility



Results of Retrofitted Specimens

	Cores				Jackets			
Specimens	δ_{peak} (mm)	δ_u (mm)	P_{peak} (kN)	E_{ntot} (MJ/m³)	δ_{peak} (mm)	δ_u (mm)	P_{peak} (kN)	E_{ntot} (MJ/m³)
$B\text{-}D_mR_cR_j\text{-}3$	3.25	4.92	525.49	0.13	3.78	52.23	814.22	1.79
$B\text{-}R_cR_jD_b\text{-}7$	3.50	3.50	533.00	0.13	2.50	44.60	876.38	1.90
$B\text{-}R_cR_jD_w\text{-}9$	4.65	4.25	599.18	0.10	1.58	87.98	1127.72	2.96
$B\text{-}D_mR_cR_jD_b\text{-}4$	3.90	5.45	441.90	0.18	6.20	50.95	1062.98	2.90
$B\text{-}R_cR_jD_b\text{-}8$	3.60	4.85	612.00	0.12	3.17	145.94	1110.78	6.83
$D\text{-}D_mR_cR_jD_b\text{-}5$	7.00	10.00	553.29	0.15	3.75	36.00	2111.24	0.70
$D\text{-}R_cR_jD_b\text{-}6$	-	.	-	-	4.73	43.38	922.34	1.62
$D\text{-}R_cR_jD_w\text{-}7$	-	.	-	-	5.87	46.54	876.39	1.75
Note:	δ_{peak}: deformation corresponding to peak load							
	δ_u: deformation corresponding to 20% of the peak load							
	P_{peak}: peak load (maximum presented load)							
	E_{ntot}: total absorbed energy							

Even when the jacket is designed to be full height, the jacket shrinks a little, causing the load to be directly applied to the column only.

Effectiveness of the Method:
The maximum resistance load and dissipated energy of the initially damaged specimens decreased. Surpassing a certain level of damage, repaired columns could not reach a certain strain capacity. Welded bars lead to buckling of longitudinal bars and reduction of secant stiffness, but increase the initial stiffness of the column. Loading the entirety of the cross-section directly enables larger maximum load since its confinement capacity starts to act immediately. Dowels increase the maximum load on a damaged column and create a plastic region around the connection bar resulting in failure and high displacement values.

Bett, B.J., Klinger R.E, and Jirsa, J.O. 1988. "Lateral Load Response of Strengthened and Repared Reinforced Concrete Columns," ACI Structural Journal, V.85, No.5, Pp. 499-508.

Significance

The study focused on the behavior of short column repaired/retrofitted by reinforced concrete jacketing. Test specimen were subjected to constant axial load with cyclic loading. Results of the test revealed that the repaired column behaved analogous to retrofitted specimens 2 and 3. However, retrofitted specimen exhibited combined shear and flexure failure, while the as built and repaired specimen presented shear failure.

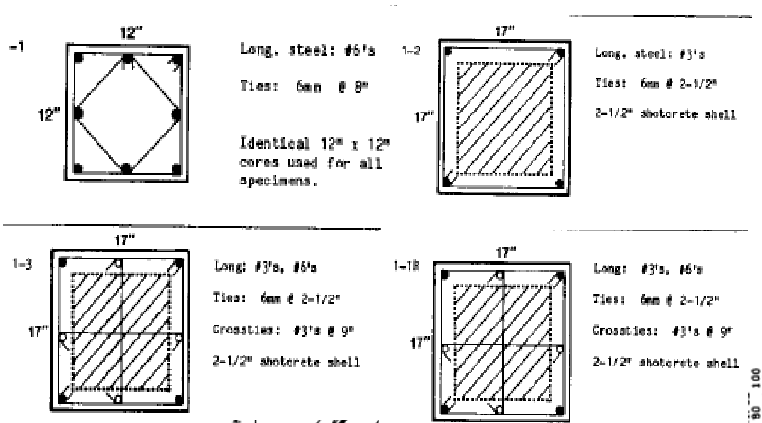
Test Results

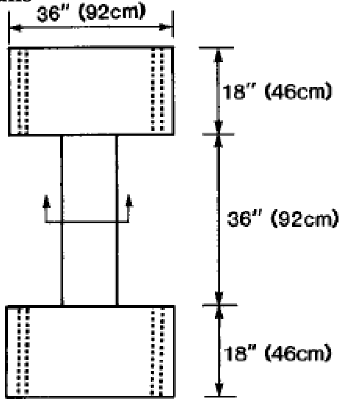
Column Designation	Maximum Load (kN)	Yield Disp (mm)	Max Disp (mm)	Displacement Ductility (predicted)
1-1	47	0.2	0.6	3.2
1-2	97	0.3	0.8	2.4
1-3	95	0.3	0.8	2.4
1-1R	90	0.4	0.9	2.3

Details of Original Specimen

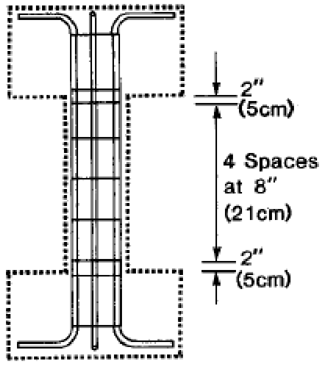
Yield strength of longitudinal reinforcement	67 ksi
Yield strength of Transverse reinforcement	60 ksi
Concrete strength	3.83 ksi
Concrete strength (jacket)	4.69 ksi

Column Details

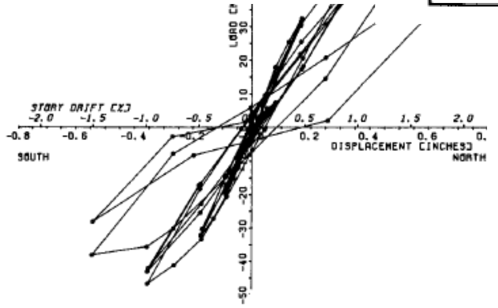




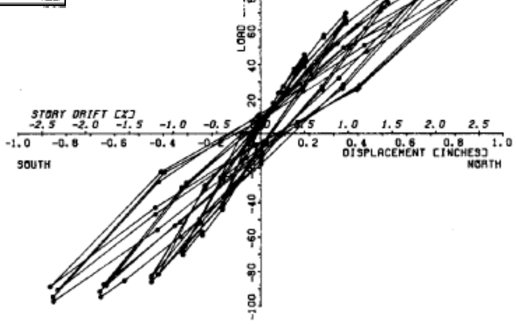
Elevation



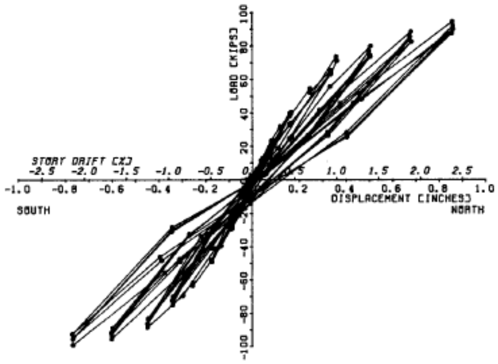
Reinforcement



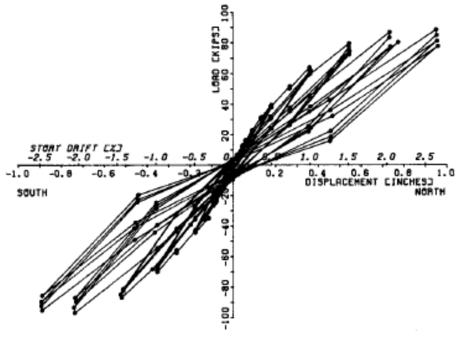
Specimen 1-1



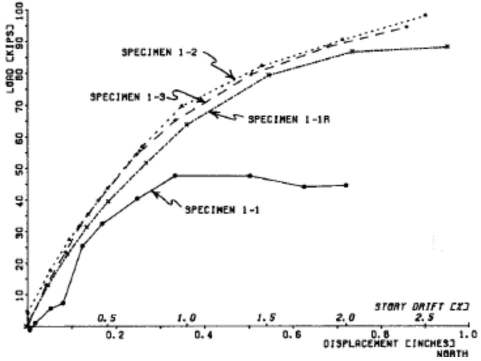
Specimen 1-2



Specimen 1-3



Specimen 1-1R



Comparison of Envelopes

Effectiveness of Method

Shear capacity of the original column was increased to avoid a brittle failure, but the flexural bars did not yield. Assuming complete compatibility between the jacket and the column, the lateral capacity can be reliably predicted. Additional midface longitudinal bars in the jacket did not significantly affect the stiffness or strength of the column under monotonic loading, but improved both under cyclical lateral loading. Repairing a badly damaged column with the same jacket as an undamaged column resulted in nearly the same strength and stiffness.

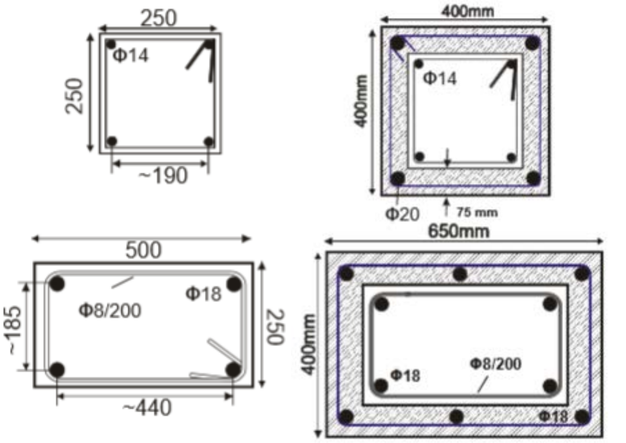
Bousias, S., Spathis, A., and Fardis, M. N. (August 01, 2004). Seismic Retrofitting of Columns with Lap-Splices via RC Jackets. 13th World conference on Earthquake Engineering.

Significance:

The effectiveness of rectangular RC columns with poor seismic detailing, particularly with lap-splicing, retrofitted using RC jackets was analyzed. 14 approximately half-scale columns with typical design and detailing of old RC buildings with insufficient seismic capacity were tested. Square and rectangular columns were tested. Cyclical tests were performed on four cantilever columns with smooth bars and hooked ends. The type of longitudinal reinforcement (smooth or ribbed) varied at the base of the column.

Loading Images:

Column Cross-Sections



Specimen Characteristics

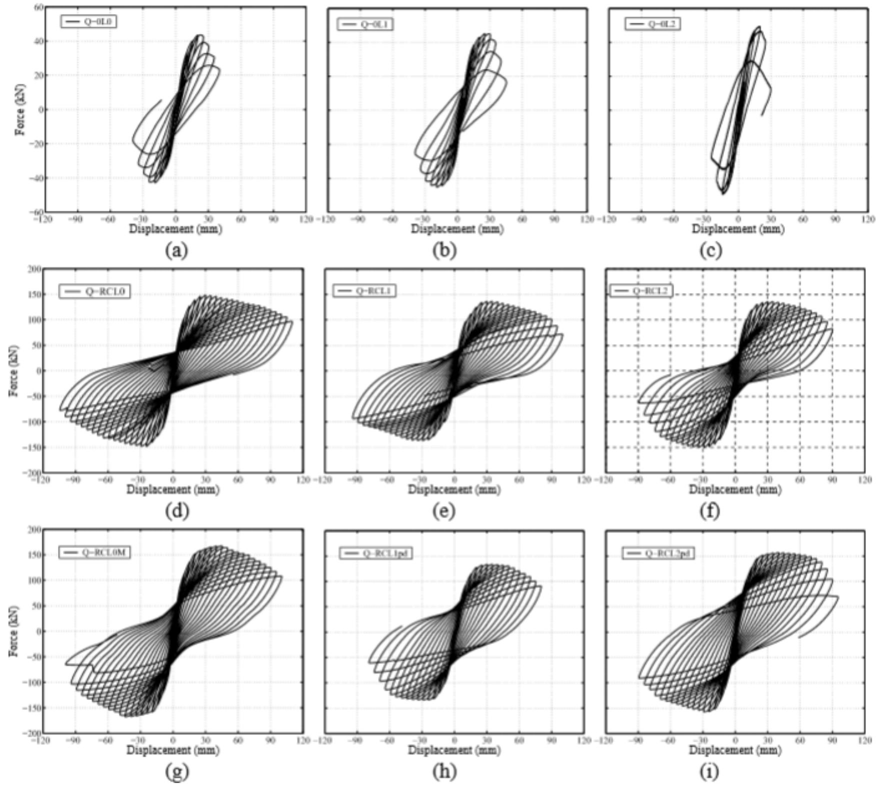
Specimen	Lapping	Concrete strength f_c in original column (MPa)	Jacket concrete strength f_c (MPa)	Axial load ratio $v=N/A_cf_c$ in original column	Axial load ratio $v=N/A_cf_c$ in jacketed column[2]	Yield moment with P-Δ (kNm)	Drift at "failure" (%)	Max. drift attained in test (%)
Q-0L0	-	27.0	-	0.44	-	73.8	2.2	2.5
Q-0L1	$15d_b$	30.3	-	0.41	-	82.4	2.5	2.8
Q-0L2	$25d_b$	30.3	-	0.42	-	81.3	1.6	1.9
Q- RCL0	-	26.3	55.8	0.35	0.079	244.5	5.3	7.2
Q- RCL0M[1]	-	30.6	-	0.18	0.18	262.4	5.3	6.2
Q-RCL1	$15d_b$	27.5	55.8	0.35	0.084	223.8	5.6	6.2
Q-RCL2	$25d_b$	25.6	55.8	0.38	0.084	227.0	5.3	5.6
Q-RCL1pd	$15d_b$	28.1	20.7	0.38	0.25	212.0	4.4	5.0
Q-RCL2pd	$25d_b$	28.6	20.7	0.40	0.27	254.4	5.3	5.9
R-0L0	-	31.0	-	0.26	-	306.4	2.5	2.8
R-0L1	$15d_b$	18.0	-	0.23	-	230.9	1.9	2.8
R-0L3	$30d_b$	18.0	-	0.28	-	287.0	1.9	3.1
R-0L4	$45d_b$	18.0	-	0.28	-	281.0	2.5	2.8
R-RCL1	$15d_b$	36.7	55.8	0.21	0.066	545.2	4.2	4.8
R-RCL3	$30d_b$	36.8	55.8	0.21	0.066	572.8	3.8	4.5
R-RCL4	$45d_b$	36.3	55.8	0.16	0.052	532.1	4.7	5.1

[1] Specimen Q- RCL0M, has similar geometry and reinforcement as the final jacketed column Q-RCL0, but was constructed as monolithic.

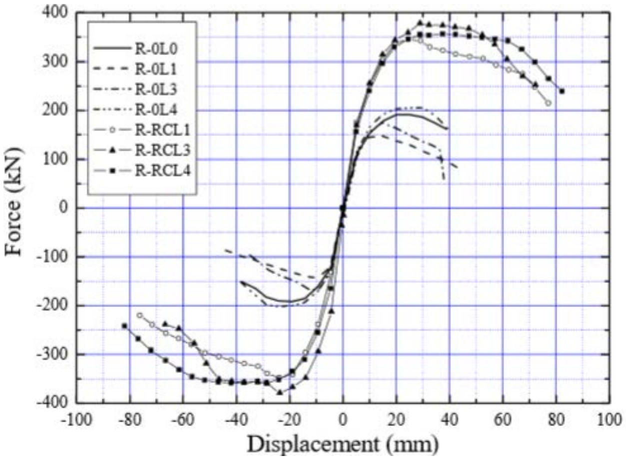
[2] The axial load ratio of the jacketed column is calculated on the basis of the concrete strength of the jacket

Results:

Q-type Columns Curves: (a) Q-0L0, (b) Q-0L1, (c) Q-0L2; (d) Q-RCL0, (e) Q-RCL1, (f) Q-RCL2; (g) monolithic Q-RCL0M; (h) pre-damaged jacketed Q-RCL1pd, (i) pre-damaged jacketed Q-RCL2pd



Comparison of Envelope Curves in Type-R Columns



Effectiveness of the Method:

Concrete jackets effectively remove the negative effects of lap-splicing straight ribbed bars even for short lap lengths. A lap-length of 15-bar diameters is enough to transfer the forces to the hooked ends. This RC jacket was as effective at repairing and retrofitting the columns with smooth bar lap splices cyclically damaged as for an undamaged column. Lapping is at least 45-bar diameters for columns with ribbed bars at the base results in acceptable cyclic deformation capacity and energy dissipation. Lapping only 15-bar diameters results in diminished flexural resistance, degradation of post-peak strength and stiffness, and low energy dissipation capacity.

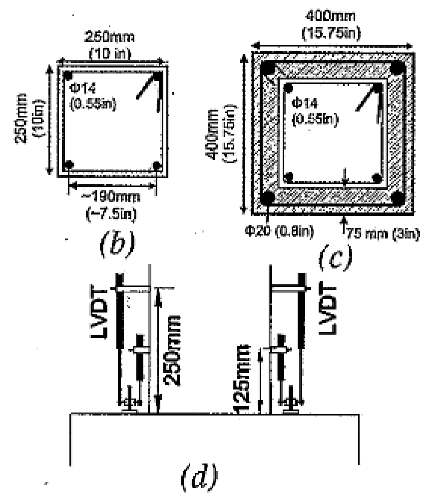
Bousias, S. N., Biskinis, D. E., and Fardis, M. N. (September 01, 2007a). Strength, Stiffness and Cyclic Deformation Capacity of Concrete Jacketed Members. ACI Structural Journal, 104, 5, 521-531.

Significance:

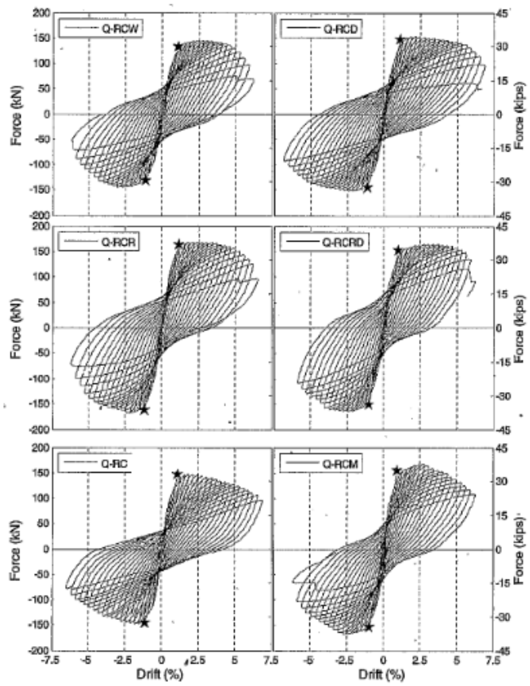
Bousias et al. examined the effect of using different connection means of shotcrete jackets on columns with no earthquake details. Test results are compared with other test results. Rules for calculating the yield moment, drift at yielding, secant-to-yield stiffness, and ultimate drift in cyclically loaded columns were developed. One control monolithic column and five columns with a 3 in jacket are tested.

Loading/beam Images:

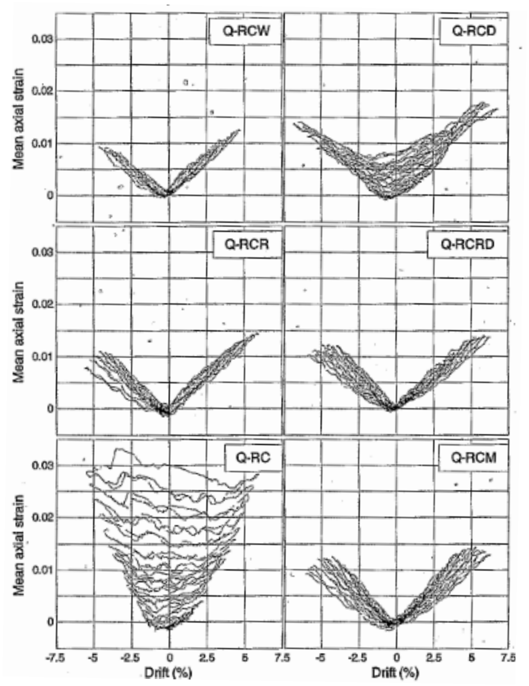
Cross-section of Columns



Force-Drift Loops of Columns

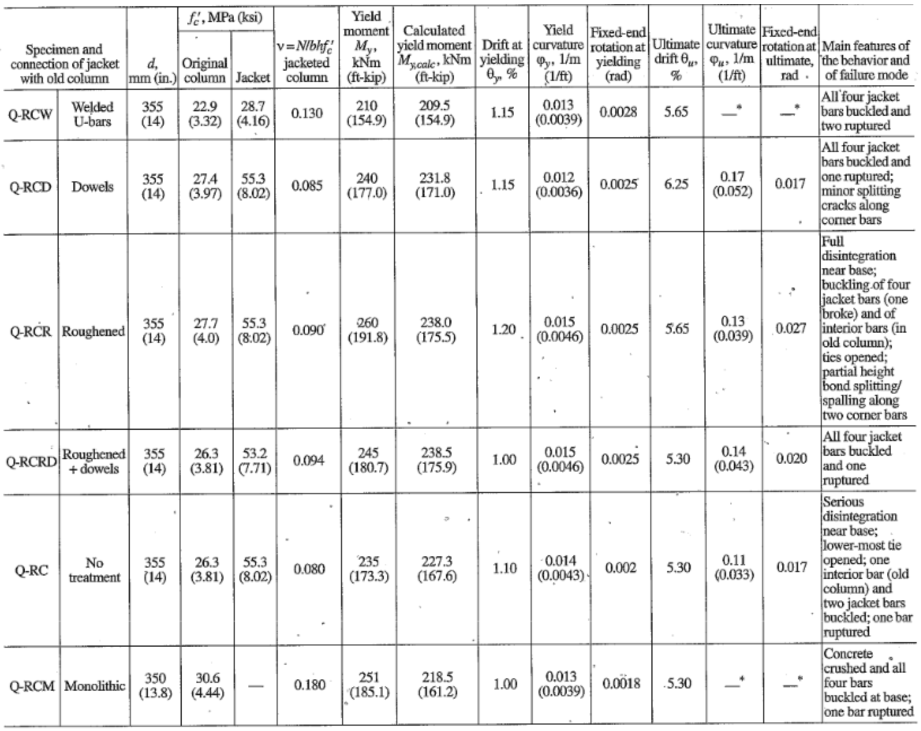


Mean Vertical Strain at Center with Drift



Results:

Jacketed Columns Parameters and Results



Specimen and connection of jacket with old column		d, mm (in.)	f_c', MPa (ksi)		$\nu = N/bhf_c'$ jacketed column	Yield moment M_y, kNm (ft-kip)	Calculated yield moment $M_{y,calc}$, kNm (ft-kip)	Drift at yielding θ_y, %	Yield curvature φ_y, 1/m (1/ft)	Fixed-end rotation at yielding (rad)	Ultimate drift θ_u, %	Ultimate curvature φ_u, 1/m (1/ft)	Fixed-end rotation at ultimate, rad	Main features of the behavior and of failure mode
			Original column	Jacket										
Q-RCW	Welded U-bars	355 (14)	22.9 (3.32)	28.7 (4.16)	0.130	210 (154.9)	209.5 (154.9)	1.15	0.013 (0.0039)	0.0028	5.65	—*	—*	All four jacket bars buckled and two ruptured
Q-RCD	Dowels	355 (14)	27.4 (3.97)	55.3 (8.02)	0.085	240 (177.0)	231.8 (171.0)	1.15	0.012 (0.0036)	0.0025	6.25	0.17 (0.052)	0.017	All four jacket bars buckled and one ruptured; minor splitting cracks along corner bars
Q-RCR	Roughened	355 (14)	27.7 (4.0)	55.3 (8.02)	0.090	260 (191.8)	238.0 (175.5)	1.20	0.015 (0.0046)	0.0025	5.65	0.13 (0.039)	0.027	Full disintegration near base; buckling of four jacket bars (one broke) and of interior bars (in old column); ties opened; partial height bond splitting/spalling along two corner bars
Q-RCRD	Roughened + dowels	355 (14)	26.3 (3.81)	53.2 (7.71)	0.094	245 (180.7)	238.5 (175.9)	1.00	0.015 (0.0046)	0.0025	5.30	0.14 (0.043)	0.020	All four jacket bars buckled and one ruptured
Q-RC	No treatment	355 (14)	26.3 (3.81)	55.3 (8.02)	0.080	235 (173.3)	227.3 (167.6)	1.10	0.014 (0.0043)	0.002	5.30	0.11 (0.033)	0.017	Serious disintegration near base; lower-most tie opened; one interior bar (old column) and two jacket bars buckled; one bar ruptured
Q-RCM	Monolithic	350 (13.8)	30.6 (4.44)	—	0.180	251 (185.1)	218.5 (161.2)	1.00	0.013 (0.0039)	0.0018	5.30	—*	—*	Concrete crushed and all four bars buckled at base; one bar ruptured

Effectiveness of the Method:

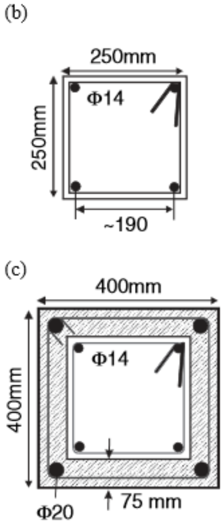
The differing jacket to column connections did not have a significant effect on the yield moment and effective stiffness of the columns. However, The benefits of dowels and surface roughening were cancelled out when both were applied to a column together. Due to comparison with previous tests, the external dimensions and jacket reinforcement should be used to calculate the shear resistance.

Bousias, S., Spathis, A.-L., and Fardis, M. N. (September 01, 2007b). Seismic Retrofitting of Columns with Lap Spliced Smooth Bars Through FRP or Concrete Jackets. Journal of Earthquake Engineering, 11, 5.)

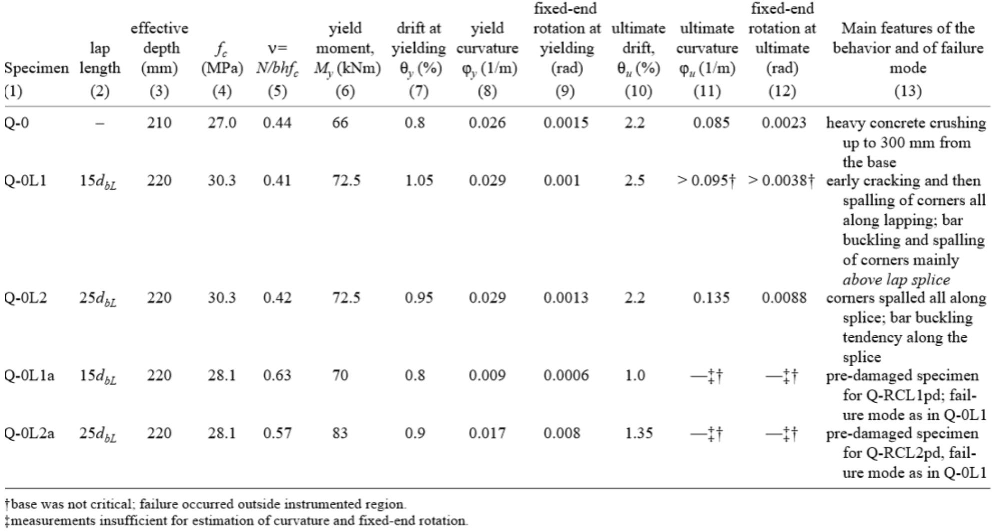
Significance:
The focus of this paper was on evaluating the effectiveness of RC jackets or FRP wrapping under seismic loading. 6 RC jacketed columns were tested cyclically up to deformation.

Loading/Images:

Cross-Sections of Original and RC-Jackets



Unretrofitted Columns: Test Parameters and Key Results

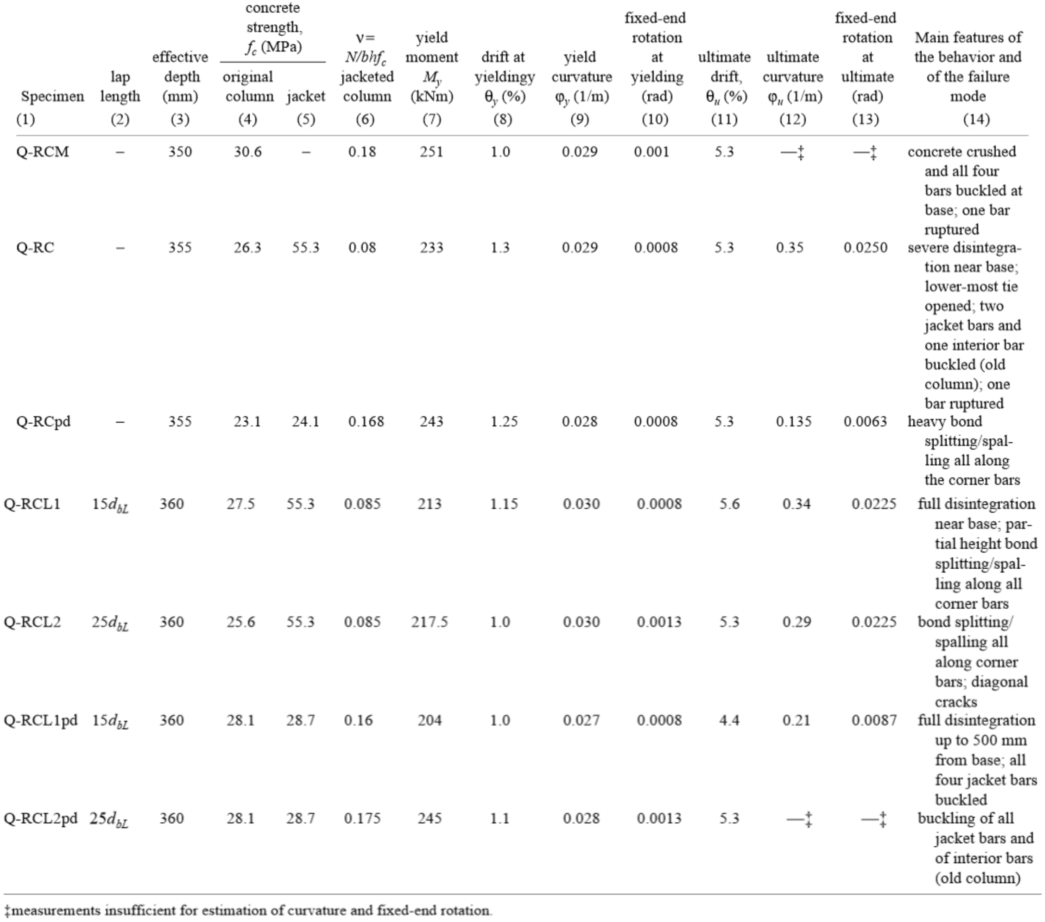


Specimen (1)	lap length (2)	effective depth (mm) (3)	f_c (MPa) (4)	$\nu = N/bhf_c$ (5)	yield moment, M_y (kNm) (6)	drift at yielding θ_y (%) (7)	yield curvature φ_y (1/m) (8)	fixed-end rotation at yielding (rad) (9)	ultimate drift, θ_u (%) (10)	ultimate curvature φ_u (1/m) (11)	fixed-end rotation at ultimate (rad) (12)	Main features of the behavior and of failure mode (13)
Q-0	–	210	27.0	0.44	66	0.8	0.026	0.0015	2.2	0.085	0.0023	heavy concrete crushing up to 300 mm from the base
Q-0L1	$15d_{bL}$	220	30.3	0.41	72.5	1.05	0.029	0.001	2.5	> 0.095†	> 0.0038†	early cracking and then spalling of corners all along lapping; bar buckling and spalling of corners mainly *above lap splice*
Q-0L2	$25d_{bL}$	220	30.3	0.42	72.5	0.95	0.029	0.0013	2.2	0.135	0.0088	corners spalled all along splice; bar buckling tendency along the splice
Q-0L1a	$15d_{bL}$	220	28.1	0.63	70	0.8	0.009	0.0006	1.0	—‡†	—‡†	pre-damaged specimen for Q-RCL1pd; failure mode as in Q-0L1
Q-0L2a	$25d_{bL}$	220	28.1	0.57	83	0.9	0.017	0.008	1.35	—‡†	—‡†	pre-damaged specimen for Q-RCL2pd, failure mode as in Q-0L1

†base was not critical; failure occurred outside instrumented region.
‡measurements insufficient for estimation of curvature and fixed-end rotation.

Results:

RC-jacket Columns Test Parameters and Key Results



Specimen (1)	lap length (2)	effective depth (mm) (3)	concrete strength, f_c (MPa): original column (4)	concrete strength, f_c (MPa): jacket (5)	$\nu = N/bhf_c$ jacketed column (6)	yield moment M_y (kNm) (7)	drift at yieldingy θ_y (%) (8)	yield curvature φ_y (1/m) (9)	fixed-end rotation at yielding (rad) (10)	ultimate drift, θ_u (%) (11)	ultimate curvature φ_u (1/m) (12)	fixed-end rotation at ultimate (rad) (13)	Main features of the behavior and of the failure mode (14)
Q-RCM	–	350	30.6	–	0.18	251	1.0	0.029	0.001	5.3	—‡	—‡	concrete crushed and all four bars buckled at base; one bar ruptured
Q-RC	–	355	26.3	55.3	0.08	233	1.3	0.029	0.0008	5.3	0.35	0.0250	severe disintegration near base; lower-most tie opened; two jacket bars and one interior bar buckled (old column); one bar ruptured
Q-RCpd	–	355	23.1	24.1	0.168	243	1.25	0.028	0.0008	5.3	0.135	0.0063	heavy bond splitting/spalling all along the corner bars
Q-RCL1	$15d_{bL}$	360	27.5	55.3	0.085	213	1.15	0.030	0.0008	5.6	0.34	0.0225	full disintegration near base; partial height bond splitting/spalling along all corner bars
Q-RCL2	$25d_{bL}$	360	25.6	55.3	0.085	217.5	1.0	0.030	0.0013	5.3	0.29	0.0225	bond splitting/spalling all along corner bars; diagonal cracks
Q-RCL1pd	$15d_{bL}$	360	28.1	28.7	0.16	204	1.0	0.027	0.0008	4.4	0.21	0.0087	full disintegration up to 500 mm from base; all four jacket bars buckled
Q-RCL2pd	$25d_{bL}$	360	28.1	28.7	0.175	245	1.1	0.028	0.0013	5.3	—‡	—‡	buckling of all jacket bars and of interior bars (old column)

‡measurements insufficient for estimation of curvature and fixed-end rotation.

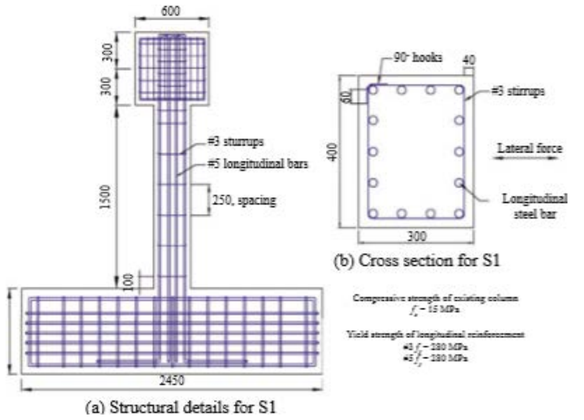
Effectiveness of the Method:
Old columns with smooth vertical bars have low deformation and energy dissipation capacity under cyclic loading, but lap-splicing with at least 15-bar diameters does not impair this capacity much. RC jackets successfully increases their deformation capacity to sufficient levels for earthquake resistance. Previous cyclical loading damage does not reduce the effectiveness noticeably. Not adequately bonding old concrete to the jacket causes significant slippage but does not adversely affect lateral load resistance, deformation capacity, or energy dissipation.

Chang, S.-Y., Chen, T.-W., Tran, N.-C., and Liao, W.-I. (June 01, 2014). Seismic Retroftting of RC Columns with RC Jackets and Wing Walls with Different Structural Details. Earthquake Engineering and Engineering Vibration, 13, 2, 279-292.

Significance:
Four strengthened columns, two with RC jackets and two with wing walls, and an unretrofitted column are tested. The original columns were designed to meet old (pre-1999) design standards. Two details were prepared for each retrofit method. For the RC jackets, one column had transverse adhesive anchors, the other did not. For the wing walled columns, one column had one row of transverse adhesive anchors, the other had two rows. The columns were tested under lateral cyclic loads.

Loading/beam Images:

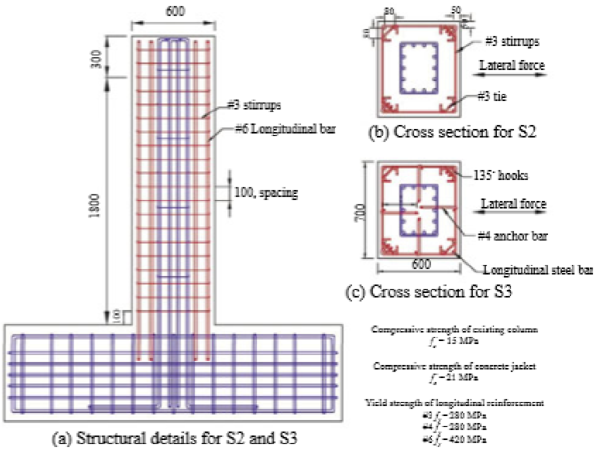
Original Column Details



(a) Structural details for S1

(b) Cross section for S1

RC Jacket Details

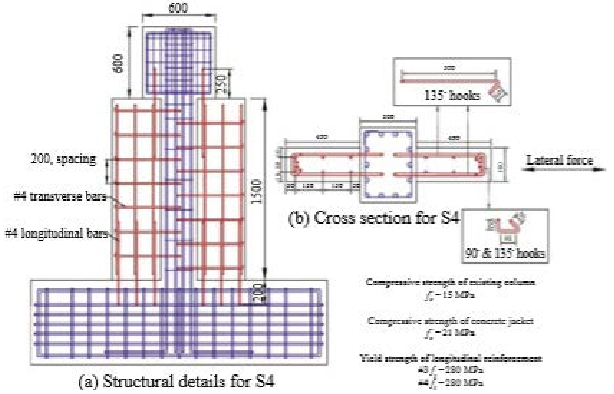


(a) Structural details for S2 and S3

(b) Cross section for S2

(c) Cross section for S3

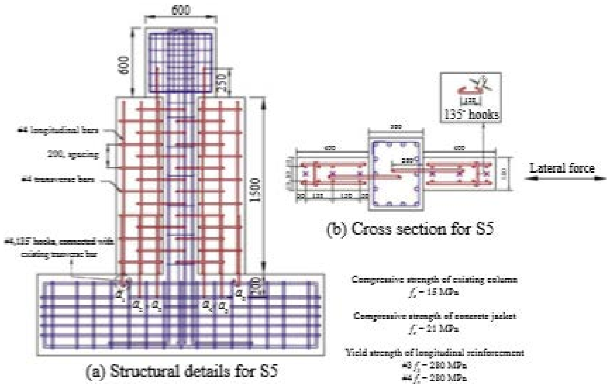
Wing Wall Details for S4



(a) Structural details for S4

(b) Cross section for S4

Wing Wall Details for S5

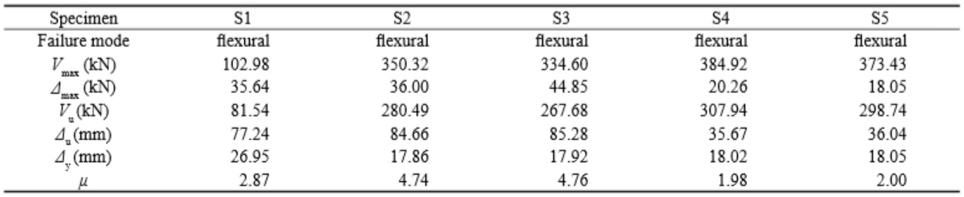


(a) Structural details for S5

(b) Cross section for S5

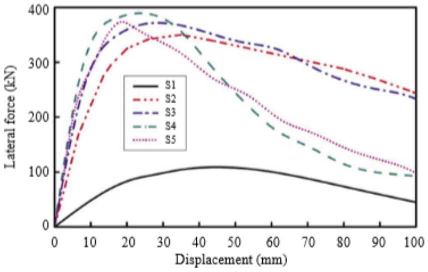
Results:

Specimen Results

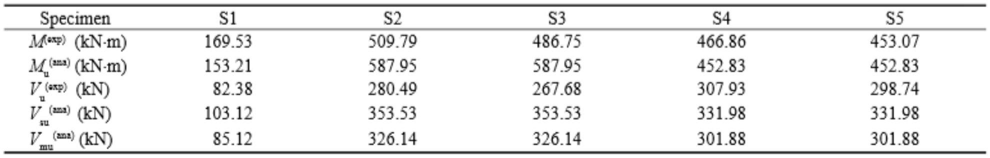


Specimen	S1	S2	S3	S4	S5
Failure mode	flexural	flexural	flexural	flexural	flexural
V_{max} (kN)	102.98	350.32	334.60	384.92	373.43
Δ_{max} (kN)	35.64	36.00	44.85	20.26	18.05
V_u (kN)	81.54	280.49	267.68	307.94	298.74
Δ_u (mm)	77.24	84.66	85.28	35.67	36.04
Δ_y (mm)	26.95	17.86	17.92	18.02	18.05
μ	2.87	4.74	4.76	1.98	2.00

Lateral Force vs. Displacement

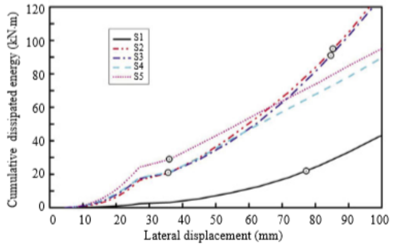


Experimental vs Analytical Strength



Specimen	S1	S2	S3	S4	S5
$M^{(exp)}$ (kN·m)	169.53	509.79	486.75	466.86	453.07
$M_u^{(ana)}$ (kN·m)	153.21	587.95	587.95	452.83	452.83
$V_u^{(exp)}$ (kN)	82.38	280.49	267.68	307.93	298.74
$V_{su}^{(ana)}$ (kN)	103.12	353.53	353.53	331.98	331.98
$V_{mu}^{(ana)}$ (kN)	85.12	326.14	326.14	301.88	301.88

Cumulative Dissipated Energy



Effectiveness of the Method:
Either RC jacket or wing walls efficiently improve the stiffness and strength of the original column. RC jackets have better energy dissipation and ductility versus those with wing walls, due to jackets having a flexural failure mode versus shear for wing walls. Therefore, the RC jacketed column had a significant decrease of maximum lateral strength and ductility. Standard hooks are better than post-installed anchors since there are many variables in post-installing.

da Porto, F., Stievanin, E., and Pellegrino, C. (April 01, 2012). Efficiency of RC square columns repaired with polymer-modified cementitious mortars. Cement and Concrete Composites, 34, 4, 545-555.

Significance:

This article focuses on strengthening columns with polymer-modified cementitious mortars on eight square reinforced concrete columns, six of which were repaired with three types of mortars on all faces, and two were non-damaged and non-repaired. Tests focused on mechanical properties such as elastic modulus and compressive strength, maintaining repair thickness. Displacment transducers were placed on the columns to measure horizontal and vertical strains.

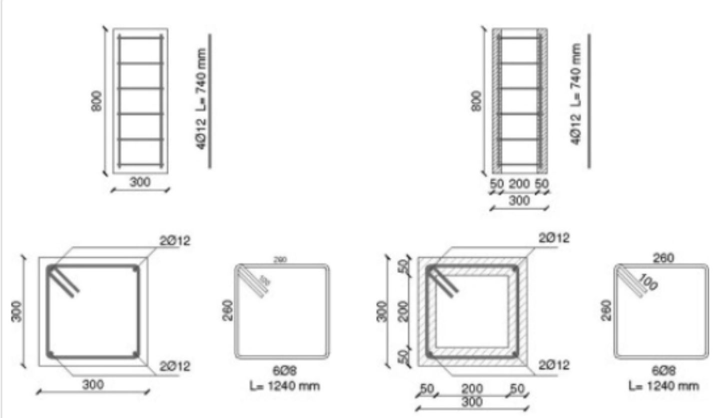
Loading/beam Images:

Specimen Details

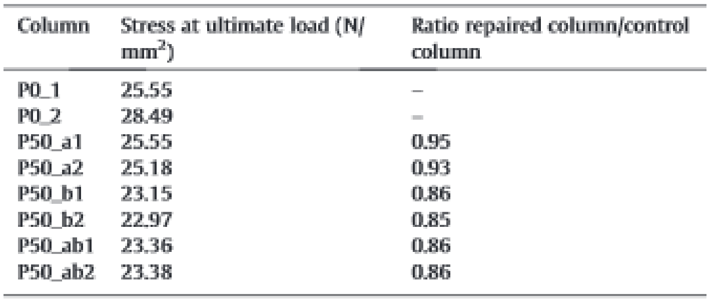
Type and no. of elements	Condition	Designation	Section (mm^2)	Longitudinal reinforcement	ρ_l (%)	Transverse reinforcement	ρ_w (%)
2 Columns	Control	P0_1; P0_2	300 × 300	4ø12	0.50	1ø8/140 mm	0.24
2 Columns	Repair *a*	P50_a1; P50_a2					
2 Columns	Repair *b*	P50_b1; P50_b2					
2 Columns	Repair *ab*	P50_ab1; P50_ab2					

Results:

Dimensions, Bars, and Repair Details

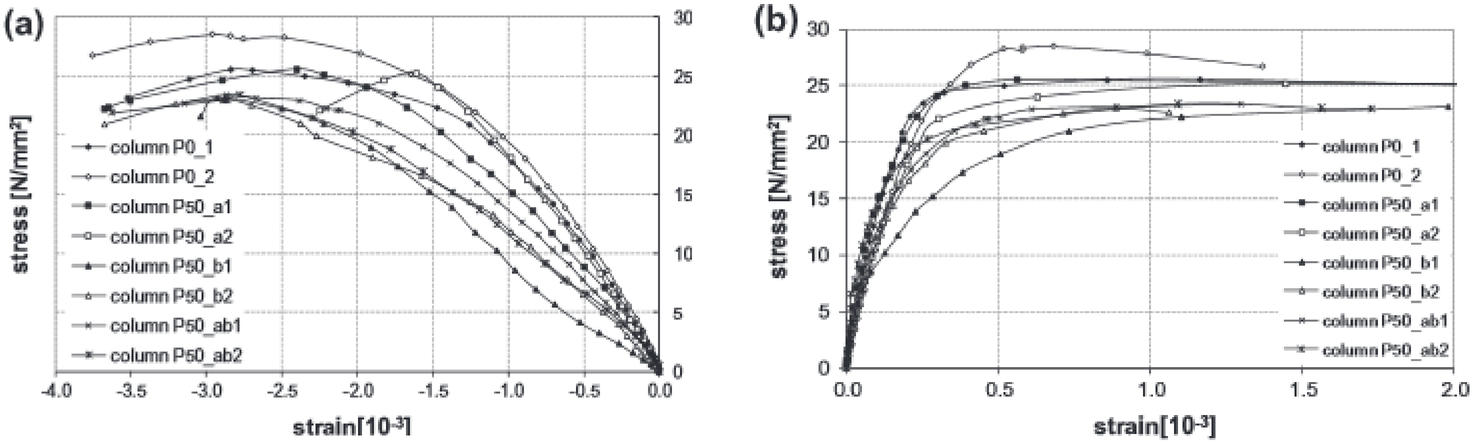


Axial Test Results

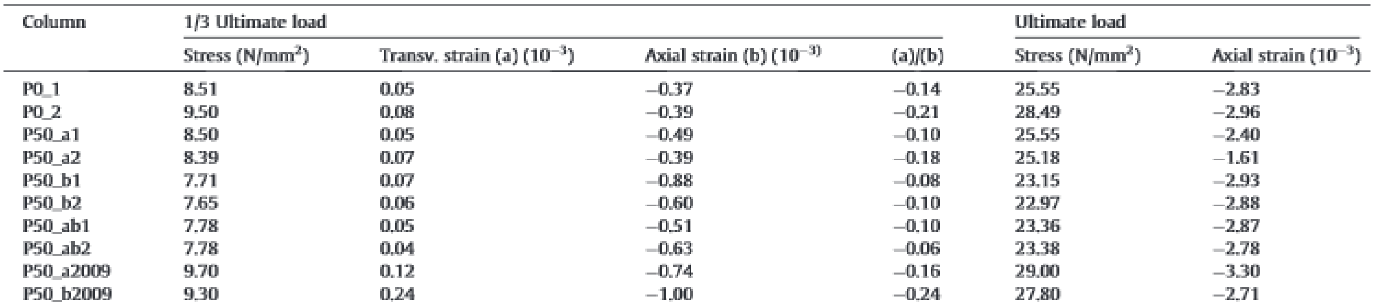


Column	Stress at ultimate load (N/mm^2)	Ratio repaired column/control column
P0_1	25.55	–
P0_2	28.49	–
P50_a1	25.55	0.95
P50_a2	25.18	0.93
P50_b1	23.15	0.86
P50_b2	22.97	0.85
P50_ab1	23.36	0.86
P50_ab2	23.38	0.86

Average Axial Stress-Strain Results **Average Transverse Stress-Strain Results**



Stress and Strain Values of Axial Tests



Column	1/3 Ultimate load				Ultimate load	
	Stress (N/mm^2)	Transv. strain (a) (10^{-3})	Axial strain (b) (10^{-3})	(a)/(b)	Stress (N/mm^2)	Axial strain (10^{-3})
P0_1	8.51	0.05	–0.37	–0.14	25.55	–2.83
P0_2	9.50	0.08	–0.39	–0.21	28.49	–2.96
P50_a1	8.50	0.05	–0.49	–0.10	25.55	–2.40
P50_a2	8.39	0.07	–0.39	–0.18	25.18	–1.61
P50_b1	7.71	0.07	–0.88	–0.08	23.15	–2.93
P50_b2	7.65	0.06	–0.60	–0.10	22.97	–2.88
P50_ab1	7.78	0.05	–0.51	–0.10	23.36	–2.87
P50_ab2	7.78	0.04	–0.63	–0.06	23.38	–2.78
P50_a2009	9.70	0.12	–0.74	–0.16	29.00	–3.30
P50_b2009	9.30	0.24	–1.00	–0.24	27.80	–2.71

Effectiveness of the Method:

Repaired columns developed less capacity than non-damaged, non-repaired columns. Mortars with a similar elastic modulus to the substrate concrete and higher compressive strength had a confining effect on the column. Mortar a also performed the best restoring 95% of the column capacity. All retrofitting specimens had more widespread cracking pattern than for the control columns. The repair layer detaches locally after reaching the ultimate load.

Ersoy, U., Tugrul, T. A., and Suleiman, R. (May 01, 1993). Behavior of Jacketed Columns. ACI Structural Journal, 90, 3, 288.

Significance:

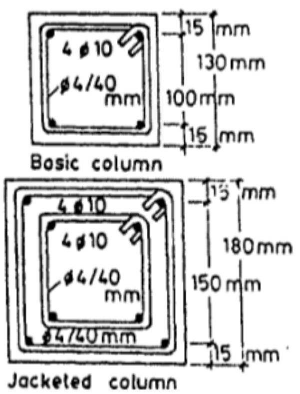
Ersoy et al. evaluated the effectiveness of repair and strengthening jackets with the differences between jackets during and after loading. Four jacketed columns and one monolithic column were tested uniaxially. In the second series of testing, three jacketed columns and two monolithic columns were tested under combined axial load and bending. The efficacy of the repair and strengthening jackets was determined by the strength, stiffness, and energy dissipation. Load history on the jacketed columns was also analyzed. Even though unloading the columns before jacketing is preferable, jacketing columns under load was tested since unloading is not always possible.

Loading/beam Images:

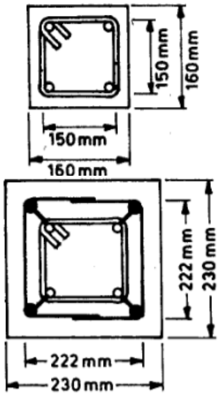
Series 1 Abbreviations

M	Monolithic
L	Jacket under load
U	Jacket after loading
S	Strengthening
R	Repair

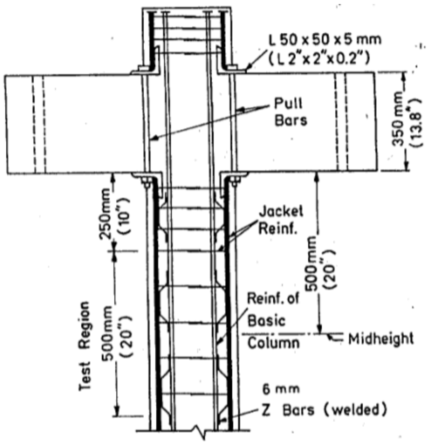
Series 1 Cross-sections



Series 2 Cross-sections



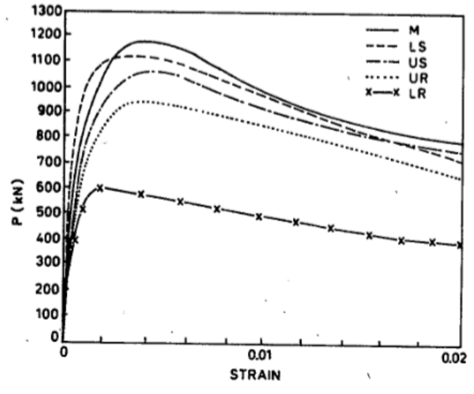
Reinforcement of Series 2 Jacket

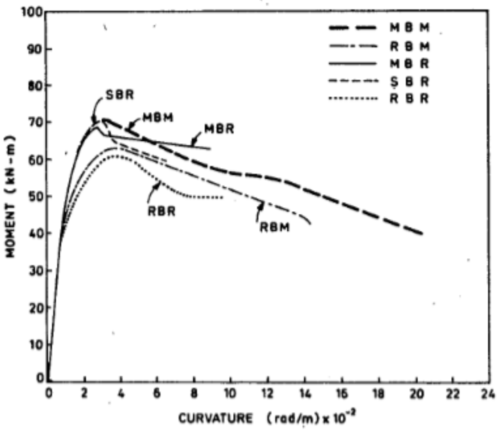


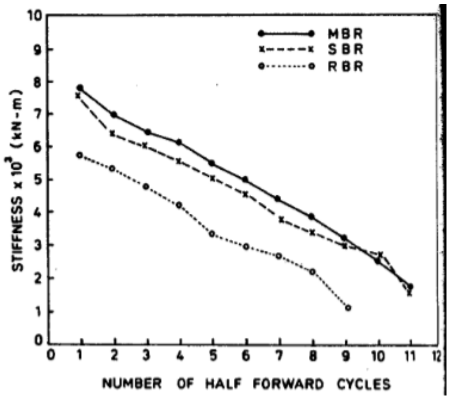
Series 2 Specimens

Column	Jacket Type	Type of Loading		Concrete Strength		Initial Rigidity (kNm^2)	Rigidity at .85Mmax (kNm^2)	Total axial load at Mmax (kN)	Mmax (test) (kNm)	Deformations at Mmax			Maximum Deformations		
		Basic	Jacketed	Basic (MPa)	Jacket (MPa)					Midheight deflection (mm)	Compressive concrete strain	Curvature (rad/m)	Midheight deflection (mm)	Compressive concrete strain	Curvature (rad/m)
MBM	Monolithic		Monotonic	27.0	27.0	7820	3300	620.0	71.5	14.9	0.0041	0.033	50.9	0.0294	0.217
RBM	Repair	Monotonic	Monotonic	33.1	30.6	5860	2880	317.5	63.4	15.0	0.0044	0.035	40.0	0.0189	0.134
MBR	Monolithic		Reversed Cyclic	31.5	31.5	7780	2490	630.0	71.1	16.4	0.0049	0.040	36.0	0.0137	0.095
RBR	Repair	Reversed Cyclic	Reversed Cyclic	34.5	30.7	5800	1670	620.0	65.9	17.3	0.0046	0.038	34.6	0.0134	0.092
SBR	Strengthening	Reversed Cyclic	Reversed Cyclic	40.3	33.0	7920	2210	635.0	73.2	17.5	0.0040	0.033	30.0	0.0074	0.061

Results:







Columns exhibited crushing of concrete on the compressing face and buckling of longitudinal bars with significant deflection near failure. Column SBR was unloaded by mistake after buckling of longitudinal bars. SBR may have had higher loads if load had not been released.

Effectiveness of the Method:

Stiffness degradation of the repaired column followed a similar stiffness degradation curve despite starting at a lower stiffness. Jackets added after loading resulting in 80%-90% of the monolithic column strength. Columns strengthened under load performed well. Repaired columns could only hold 50% of the axial load. Repaired jackets had significantly less rigidity (25% of control specimen). Load history did not have a significant effect on the strength, but did influence rigidity (cyclic rigidity 40% of some monotonic specimen). Deformation capacity of jacketed columns was less than that of reference columns.

Júlio, E. S., Branco, F., and Silva, V. D. (January 01, 2003). Structural rehabilitation of columns with reinforced concrete jacketing. Progress in Structural Engineering and Materials, 5, 1, 29-37.

Significance:
Julio et al. evaluated the anchoring and slab crossing of added longitudinal reinforcement, interface surface preparation, spacing of added stirrups, and temporary shoring of structure for reinforced concrete jacketing columns. Literature review of many of the variables in reinforced concrete jacketing was performed and the synthesis of the results was presented.

Results:

Added longitudinal reinforcement:
Anchoring to the footing:
1. Monotonic constant axial force tests with increasing moment and shear
2. Using a vacuum cleaner to clean holes drilled in footings for bars effectively transfers failure from slipping to tensile rupture.

Crossing the slab:
- Using welded wire fabric increases shear strength and ductility

Interface Surface Treatment:
Increasing Surface Roughness:
- Pneumatic hammering causing micro-cracking of the substrate.
- Sand-blasting was the most efficient roughening technique

Surface pre-wetting:
1 Moisture level of substrate may be critical in achieving a good bond
2 Excessive humidity can close substrate pores and prevent absorption of repairing material

Application of bonding agents:
- Epoxy resin on sand-blasted surfaces reduced shear and tensile strength of the interface

Addition of steel connectors
- Adding steel connectors crossing the interface did not significantly increase the debonding force, but increased the longitudinal shear strength

Synthesis:
- There is no need to improve interface surface roughness or use bonding agents

Spacing of Added Stirrups:
- Higher percentages of transverse reinforcement can cause monolithic jacket performance.
- Half the original column transverse reinforcement is recommended for the jacket.

Temporary Shoring of the Structure:
- Hydraulic jacks can be used to temporary shore the structure in order to unload the column.

Added Concrete
- Due to diminished jacket thickness, self-compacting concrete (SCC) and high-strength concrete (HSC) are often used. Often HSC also use high-durability concrete (HDC) resulting in high-performance concretes (HPC).
- Using HPC the columns had monolithic rupture failure instead of interface rupture.

Structural Behavior:
Correction of Structural Behavior:
- Bundled column bars did not have a negative effect on specimen behavior, with adequate confinement and a strong column.

Effect of Damage on Structural Behavior:
- Jacketing the most damaged elements resulted in strength at 2% and stiffness at .5% drift being 63% and 52%, respectively, of values from the undamaged specimen.
- Others stated that the effect of previous damage and the different reinforcing details had no significant effect on the seismic performance of the jacketed columns.

Effectiveness of the Method:
When jacketing RC columns focus should be placed on: the repair method of the original column, interface surface preparation, use of a bonding agent, application of steel connectors, temporary shoring, anchoring of added longitudinal reinforcement, continuity between floors, position of steel bars, added stirrups, and added concrete.

Julio N.B.S and Branco A.B. 2008. "Reinforced Concrete jacketing - Interface Influence on Cyclic Loading Response," ACI Structural Journal, V.105, No. 4, pp.471-477

Significance

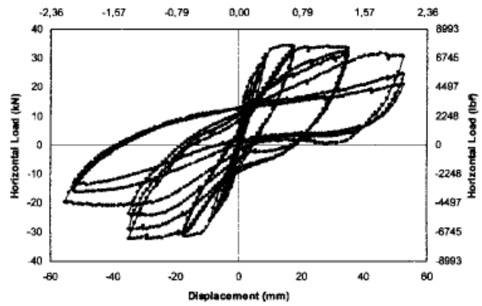
This research paper focuses on influence of interface treatment of columns strengthened by reinforced concrete jacketing subjected to cyclic loads with constant axial force. They concluded that the surface treatment was unnecessary to achieve monolithic behavior when the bending moment/shear force ratio exceeds one and the thickness of the jacket is less than 17.5% of the column width. Also no strength degradation was observed in any of the specimens, as is apparent in the hysteresis diagram shown below.

Details and Test Results

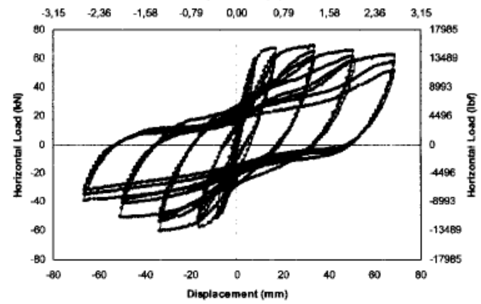
Column	Description	Boundary Conditions	R.C. Jacket (mm)		Dia of Long Reinf (mm)	Dia & Spac of Trans Reinf (mm)	Maximum Load (kN)
			Thickness	Height			
M1	Non Strengthened Column	hinge-hinge	-	-			34
M2	Column with non-adherent jacket	hinge-hinge	35	900	10	6 @ 75	68.6
M3	Column with monolithic jacket	hinge-hinge	35	900	10	6 @ 75	73.6
M4	Column jacketed without surface preparation	hinge-hinge	35	900	10	6 @ 75	80.3
M5	Column jacketed after surface preparation with sand blasting	hinge-hinge	35	900	10	6 @ 75	80.6
M6	Column jacketed after surface preparation with sand blasting and application of steel connectors	hinge-hinge	35	900	10	6 @ 75	80
M7	Column jacketed after surface preparation with sand blasting and after axial force	hinge-hinge	35	900	10	6 @ 75	82.4

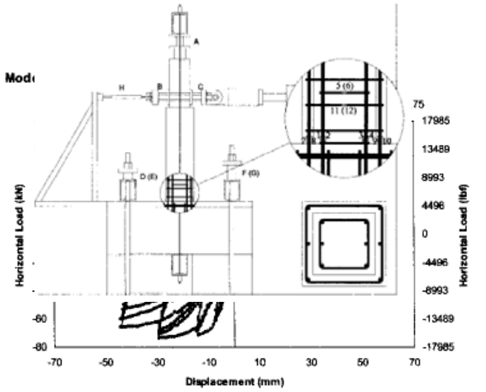
Results of the Test

Model M1

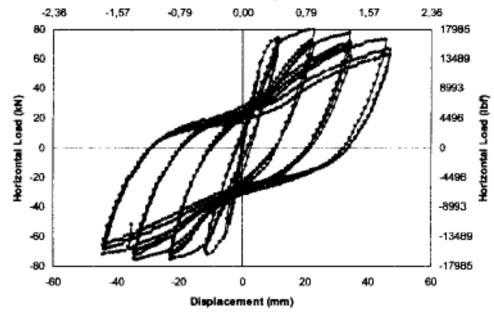


Model M2

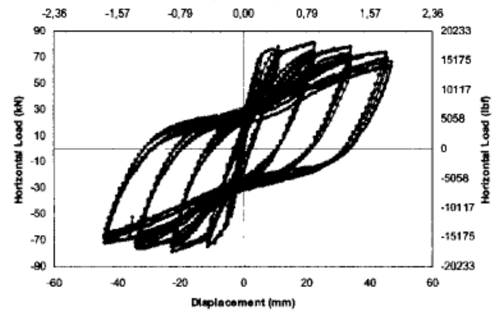




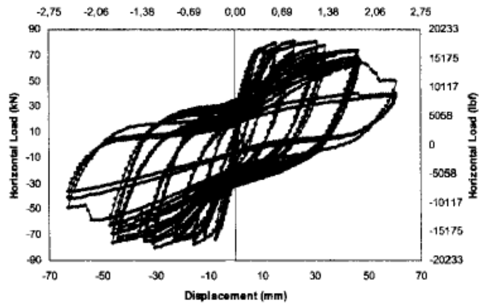
Model M4



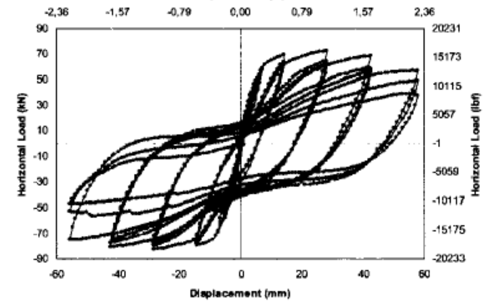
Model M5



Model M6



Model M7



Effectiveness of the Method

1) The awareness of the fact that for a column with bending moment to shear force ratio greater than one, refutes the application of shear connectors or surface roughness prior to RC jacketing, saves considerable cost and time.

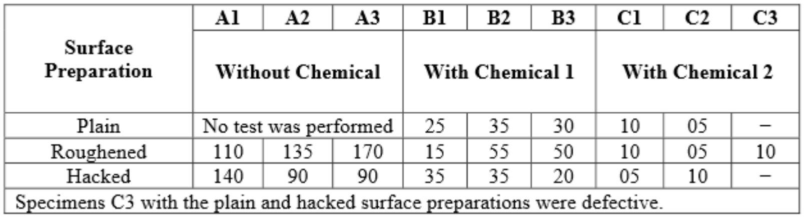
2) Since the jacket thickness should be less than 17.5% of the width of column, this technique will not work for smaller diameter columns, since the minimum jacket thickness may exceed the 17.5% mark.

Kaliyaperumal, G., and Sengupta, A. K. (June 01, 2009). Seismic Retrofit of Columns in Buildings for Flexure using Concrete Jacket. ISET Journal of Earthquake Technology, 46, 2, 77-107.

Significance:
Flexural strength and performance of jacketed columns is the main focus of this article. Slant shear tests were performed to analyze the old-new concrete interface. The column specimens were tested for their strength. The beam-column-joint sub-assemblage specimens were also tested to evaluate the ductility, energy absorption, and energy dissipation. A nonlinear analysis was performed to predict the lateral load versus displacement for the retrofitted sub-assemblage specimens. Guidelines for concrete jacketing retrofit were provided.

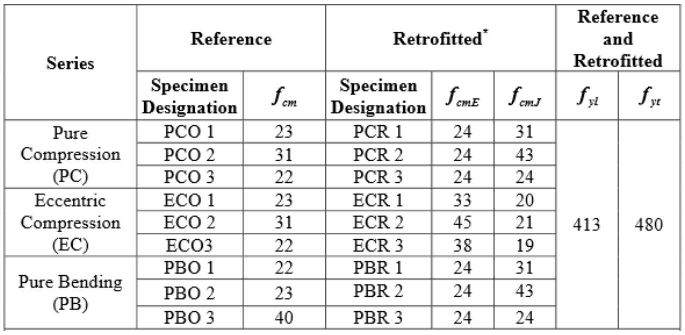
Loading/beam Images:

Failure Loads (kN) for Slant Shear Tests



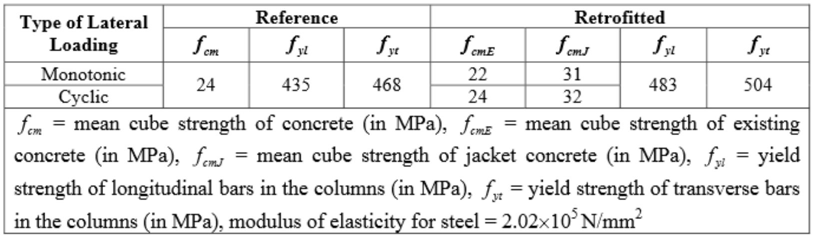
Surface Preparation	A1	A2	A3	B1	B2	B3	C1	C2	C3
	Without Chemical			With Chemical 1			With Chemical 2		
Plain	No test was performed			25	35	30	10	05	–
Roughened	110	135	170	15	55	50	10	05	10
Hacked	140	90	90	35	35	20	05	10	–
Specimens C3 with the plain and hacked surface preparations were defective.									

Material Properties for Column Specimens



Series	Reference		Retrofitted*			Reference and Retrofitted	
	Specimen Designation	f_{cm}	Specimen Designation	f_{cmE}	f_{cmJ}	f_{yl}	f_{yt}
Pure Compression (PC)	PCO 1	23	PCR 1	24	31	413	480
	PCO 2	31	PCR 2	24	43		
	PCO 3	22	PCR 3	24	24		
Eccentric Compression (EC)	ECO 1	23	ECR 1	33	20		
	ECO 2	31	ECR 2	45	21		
	ECO3	22	ECR 3	38	19		
Pure Bending (PB)	PBO 1	22	PBR 1	24	31		
	PBO 2	23	PBR 2	24	43		
	PBO 3	40	PBR 3	24	24		

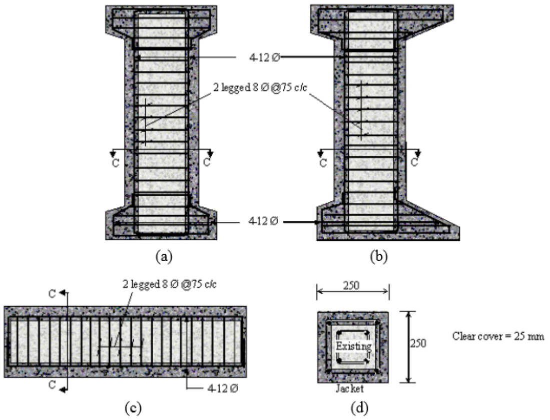
Material Properties for Sub-assemblage Specimens



Type of Lateral Loading	Reference			Retrofitted			
	f_{cm}	f_{yl}	f_{yt}	f_{cmE}	f_{cmJ}	f_{yl}	f_{yt}
Monotonic	24	435	468	22	31	483	504
Cyclic				24	32		

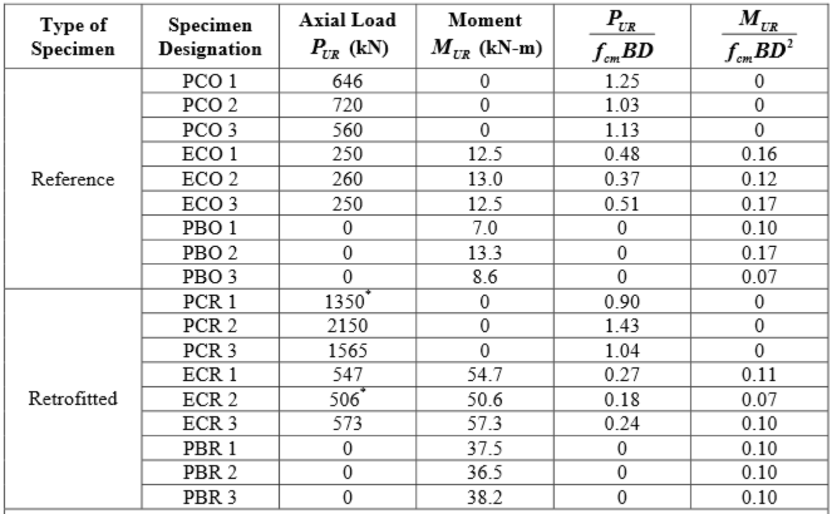
f_{cm} = mean cube strength of concrete (in MPa), f_{cmE} = mean cube strength of existing concrete (in MPa), f_{cmJ} = mean cube strength of jacket concrete (in MPa), f_{yl} = yield strength of longitudinal bars in the columns (in MPa), f_{yt} = yield strength of transverse bars in the columns (in MPa), modulus of elasticity for steel = 2.02×10^5 N/mm^2

Reinforcement Details for Column Tests



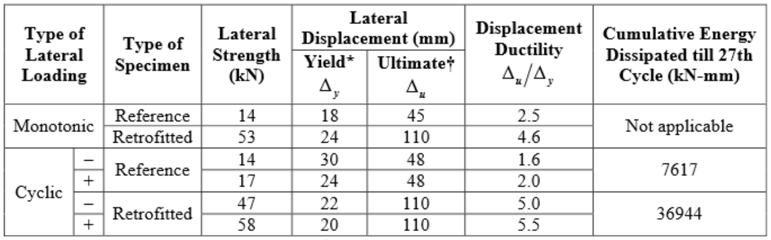
Results:

Failure Loads for Column Specimens



Type of Specimen	Specimen Designation	Axial Load P_{UR} (kN)	Moment M_{UR} (kN-m)	$\frac{P_{UR}}{f_{cm}BD}$	$\frac{M_{UR}}{f_{cm}BD^2}$
Reference	PCO 1	646	0	1.25	0
	PCO 2	720	0	1.03	0
	PCO 3	560	0	1.13	0
	ECO 1	250	12.5	0.48	0.16
	ECO 2	260	13.0	0.37	0.12
	ECO 3	250	12.5	0.51	0.17
	PBO 1	0	7.0	0	0.10
	PBO 2	0	13.3	0	0.17
	PBO 3	0	8.6	0	0.07
Retrofitted	PCR 1	1350*	0	0.90	0
	PCR 2	2150	0	1.43	0
	PCR 3	1565	0	1.04	0
	ECR 1	547	54.7	0.27	0.11
	ECR 2	506*	50.6	0.18	0.07
	ECR 3	573	57.3	0.24	0.10
	PBR 1	0	37.5	0	0.10
	PBR 2	0	36.5	0	0.10
	PBR 3	0	38.2	0	0.10

Lateral Strength and Dcutility for Sub-assemblage Specimens



Type of Lateral Loading		Type of Specimen	Lateral Strength (kN)	Lateral Displacement (mm) Yield* Δ_y	Lateral Displacement (mm) Ultimate† Δ_u	Displacement Ductility Δ_u/Δ_y	Cumulative Energy Dissipated till 27th Cycle (kN-mm)
Monotonic		Reference	14	18	45	2.5	Not applicable
		Retrofitted	53	24	110	4.6	
Cyclic	–	Reference	14	30	48	1.6	7617
	+		17	24	48	2.0	
	–	Retrofitted	47	22	110	5.0	36944
	+		58	20	110	5.5	

Effectiveness of the Method:
Self-compacting concrete was adequate for the jacket. The surface was successfully roughened with a motorized wire brush. Retrofitted column capacity was substantially larger than the existing capacity. These values were predicted through analysis. Retrofitted beam-column-joint sub-assemblage specimens showed substantial increase in lateral strength, ductility, and dissipation. Degradation of strength and stiffness of retrofitted sub-assemblage specimens under cyclic loading was limited.

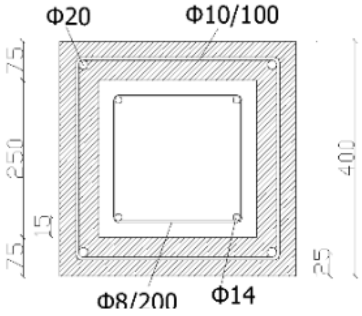
Lampropoulos, A. P., Dritsos, S. E.. (December 01, 2008). Numerical study of the effects of preloading, axial loading and concrete shrinkage on reinforced concrete elements strengthened by concrete layers and jackets. AIP Conference Proceedings, 1020, 1203-1210.

Significance:

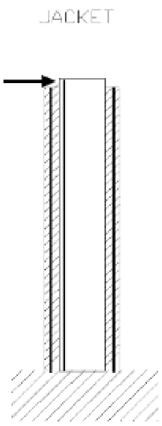
Lampropoulos et al. examined how strengthening reinforced concrete columns and beams with additional concrete layers impacts the seismic performance. Elements are modeled to compare experimental results. The columns are preloaded when jacketed with service loads. The compressive performance and shrinkage of the new layer were evaluated. The columns were tested with a 75 mm jacket and 75 mm layers. For the columns with the reinforced concrete layer, one column had shear connectors and one did not. Columns were laterally loaded and compared with monolithic columns the same size of the columns with the jacket/layer.

Loading/beam Images:

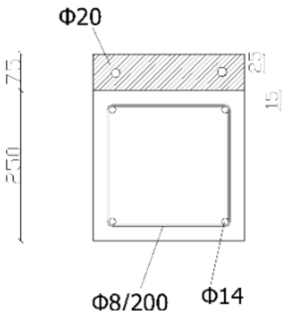
Cross Section of Jacketed Column



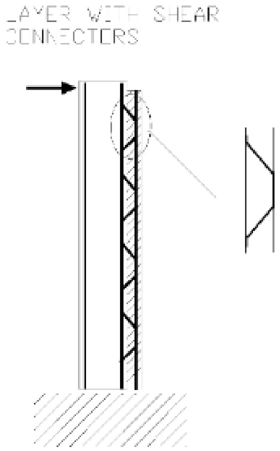
Jacket Loading



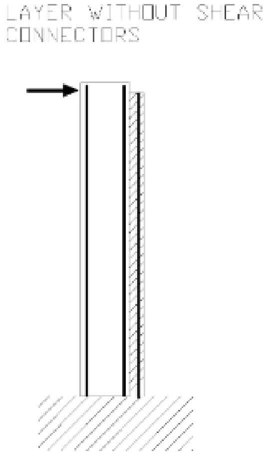
Cross Section of Layered Specimen



Layer with Shear Connector Loading

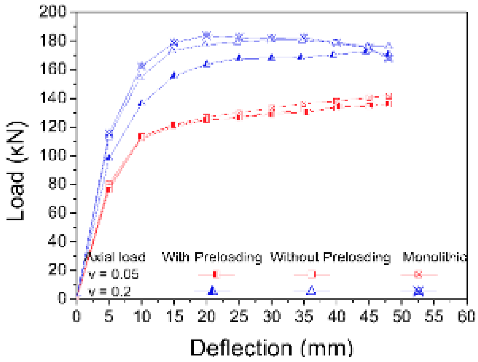


Layer without Shear Connector Loading

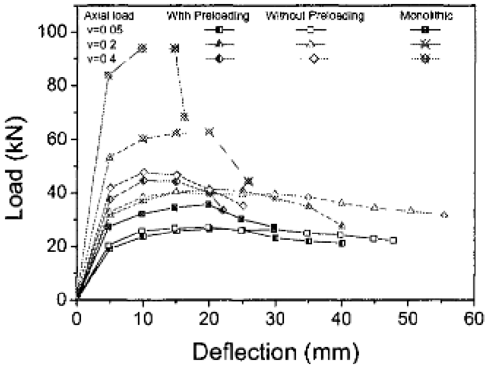


Results:

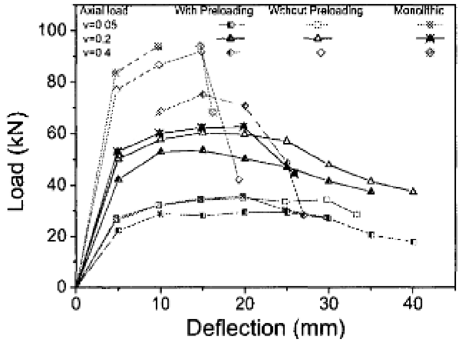
Load vs Deflection for Jacket



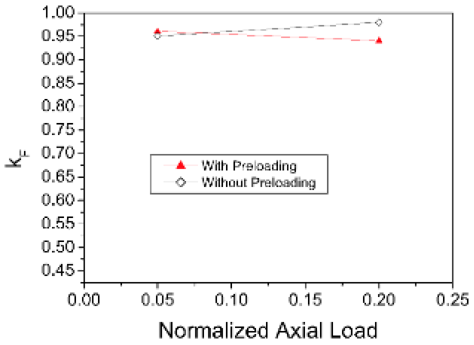
Load vs Deflection for Layer without Shear Connectors



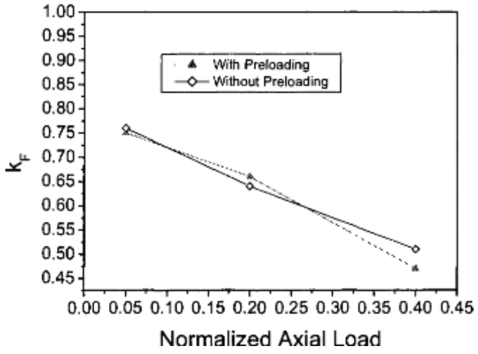
Load vs Deflection for Layer with Shear Connectors



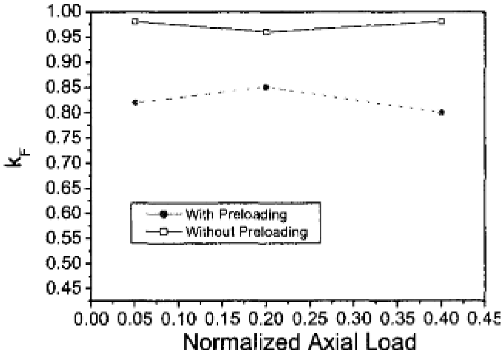
Monolithic Coefficient for Jacket



Monolithic Coefficient for Layer without Shear Connectors



Monolithic Coefficient for layer with Shear Connectors



Effectiveness of the Method:

Preloading is important when a reinforced concrete layer is used with shear connectors between old and new reinforcement, but does not significantly affect jackets or layers without shear connectors. The strengthened columns with a layer of concrete without shear connectors had much lower strength than the monolithic columns. As normalized axial load increased, monolithic coefficient values decreased and the preloading effect became negligible.

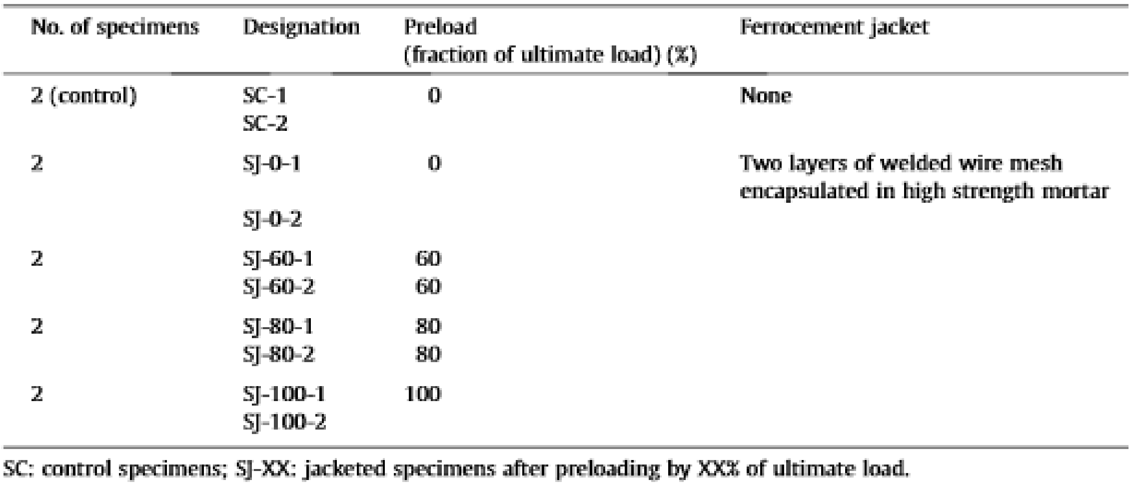
Mourad, S. M., and Shannag, M. J. (February 01, 2012). Repair and Strengthening of Reinforced Concrete Square Columns Using Ferrocement Jackets. Cement and Concrete Composites, 34, 2, 288-294.

Significance:

10 1/3 scale reinforced concrete columns were cast, preloaded under various levels of axial levels, repaired with ferrocement jackets with two layers of welded wire mesh, and retested to failure. Vertical and horizontal LVDTs and strain gauges across the columns were placed to measure the response of the jacket.

Loading/Images:

Test Column Details

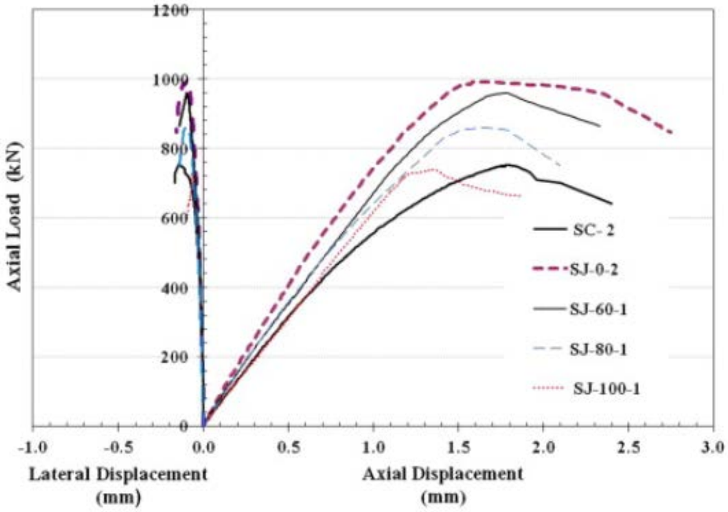


No. of specimens	Designation	Preload (fraction of ultimate load) (%)	Ferrocement jacket
2 (control)	SC-1 SC-2	0	None
2	SJ-0-1 SJ-0-2	0	Two layers of welded wire mesh encapsulated in high strength mortar
2	SJ-60-1 SJ-60-2	60 60	
2	SJ-80-1 SJ-80-2	80 80	
2	SJ-100-1 SJ-100-2	100	

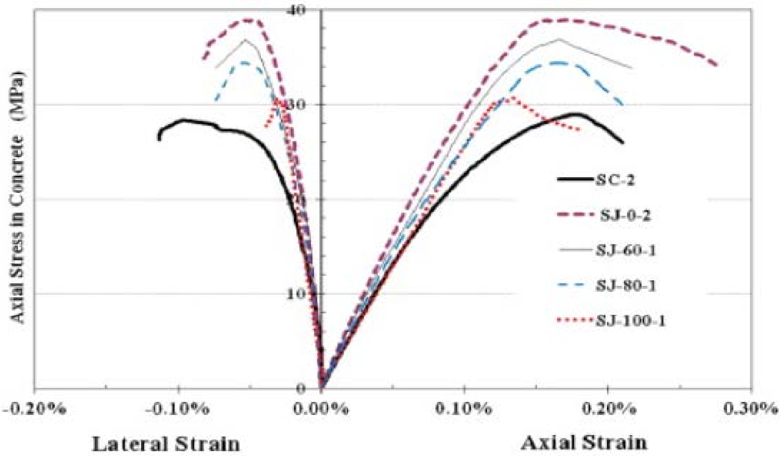
SC: control specimens; SJ-XX: jacketed specimens after preloading by XX% of ultimate load.

Results:

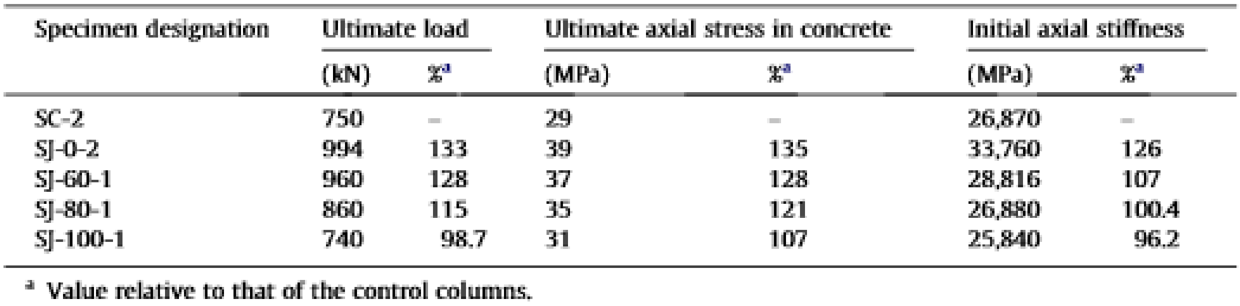
Load-Displacement Relationships



Stress-Strain Relationships



Test Results



Specimen designation	Ultimate load		Ultimate axial stress in concrete		Initial axial stiffness	
	(kN)	%[a]	(MPa)	%[a]	(MPa)	%[a]
SC-2	750	–	29	–	26,870	–
SJ-0-2	994	133	39	135	33,760	126
SJ-60-1	960	128	37	128	28,816	107
SJ-80-1	860	115	35	121	26,880	100.4
SJ-100-1	740	98.7	31	107	25,840	96.2

[a] Value relative to that of the control columns.

Effectiveness of the Method:

Columns failed in a ductile manner having restored the original load capacity and stiffness versus the brittle failure of the control columns. Axial load carrying capacity and stiffness increased 33% and 26%, respectively, when compared to the control columns. Preloading columns to 60% and 80% of the failure loads resulted in a 28% and 15%, respectively, increase in the column capacity when compared to the control columns. Jacketed columns that were fully preloaded were able to restore the capacity and stiffness of the column. Repaired failed columns had a significant loss of ductility due to the cracks in the failed columns.

Pellegrino, C., Porto, F. ., and Modena, C. (October 01, 2009). Rehabilitation of Reinforced Concrete Axially Loaded Elements with Polymer-modified Cementicious Mortar. Construction and Building Materials, 23, 10, 3129-3137.

Significance:
Pellegrino et al. examined the compatibility and efficiency of using polymer-modified cementitious mortar to rehabilitate reinforced concrete columns. Six square columns were tested monotonically with different repair thicknesses and different levels of steel reinforcement in the mortar. Columns had strain gauges along them to measure the material behavior. Test specimens were compared with numerical models.

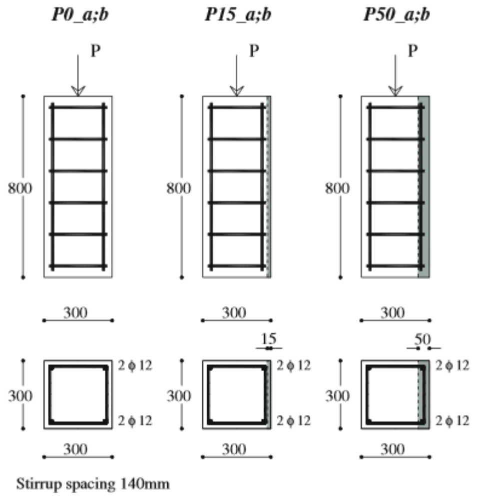
Loading/Images:

Specimen Details

Type of element/test	Section (mm^2)	Longitudinal reinforcement		ρ_l (%)	Transversal reinforcement	ρ_w (%)	Condition	Designation
		Tension	Compression					
Column Axial	300 × 300	4Φ12		0.50	1Φ8/140 mm	0.24	Control column Repair 15 mm Repair 50 mm	P00_a; P00_b P15_a; P15_b P50_a; P50_b

Results:

Dimensions, Rebar, and Repair of Columns

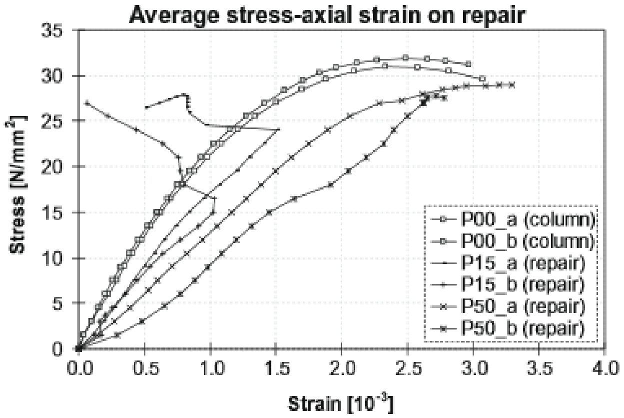


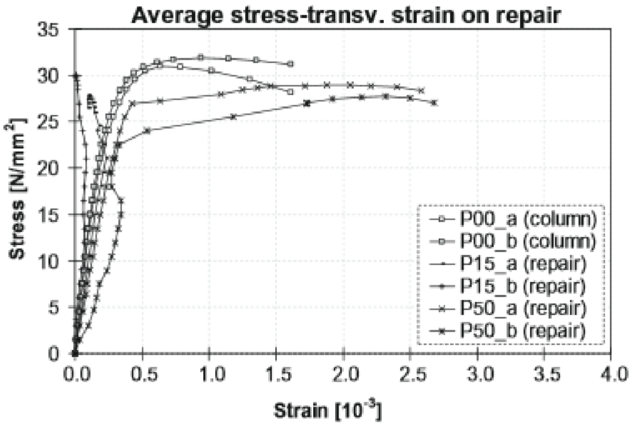
Axial Test Results

Column	Debonding load (kN) (a)	Ultimate load (kN) (b)	(a)/(b)
P00_a	–	2929	–
P00_b	–	2869	–
P15_a	1901	2507	0.76
P15_b	1575	2709	0.58
P50_a	2430 (partial)	2606	0.93
P50_b	2160 (partial)	2501	0.86

Stresses and Strains of Axial Tests

Column		Stress (N/mm^2)	1/3 Ultimate load		(a)/(b)	Stress (N/mm^2)	Debonding		Ultimate Load	
			Transv. strain (a) (10^{-3})	Axial strain (b) (10^{-3})			Transv. strain (10^{-3})	Axial strain	Stress (N/mm^2)	Axial Strain (10^{-3})
P00_a		10.3	0.08	–0.41	–0.19	–	–	–	31.0	–2.41
P00_b		10.6	0.08	–0.39	–0.20	–	–	–	31.9	–2.52
P15_a	Column	9.3	0.06	–0.31	–0.21	21.1	0.20	–0.97	27.9	–2.25
	Repair		0.09	–0.51	–0.18		0.23	–1.30		–0.79
P15_b	Column	10.0	0.06	–0.30	–0.21	17.5	0.13	–0.55	30.1	–2.11
	Repair		0.06	–0.38	–0.15		0.06	–1.08		–0.54
P50_a	Column	9.7	0.05	–0.23	–0.20	27.0	0.25	–1.48	29.0	–2.28
	Repair		0.12	–0.74	–0.16		0.43	–2.25		–3.30
P50_b	Column	9.3	0.05	–0.24	–0.23	24.0	0.29	–1.06	27.8	–2.21
	Repair		0.24	–1.00	–0.24		0.54	–2.40		–2.71





Effectiveness of the Method:
This polymer-modified cementitious mortar can be effective, but depends upon the position and thickness of the repair layer. The layers (15 mm and 50 mm) for each of the columns tested debonded before failure—demonstrating the importance of a durable interface mechanism. This method could not restore the original load-bearing capacity of columns, but did improve the capacity. Including longitudinal reinforcement is recommended, since it results in stable behavior, loading sharing, and material plasticization before failure.

Rodriguez M., and Park K. 1994. "Seismic Load Tests on Reinforced Concrete Columns Strengthened by Jacketing," ACI Structural Journal, 91, No.2, 150-159

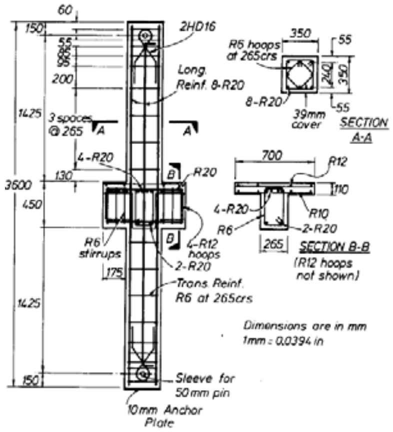
Significance

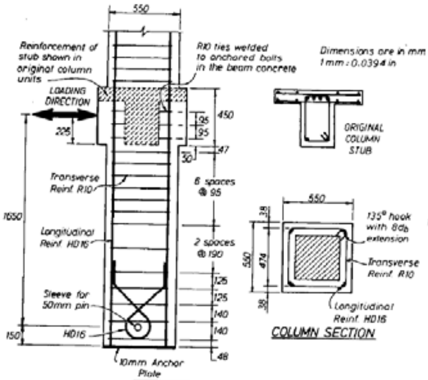
This research is focused on enhancing the strength, stiffness and ductility of existing Reinforced Concrete columns by using reinforced concrete jacketing. For the study the details of existing 7 story building is taken built during 1950. A total of four columns were built and tested and jacketed, subjecting them to simulated seismic loading. Results of the test indicated that strength and stiffness increased by 3 folds for the jacketed column. Directly strengthened specimen exhibited slightly higher strength compared to repaired and strengthened specimen'. However, ductility performance remained the same.

Specimen Properties and Results:

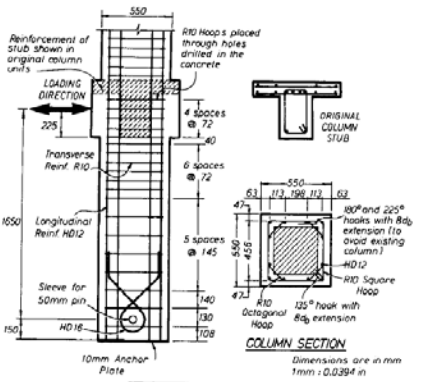
Column	Diam of retrofit long. reinf. (mm)	Maximum Load (kN)	Displacement Ductility
S1		250	6.1
S4		225	5.6
SS1	16	700	8.8
SS2	16	800	9
SS3	12	600	10.6
SS4	12	550	9.9

Height: 3300 mm	Yield strength of transverse steel: 350 MPa
Cross-section: 350 mm x 350 mm	Yield strength longitudinal Steel: 300 MPa
Concrete strength: 20 MPa	Diam/spacing of transverse reinforcement in RCJ: 10 mm
Boundary: Fixed-Fixed	RC jacket thickness: 100 mm
RCJ height: 900 mm	

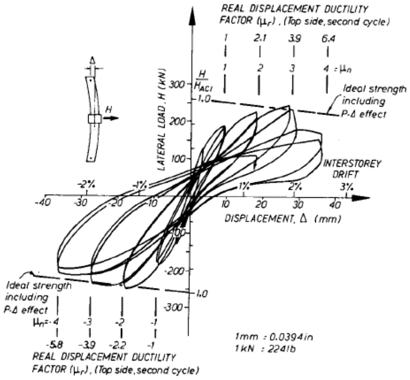




(a) UNITS SS1 & SS2



(b) UNITS SS3 & SS4



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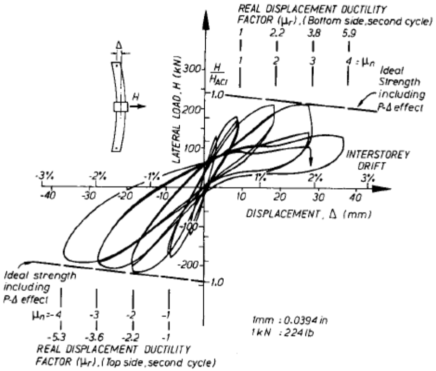

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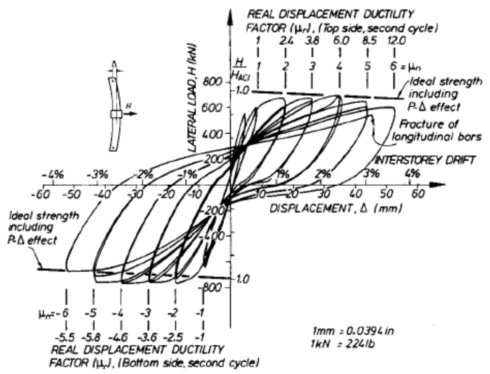

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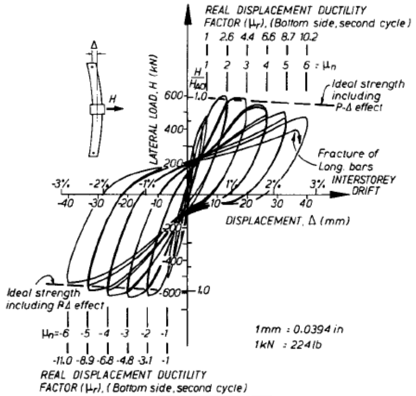

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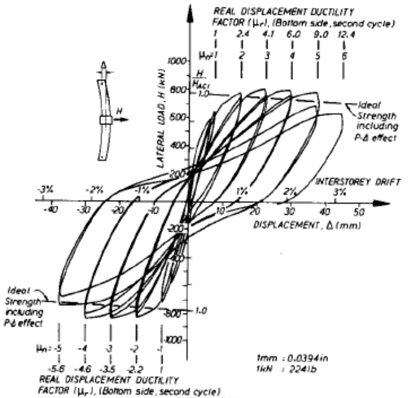

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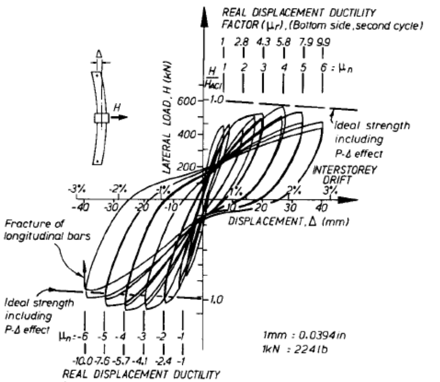


(d) UNIT SS4

Effectiveness of the Method

1) The surface treatment of as built column by chipping guaranteed good bonding between the jacket and column.
2) The octagonal shape of transverse reinforcement provided better confinement to column for retrofitted specimen.

Sengottian, K., and Jagadeesan, K. (November 11, 2013). Retrofitting of Columns with RC Jacketting an Experimental Behavior. Journal of Theoretical and Applied Information Technology, 56, 3, 349-354.

Significance:
Helical ties and vertical rods were tested in reinforced concrete jackets to improve the strength of reinforced concrete columns. 6 sets of 3 columns for a total of 18 columns were tested axially. The average of each set of 3 columns was used in results and calculations. Gauges were used to measure lateral displacements at the column mid-height. Strain gauges measured the concrete strain.

Loading/Images:
Concrete Properties:

M25 Grade Concrete	W/C ratio .45
6 mm diameter reinforcement	100mm c/c spacing
Diameter: 150mm	Column: 1200 mm

Results:

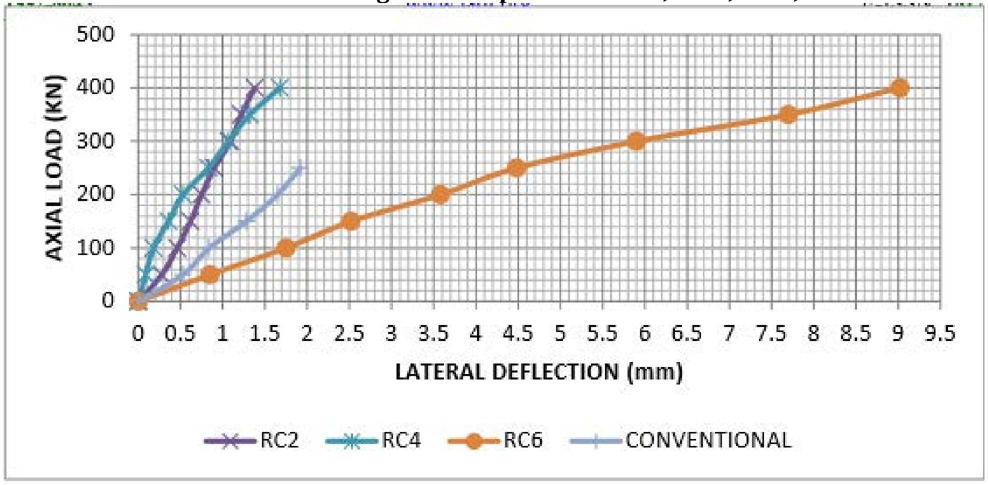
Load Carrying Capacity of Specimens

Specimen	Cracking Load (Kn)	Ultimate Load (Kn)
C	180	242
RC1	336	410
RC2	383	470
RC3	323	406
RC4	373	450
RC5	350	422
RC6	360	440

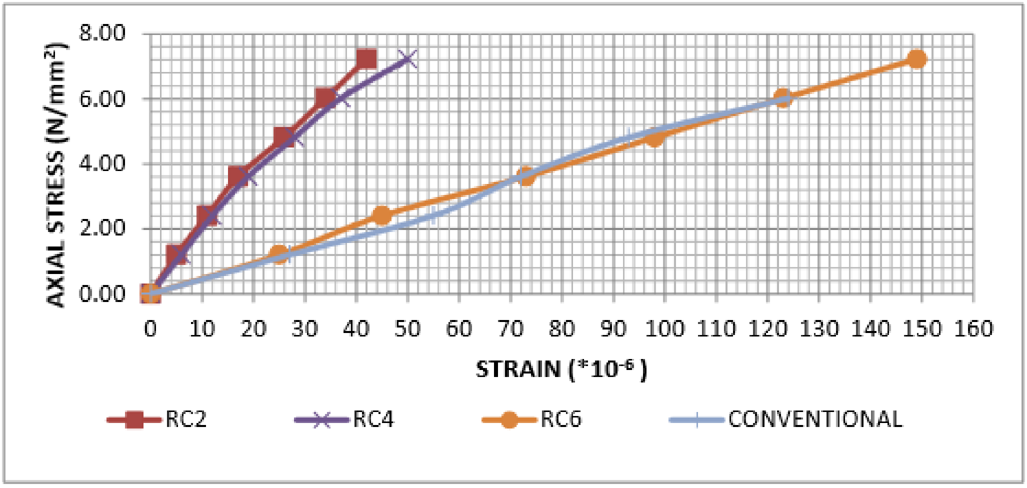
Details of Test Specimens

Group	% of ultimate load applied	Number of longitudinal reinforcement
RC1	50	2
RC2	50	6
RC3	60	2
RC4	60	6
RC5	70	2
RC6	70	6

Load versus Lateral Deflection Diagram for Specimens RC2, RC4, RC6, and Conventional



Axial Stress versus Axial Strain for Specimens RC2, RC4, RC6, and Conventional



Effectiveness of the Method:
Longitudinal and spiral reinforced concrete jackets effectively increased load carrying capacity significantly. The beginning portions of the load-deflection curves were nearly the same for the conventional columns as for the jacketed columns; however, confinement was visible in the later portion of loading. Loading to a larger percentage of ultimate load applied resulted in more ductile response.

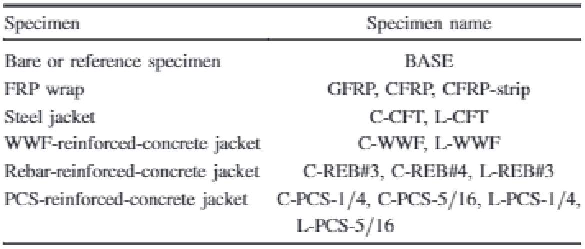
Sezen, H., and Miller, E. A. (March 01, 2011). Experimental Evaluation of Axial Behavior of Strengthened Circular Reinforced-concrete Columns. Journal of Bridge Engineering, 16, 2, 238-247.

Significance

Sezen et al. test steel jacketing, Fiber-reinforced polymer (FRP) composites, concrete jackets reinforced with spiral rebar, welded wire fabric (WWF), and a new steel reinforcement method called PCS methods to retrofit reinforced concrete columns. Fifteen columns are tested under different axial-load applications.

Loading/beam Images

Reference and Strengthened Specimen

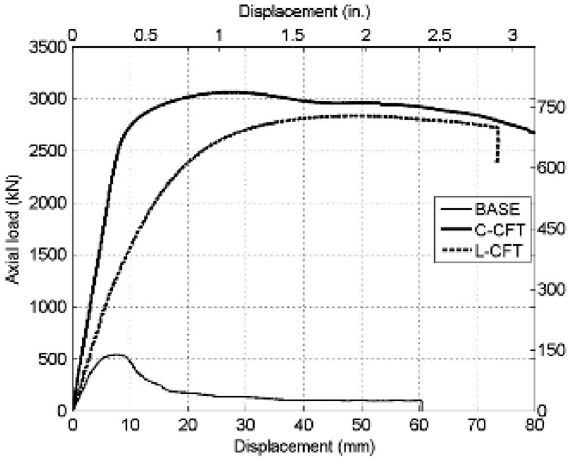


Specimen	Specimen name
Bare or reference specimen	BASE
FRP wrap	GFRP, CFRP, CFRP-strip
Steel jacket	C-CFT, L-CFT
WWF-reinforced-concrete jacket	C-WWF, L-WWF
Rebar-reinforced-concrete jacket	C-REB#3, C-REB#4, L-REB#3
PCS-reinforced-concrete jacket	C-PCS-1/4, C-PCS-5/16, L-PCS-1/4, L-PCS-5/16

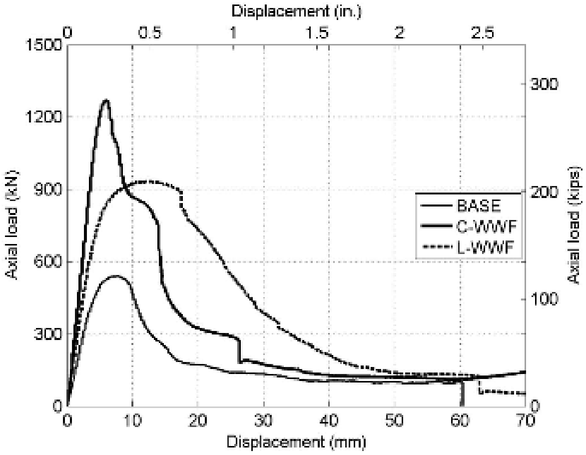
Results

The steel jacket improved initial stiffness, strength, and deformation of the retrofitted columns. When axial load was only applied to the concrete at the base, and not the jacket, the confinement provided by the steel jacket was adequate. At around the maximum axial capacity of the base column, concrete spalling occurred in the WWF columns. This method only increased deformation capacity slightly, while only providing moderate stiffness and strength increases. The concrete jacket with rebar had similar spalling. Thinner PCS reinforcement resulted in better post peak behavior. After spalling, longitudinal PCS buckled.

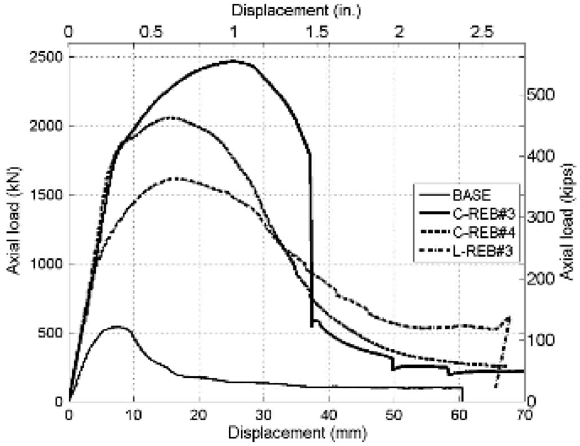
Experimental Axial Load-Displacement for BASE and SJ



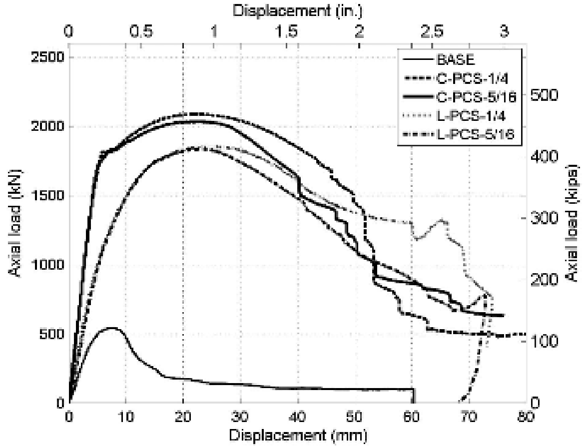
Experimental Axial Load-Displacement for BASE and WWF



Experimental Axial Load-Displacement for BASE and Rebar



Experimental Axial Load-Displacement for BASE and PCS



Effectiveness of the Method

The jacket should be extended to the top and bottom face of the column, so load is applied across the new cross-section. WWF and FRP improved capacity greatly (140%) but brittle failure occurred right after the peak capacity. FRP strips were less effective and ruptured earlier. Rebar and WWF methods had similar stiffnesses before cracking. Rebar and PCS had similar load-displacement behavior until the peak. Steel jackets improved strength, stiffness, and displacement the most. PCS was as effective until the concrete cracked.

Takeuti A.R.,Hanai J.B and Mirmiran A. 2008."Preloaded RC Columns Strengthened with High-strength Concrete Jackets Under Uniaxial Compression," Materials and structures, 41, 1251-1262.

Significance

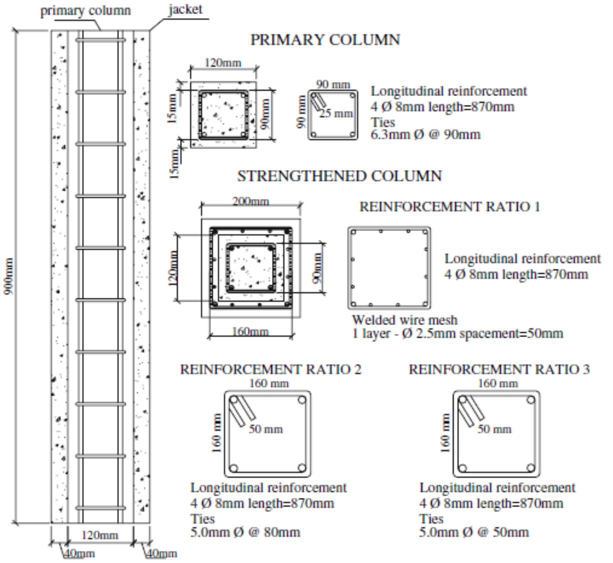
This paper describes two groups of columns strengthened with high strength reinforced concrete jackets. One group had square cross-section and the other circular. 50% of the specimens were preloaded before strengthening. Column specimens were subjected to axial force till failure and the results showed that preloading did not have much impact on axial capacity of the strengthened columns. The ductility levels were high among circular columns than the square columns.

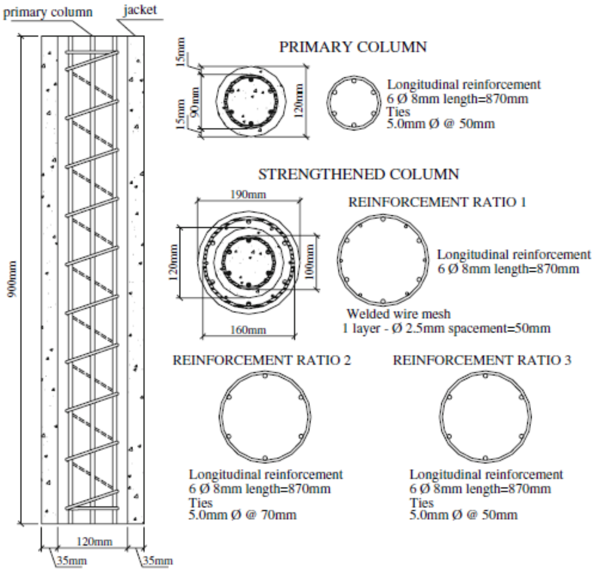
Material and retrofit properties of square columns

Column	Compressive Strength (Mpa)	Transverse Reinforcement				Jacket Compressive Strength (MPa)	Jacket			
		Type	Size (mm)	Spacing (mm)	Y.S (Mpa)		Type	Size (mm)	Spacing (mm)	Y.S (MPa)
S1P	32.7	tie	6.3	90	652	54	Mesh	2.5	50	634
S1N	32.7	tie	6.3	90	652	54	Mesh	2.5	50	634
S2P	32.7	tie	6.3	90	652	80	Tie	5	70	724
S2N	32.7	tie	6.3	90	652	80	Tie	5	70	724
S3P	24.8	tie	6.3	90	652	81.9	Tie	5	50	724
S3N	24.8	tie	6.3	90	652	81.9	Tie	5	50	724

Material and retrofit properties of circular columns

Column	Compressive Strength (Mpa)	Transverse Reinforcement				Jacket Compressive Strength (MPa)	Jacket			
		Type	Size (mm)	Spacing (mm)	Y.S (Mpa)		Type	Size (mm)	Spacing (mm)	Y.S (MPa)
C1P	31.4	Hoop	5	50	724	74	Mesh	2.5	50	634
C1N	31.4	Hoop	5	50	724	74	Mesh	2.5	50	634
C2P	31.4	Hoop	5	50	724	63.3	Hoop	5	70	724
C2N	31.4	Hoop	5	50	724	63.3	Hoop	5	70	724
C3P	24.8	Hoop	5	50	724	77.9	Hoop	5	50	724
C3N	24.8	Hoop	5	50	724	77.9	Hoop	5	50	724





Results of the test

Specimen Pair	Capacity of Primary Column (kN)	Peak Load(kN)	
		N.P	P
S1	377	1557	1675.9
S2	375.2	1650	1623.7
S3	247.1	1684	1822.2
C1	266.5	1251.8	1429.6
C2	267.3	1291.5	1436.6
C3	196.8	1303.3	1385.9

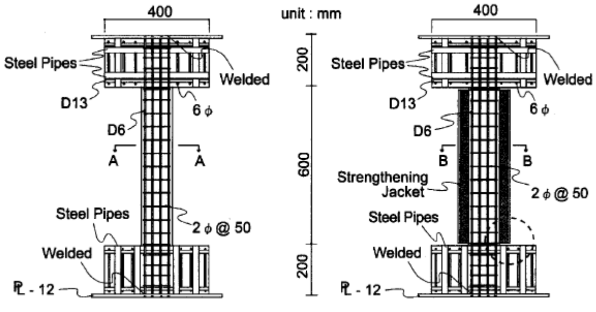
Effectiveness of the method

The application of high strength concrete results in thinner jacket, as a result occupies lesser floor area of a building. Also, the weight of the structure is reduced to some extent. However, the cost of high strength concrete is more than that of ordinary concrete, the application of which is to be debated based on the scale of construction involved.

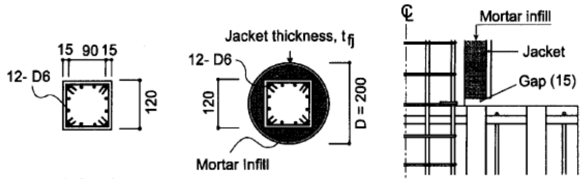
Takiguchi, K and Abdullah. 2001. "Shear Strengthening of Reinforced Concrete Columns Using Ferrocement Jacket," ACI Structural Journal, 98, 5, 696-704.

Significance

The research impetus for this paper is on increasing the shear strength of RC column by ferrocement jacket. The variables for the experiments were the number of layers of wire mesh used for retrofitting. Column specimens were subjected to cyclic loading while maintaining constant axial force. Test results showed that more the number of wire mesh layers better was the ductility performance of the column. Shear strength of the repaired column increased with respect to original column, and remained constant irrespective of the number of wire mesh layers.



(a) Original column (b) Strengthened column



A-A Section B-B Section

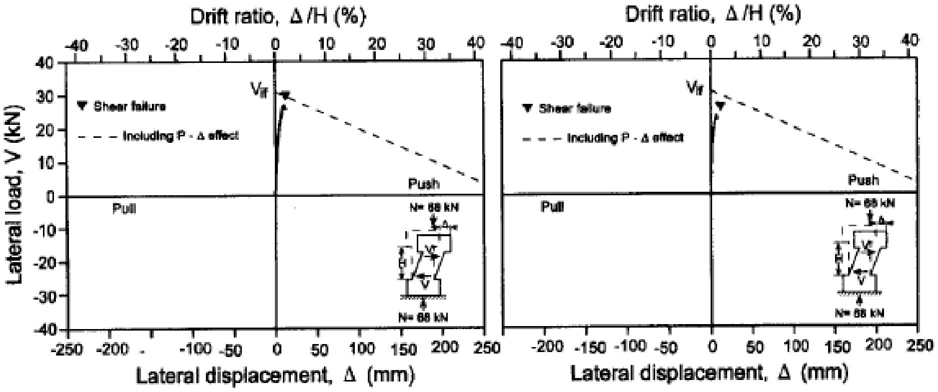
Material Properties

Yield strength of longitudinal steel: 374 Mpa

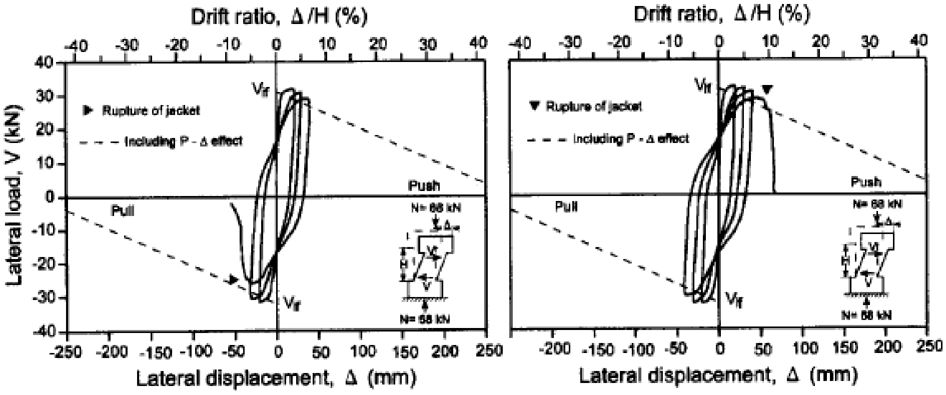
Yield strength of transverse steel: 697 Mpa

Ferrocement Jacket

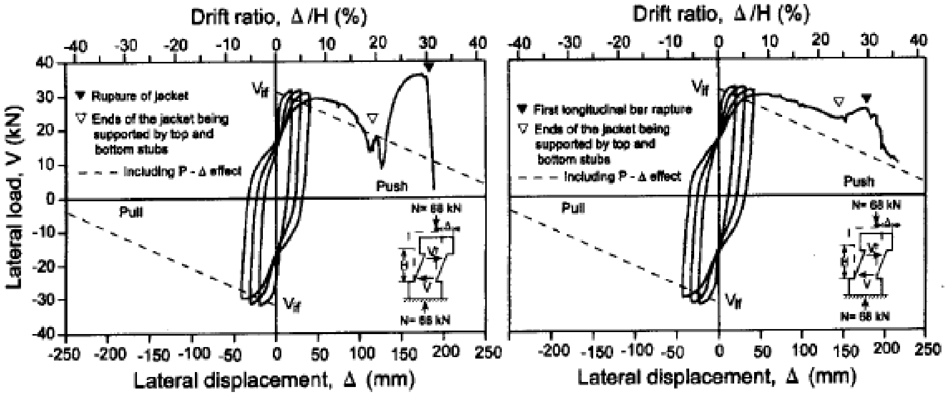
Column Specimen	Tensile Strength f_l (Mpa)	No of Layers	Volume Fraction V_{RL} (%)
FSC-2L	4.12	2	1.54
FSC-3L	5.43	3	2.03
FSC-4L	6.47	4	2.42
FSC-6L	7.99	6	2.99



(a) Column CS-1 (b) Column CS-2



(a) Column FSC-2L (b) Column FSC-3L



(c) Column FSC-4L (d) Column FSC-6L

Effectiveness of Method

Shear strength of strengthened columns improved by more than 25%. Even with only 3 layers of wire mesh, ductility improved significantly. When a 15mm gap was provided, the strengthened columns did not increase in flexural capacity--a preference to avoid overloading the footings. Columns FSC-4L and FSC-6L had ductile response until a drift ratio of 10%.

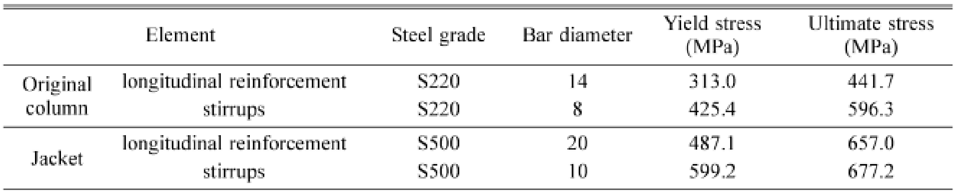
Vandoros, K. G., and Dritsos, S. E. (May 10, 2006a). Interface Treatment in Shotcrete Jacketing of Reinforced Concrete Columns to Improve Seismic Performance. Structural Engineering and Mechanics, 23, 1, 43-61.

Significance:

This experiment focused on the effectiveness of the interface connections. Connection techniques analyzed were roughening the surface, embedding steel dowels, and a combination of both options. Three strengthened columns, one unstrengthened column, and one as-built monolithic specimen were tested. Columns were half-height full-scale columns representing old Greek Code columns with shotcrete jackets. Specimens were compared based on strength, stiffness, and hysteretic response. A constant load axial load was applied and a horizontal cyclic load was applied at the top of the unjacketed part of the column.

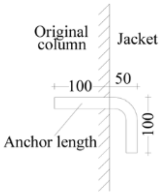
Loading/Images:

Steel Characteristics



Element		Steel grade	Bar diameter	Yield stress (MPa)	Ultimate stress (MPa)
Original column	longitudinal reinforcement	S220	14	313.0	441.7
	stirrups	S220	8	425.4	596.3
Jacket	longitudinal reinforcement	S500	20	487.1	657.0
	stirrups	S500	10	599.2	677.2

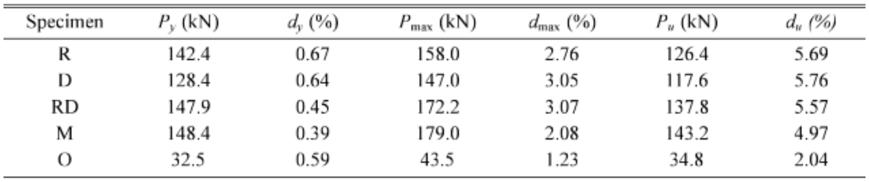
Interface Treatment for Jacket



R: Roughening D: Dowel Placement RD: Combined Roughening and Dowel Placement
Roughening a depth of 6mm using mechanical scabbler.

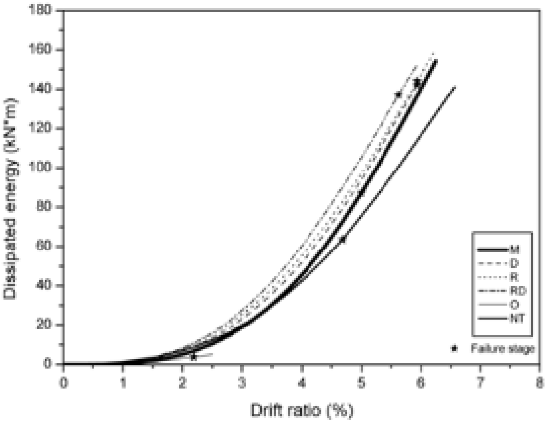
Results:

Test Results

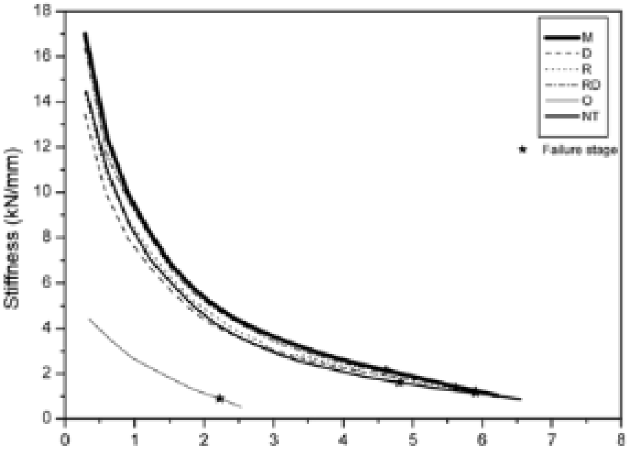


Specimen	P_y (kN)	d_y (%)	P_{max} (kN)	d_{max} (%)	P_u (kN)	d_u (%)
R	142.4	0.67	158.0	2.76	126.4	5.69
D	128.4	0.64	147.0	3.05	117.6	5.76
RD	147.9	0.45	172.2	3.07	137.8	5.57
M	148.4	0.39	179.0	2.08	143.2	4.97
O	32.5	0.59	43.5	1.23	34.8	2.04

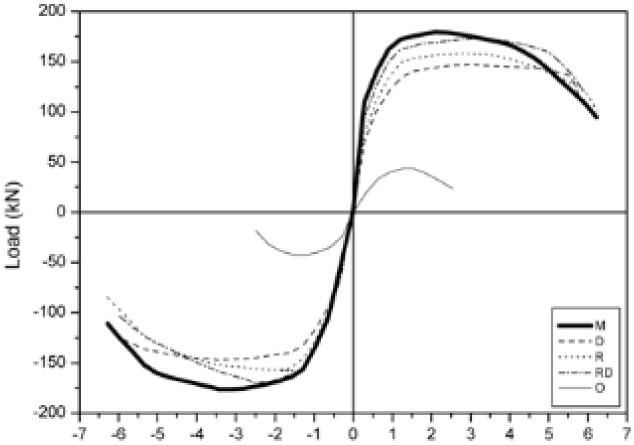
Dissipated Energy Rate for All Specimens



Stiffness Against Displacement Envelopes for All Specimens



Load Against Drift Ratio Envelopes for All Specimens



During all loading stages RD performed similarly to the monolithic column, and dowels were the least effective.
All strengthened columns had larger drift ratios at all stages due to interface slippage. The weaker columns had larger drift ratios and less stiffness than the stronger columns. All strengthened columns had larger dissipated energy rates.

Effectiveness of the Method:

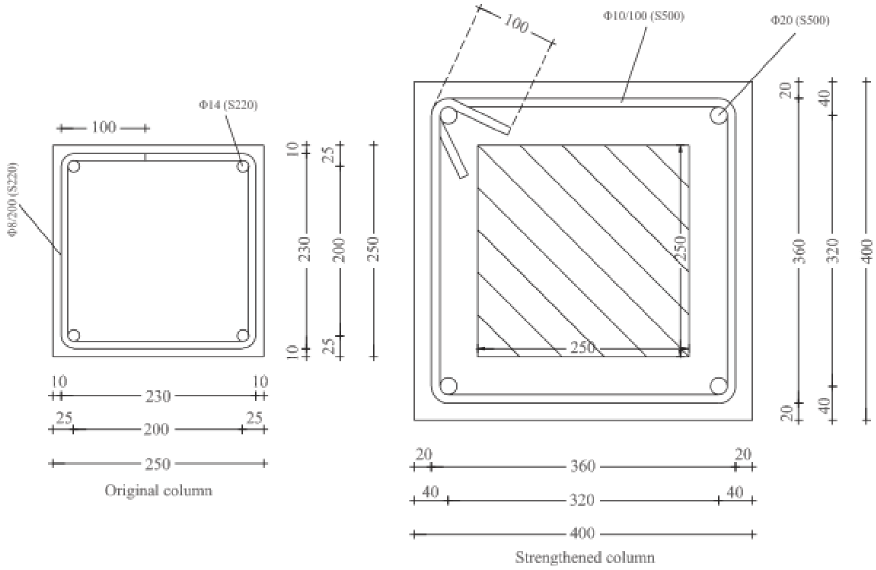
The different methods of interface treatment can influence the failure mechanism and crack patterns. Roughening with dowel placement performed the best, but all strengthened columns were better at dissipating energy. The strengths and stiffness of strengthened specimens were slightly lower than for the monolithic specimen, but drift ratios and energy dissipation rates were higher during all loading stages. The additional energy dissipation mechanisms of friction at the interface and dowel action can cause these larger energy dissipation rates. Providing dowels and roughening the surface develops capacity similar to a monolithic column, and monolithic behavior can be assumed.

Vandoros, K. G., and Dritsos, S. E. (July 01, 2006b). Axial Preloading Effects when Reinforced Concrete Columns are Strengthened by Concrete Jackets. Progress in Structural Engineering and Materials, 8, 3, 79-92.

Significance:
The axial preloading effects on concrete columns with concrete jackets are analyzed in this article. Different concrete strengths, jacket strengths and axial loads are compared. The columns are tested with a horizontal displacement actuator with a poor interface connection at the original column and jacket. Two monolithic control specimens were tested as well.

Loading/beam Images:

Cross-Sectional Characteristics



Original column

Strengthened column

Results:

Test Summary and Results

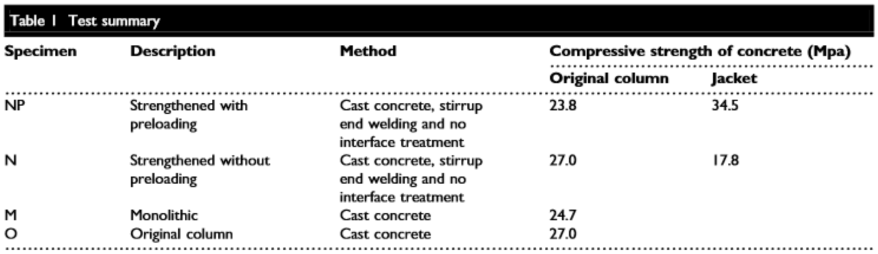


Table 1 Test summary

Specimen	Description	Method	Compressive strength of concrete (Mpa)	
			Original column	Jacket
NP	Strengthened with preloading	Cast concrete, stirrup end welding and no interface treatment	23.8	34.5
N	Strengthened without preloading	Cast concrete, stirrup end welding and no interface treatment	27.0	17.8
M	Monolithic	Cast concrete	24.7	
O	Original column	Cast concrete	27.0	

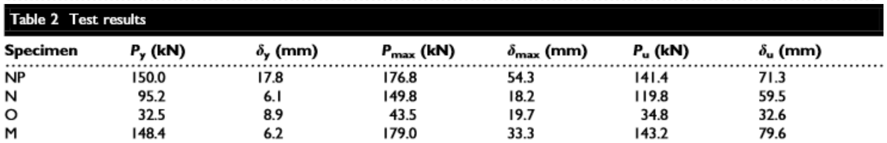
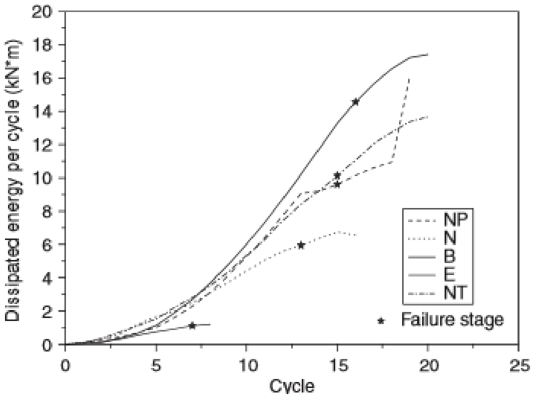


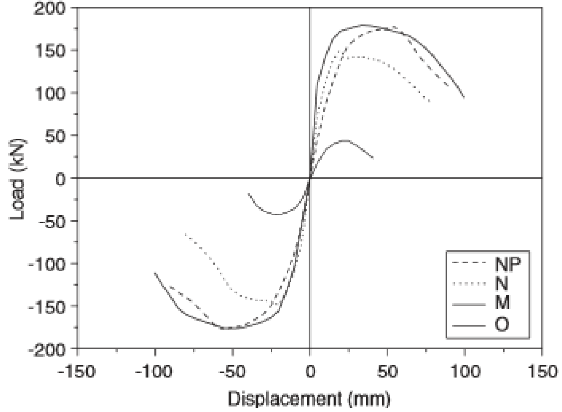
Table 2 Test results

Specimen	P_y (kN)	δ_y (mm)	P_{max} (kN)	δ_{max} (mm)	P_u (kN)	δ_u (mm)
NP	150.0	17.8	176.8	54.3	141.4	71.3
N	95.2	6.1	149.8	18.2	119.8	59.5
O	32.5	8.9	43.5	19.7	34.8	32.6
M	148.4	6.2	179.0	33.3	143.2	79.6

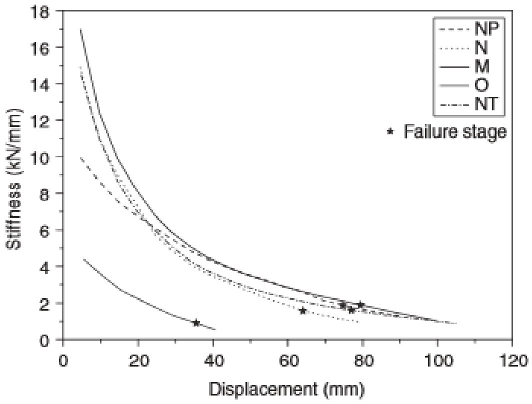
Dissipated Energy Rate Per Cycle



Load vs Displacement Envelopes



Stiffness vs Displacement Envelopes



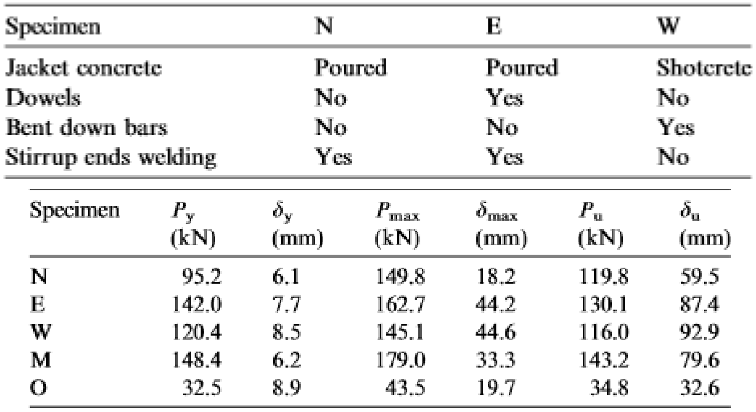
Effectiveness of the Method:
Strengthened columns improved in strength, stiffness, deformation capacity, and energy dissipation. The preloaded column had higher strengths, displacements, and retained stiffness, but had reduced initial stiffness, than the column that was not preloaded. Preloading helped the column dissipate energy during testing more than when constructing the jacket, due to the lower jacket stresses. Shoring of columns is recommended so jacket can carry much of the axial load. Theoretical values were determined assuming monolithic behavior. As a result, the lateral load test results were all lower than the theoretical values.

Vandoros, K. G., and Dritsos, S. E. (March 01, 2008). Concrete Jacket Construction Detail Effectiveness when Strengthening RC Columns. Construction and Building Materials, 22, 3, 264-276.

Significance:
Three methods for retrofitting half-height full-size concrete columns strengthened with concrete jackets were compared. Columns represented typical ground floor columns based on 1950s Greek Codes. Jackets were compared based on strength, stiffness, and hysteretic response. The columns tested were a column with welded jacket stirrup ends, one with dowels and jacket stirrup end welding, and bent down steel connector bars welded to the original column longitudinal bars and jacket bars. One monolithic and one unstrengthened column were also tested. A constant axial load and horizontal cyclic loads were applied.

Loading/Images:

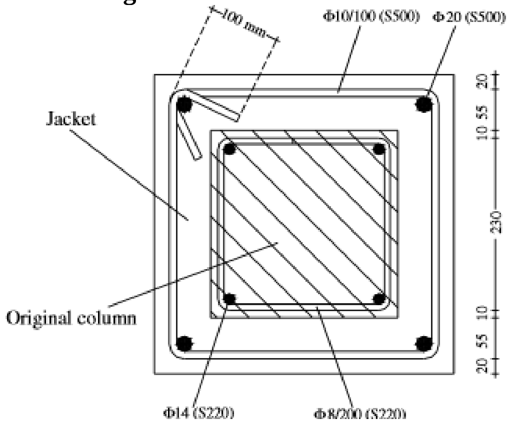
Specimen Characteristics and Results



Specimen	N	E	W
Jacket concrete	Poured	Poured	Shotcrete
Dowels	No	Yes	No
Bent down bars	No	No	Yes
Stirrup ends welding	Yes	Yes	No

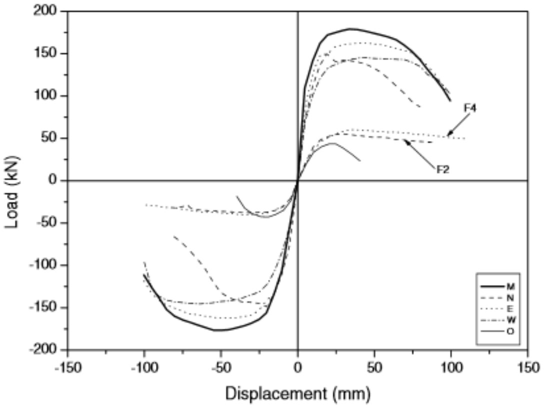
Specimen	P_y (kN)	δ_y (mm)	P_{max} (kN)	δ_{max} (mm)	P_u (kN)	δ_u (mm)
N	95.2	6.1	149.8	18.2	119.8	59.5
E	142.0	7.7	162.7	44.2	130.1	87.4
W	120.4	8.5	145.1	44.6	116.0	92.9
M	148.4	6.2	179.0	33.3	143.2	79.6
O	32.5	8.9	43.5	19.7	34.8	32.6

Strengthened Column Cross-Section

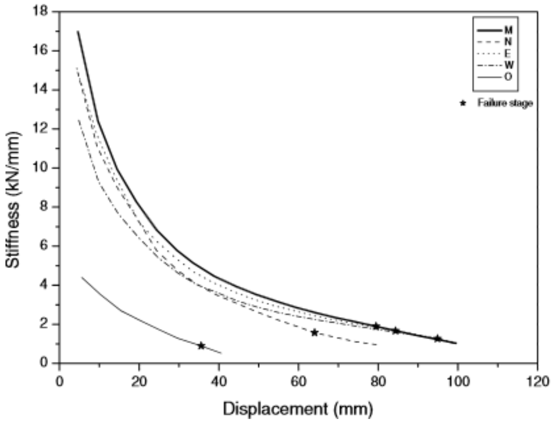


Results:

Load vs Displacement Envelopes for All Specimens



Stiffness Against Displacement Envelopes for All Specimens



Dissipated Energy Rate for All Specimens

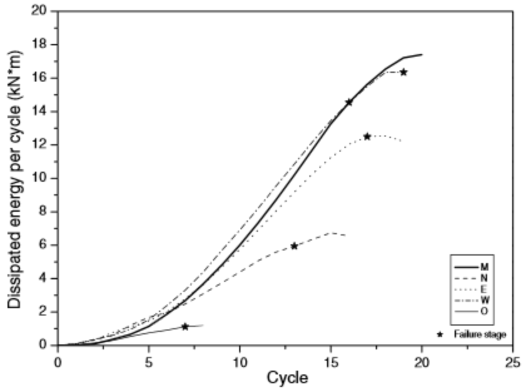


Fig. 22. Dissipated energy rate for all specimens.

Cumulative Dissipated Energy for All Specimens

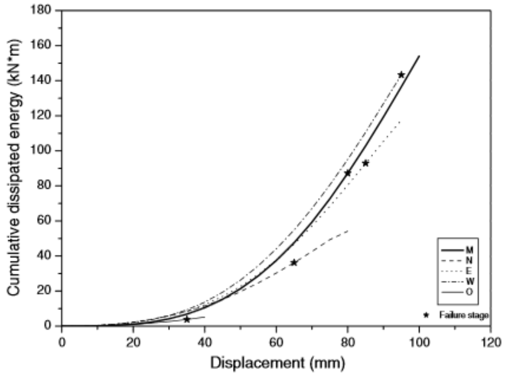


Fig. 23. Cumulative dissipated energy for all specimens.

Effectiveness of the Method:
Even columns with no treatment showed significant strength and stiffness increases. While the column with no treatment had significantly lower capacity, the differences up to the maximum loading stage were negligible. Welding jacket stirrup ends stopped longitudinal bars in the jacket from buckling. Concrete jackets improve the ductility and greatly improves the strength and stiffness of strengthened columns versus those with CFRP. Column E performed closest to the monolithic column due to the higher concrete strength and that W had minor cracking. Improving the strength of poured concrete jackets instead of shotcrete jackets can be accomplished by welding stirrup ends together. Concrete jackets increase the strength and stiffness of columns, while CFRP increase ductility.

Appendix B: Steel Jacketing One-Pagers

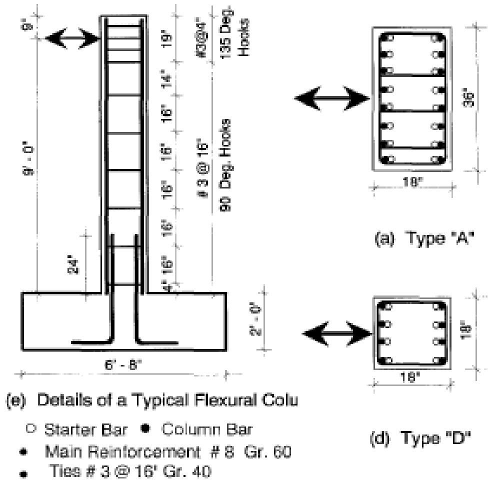
Aboutaha, R.S., Engelhardt, M.D., Jirsa, J.O., and Kreger, M.E. 1996. "Retrofit of Concrete Columns with Inadequate Lap Splices by the Use of Rectangular Steel Jackets," Earthquake Spectra, V.12, No.4, pp. 693-714.

Significance

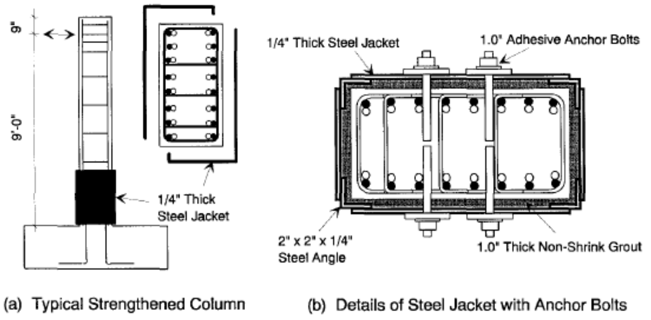
This research is focussed on retrofit of splice defecient columns by providing steel plates in the potential plastic hinge regions of the columns. All columns were provided with anchor bolts in addition to steel jacket. Test results indicated that flexural strength of the columns were maintained at large drift ratios. Anchor bolts enhanced the stiffness of the steel jackets. Overall, the retrofitted specimen showed improved cyclic behavior.

Material and Retrofit Properties

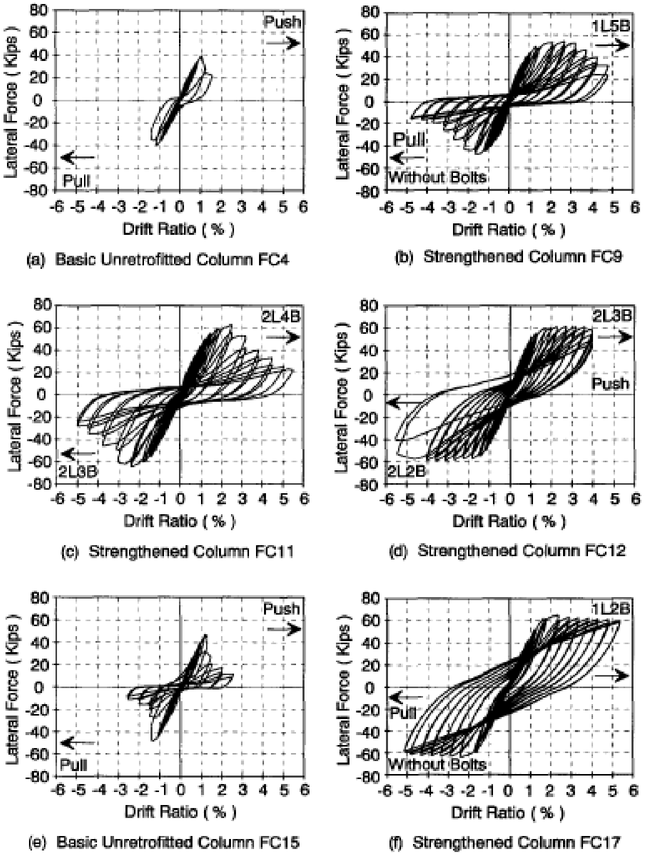
Specimen	Type	X-Sec.	Concrete Strength fc' (psi)	Retrofit	Bolts	Bolt Vertical Spacing (in.)	Comment
FC4	Basic	A	3170	N/A	N/A	-	LSJ - Long steel Jacket(34.5" high)
FC9	Strengthened	A	3075	LSJ/B	1L5B	6	SSJ - Short steel Jacket(27" high)
FC11	Strengthened	A	2725	SSJ/B	2L4B	6	B - Adhesive Anchor Bolts
FC12	Strengthened	A	3225	LSJ/B	2L3B	12	L - Vertical Line
FC15	Basic	D	4165	N/A	N/A	-	*(2L3B indicates 2 vertical*
FC17*	Strengthened	D	2600	LSJ/B	1L2B	20	*lines of bolt, with 3 bolts in each line)*
* specimen has additional angles at the corners(3" x 3" x 1/4")							



Details of Basic Test Columns



Details of Strengthened Columns



Hysteretic Response of Test Columns

Effectiveness of the Method

The best bet in terms of seismic performance is the specimen FC17, since this has the maximum energy dissipation and has fewer bolts which reduces the cost and labour. Closer the spacing of bolts in the specimen, pinching of the hysterisis loop was observed. This resulted in degradation of lateral force with increasing drift ratio.

Test Results

Specimen	Displacement Ductility, μ (predicted)	Lateral Force Peak(kN)
FC4	2.5	40
FC9	6	55
FC11	6.87	63
FC12	5.71	61
FC15	3.12	48
FC17	5	63

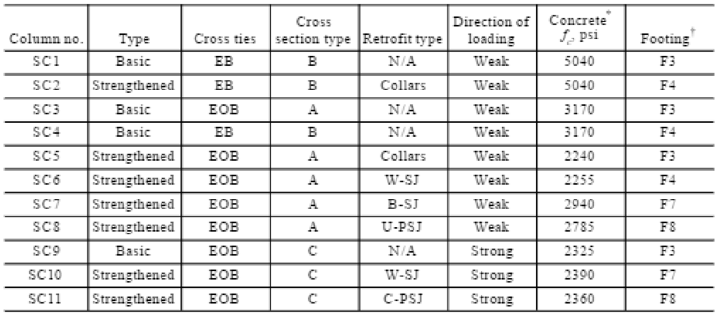
Aboutaha, R. S., Engelhardt, M. D., Jirsa, J. O., & Kreger, M. E. (January 01, 1999). Rehabilitation of Shear Critical Concrete Columns by Use of Rectangular Steel Jackets. ACI Structural Journal, 96, 1, 68.

Significance

Aboutaha et al. tested rectangular steel jackets on 11 non-ductile reinforced concrete frame columns with inadequate shear strength for seismic retrofit. Different types of steel jackets were tested, including solid and partial jackets. Cyclic lateral forces were applied to the half scale column. The column was cantilevered and framed into a fixed end large footing.

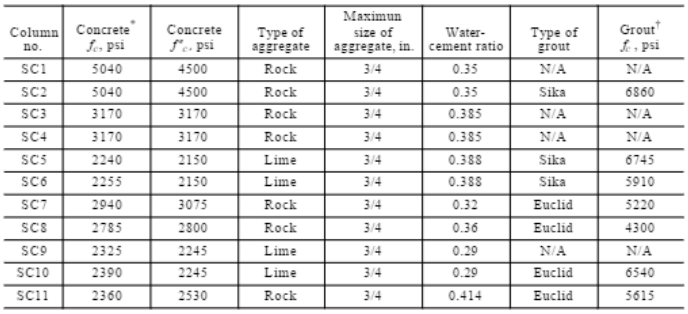
Loading/beam Images

Summary of Shear Columns



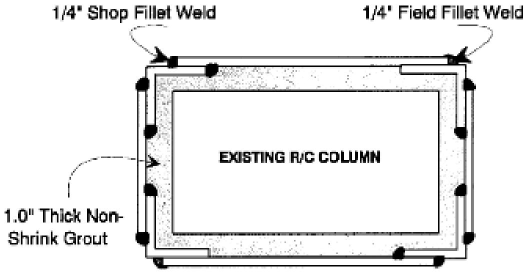
Column no.	Type	Cross ties	Cross section type	Retrofit type	Direction of loading	Concrete* f_c, psi	Footing†
SC1	Basic	EB	B	N/A	Weak	5040	F3
SC2	Strengthened	EB	B	Collars	Weak	5040	F4
SC3	Basic	EOB	A	N/A	Weak	3170	F3
SC4	Basic	EB	B	N/A	Weak	3170	F4
SC5	Strengthened	EOB	A	Collars	Weak	2240	F3
SC6	Strengthened	EOB	A	W-SJ	Weak	2255	F4
SC7	Strengthened	EOB	A	B-SJ	Weak	2940	F7
SC8	Strengthened	EOB	A	U-PSJ	Weak	2785	F8
SC9	Basic	EOB	C	N/A	Strong	2325	F3
SC10	Strengthened	EOB	C	W-SJ	Strong	2390	F7
SC11	Strengthened	EOB	C	C-PSJ	Strong	2360	F8

Concrete and Grout Properties for Shear Columns

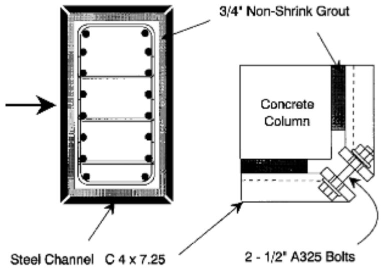


Column no.	Concrete* f_c, psi	Concrete f''_c, psi	Type of aggregate	Maximun size of aggregate, in.	Water-cement ratio	Type of grout	Grout† f_c, psi
SC1	5040	4500	Rock	3/4	0.35	N/A	N/A
SC2	5040	4500	Rock	3/4	0.35	Sika	6860
SC3	3170	3170	Rock	3/4	0.385	N/A	N/A
SC4	3170	3170	Rock	3/4	0.385	N/A	N/A
SC5	2240	2150	Lime	3/4	0.388	Sika	6745
SC6	2255	2150	Lime	3/4	0.388	Sika	5910
SC7	2940	3075	Rock	3/4	0.32	Euclid	5220
SC8	2785	2800	Rock	3/4	0.36	Euclid	4300
SC9	2325	2245	Lime	3/4	0.29	N/A	N/A
SC10	2390	2245	Lime	3/4	0.29	Euclid	6540
SC11	2360	2530	Rock	3/4	0.414	Euclid	5615

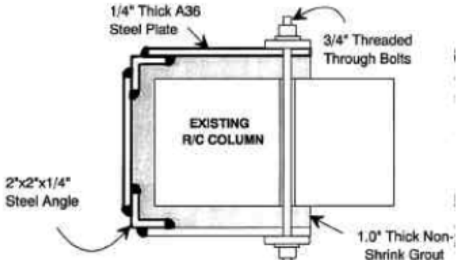
Details of Welded Solid Steel Jacket



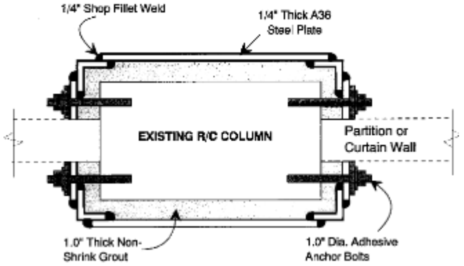
Details of Steel Collars



Details of U-Shaped Partial Steel jacket

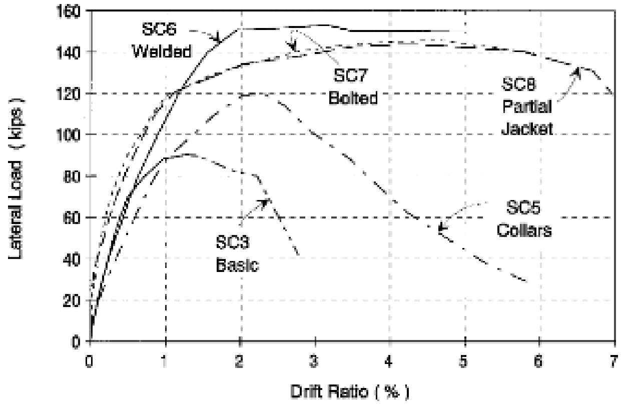


Details of C-Shaped Partial Steel Jacket

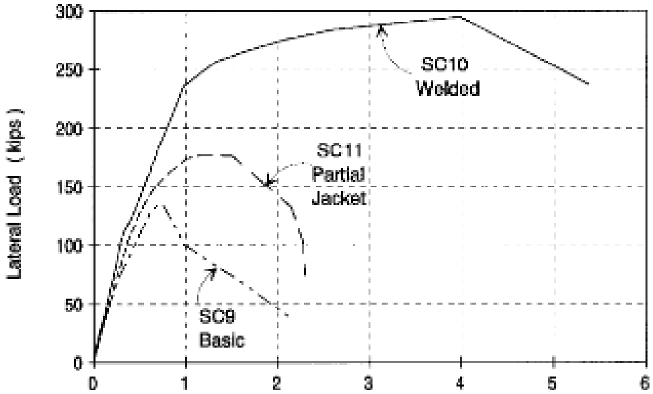


Results

Cyclic Response Envelopes for Loading in the Weak Direction



Cyclic Response Envelopes for Loading in the Strong Direction



Effectiveness of the Method

A thin rectangular steel jacket can be highly effective at retrofitting reinforced concrete columns with inadequate shear strength. The steel jackets were effective at improving flexural yield capacity, improving ductility, and having a higher energy dissipation. Despite large lateral displacements, the steel jackets had low maximum strains due to the confinement preventing major shear cracks from opening. Yielding in the steel jacket may reduce stiffness and strength with more crack openings; thus, jacket yielding should be prevented for better performance. Welded or bolted connections at the jacket corners adequately developed the forces in the ties.

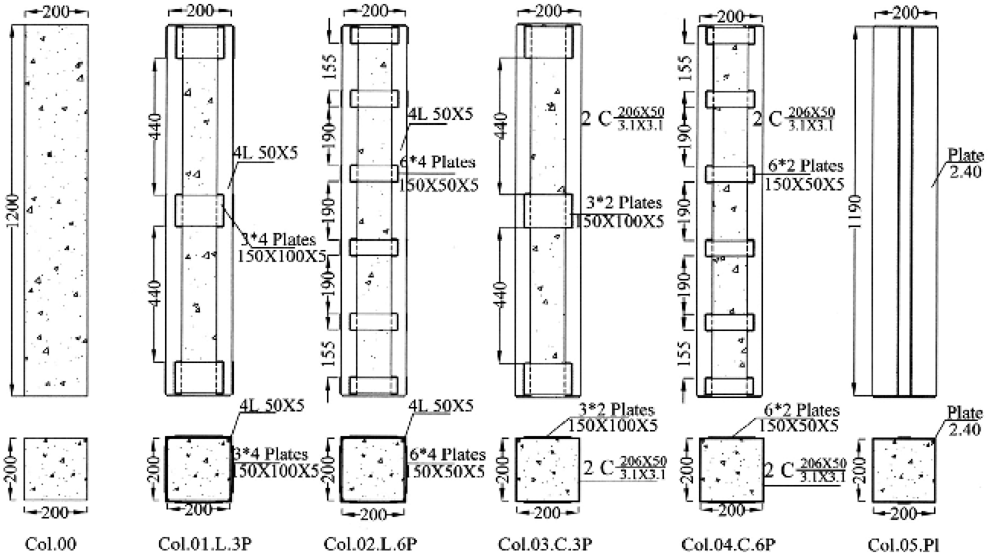
Belal, M. F., Mohamed, H. M., and Morad, S. A. (August 01, 2015). Behavior of Reinforced Concrete Columns Strengthened by Steel Jacket. HBRC Journal, 11, 2, 201-212.

Significance

The primary focus of this experiment was testing different cross sections of steel jackets on reinforced concrete columns using angles, channels, and plate cross sections. Additionally, the size and number of batten plates varied. Seven columns were tested, two unstrengthened ones, two with angles, two with channels, and 1 with plates. All jackets had the same vertical cross section area. Finite element models were created to compare the behavior between experimental and theoretical tests. Vertical load was applied using a load cell, while the columns have LVDT's and strain gauges along them.

Loading/beam Images

Concrete strength: 34 MPa (4931 psi)

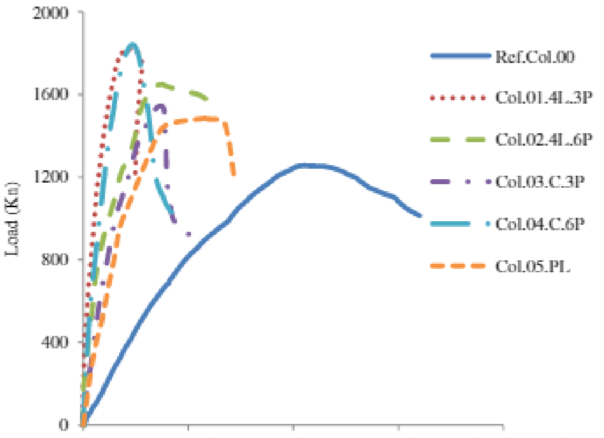


Results

Fig. 1 Specimen dimensions and steel jacket configuration.

Failure loads, displacements, and modes					
Specimen	Failure Load P_u (kN)	$P_u/P_{u(ref)}$	Disp. δ (mm)	δ/δ_{ref}	Failure mode
Col.00 (Ref.)	1255	1.00	4.24	1.00	Buckling (reinforcement) and spalling
Col.01.L.3P	1821	1.45	.89	.21	Spalling, buckling (reinf., L), weld failure
Col.02.L.6P	1649	1.31	1.55	.37	Spalling, weld failure
Col.03.C.3P	1545	1.23	1.46	.35	Buckling (Channel), spalling
Col.04.C.6P	1841	1.47	.93	.22	Spalling, minor buckling (batten, C flange)
Col.05.Pl	1489	1.19	2.45	.58	Significant buckling

Larger battens improved confining stress and column capacity with using angles vertically, while more battens improved the continuity and confinement for the columns with channel jackets.



Effectiveness of the Method

All methods tested improved the strength by at least 20%. Different strengthening methods, including angles, channels, and plates, have a significant impact on the failure load of columns. The effectiveness of using angles versus channels is minor; meanwhile, steel plates had significantly less capacity due to the thinness of the plates. The number of batten plates has variable results since more plates was better with channels, but worse when using angles. Steel jackets helped the columns have a more ductile failure mode. Experimental and modelled behavior had a good match.

Chai, Y. H., Priestley, M.J. N., and Seible, F. 1991."Seismic Retrofit of Circular Bridge Columns for Enhanced Flexural Performance," ACI Structural Journal, V.88, No.5, pp. 572-584

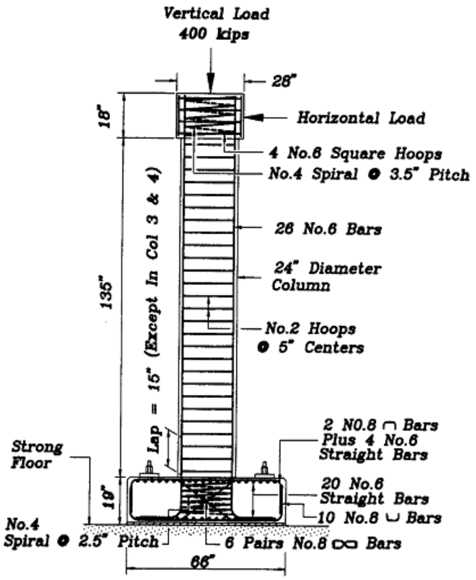
Significance

The authors focused on enhancing the flexural performance of Bridge column by encasing the plastic hinge region with steel jacket. One of the reference specimen had lap splice and the other had continuous reinforcement in the plastic hinge region. Subsequently, these specimens were repaired after damage and again tested for failure. Results of the cyclic test showed that the performance of the retrofitted specimen was identical for specimen with lap splice and continuous reinforcement. The failure of these retrofitted specimen was due to low cycle fatigue of longitudinal reinforcement.

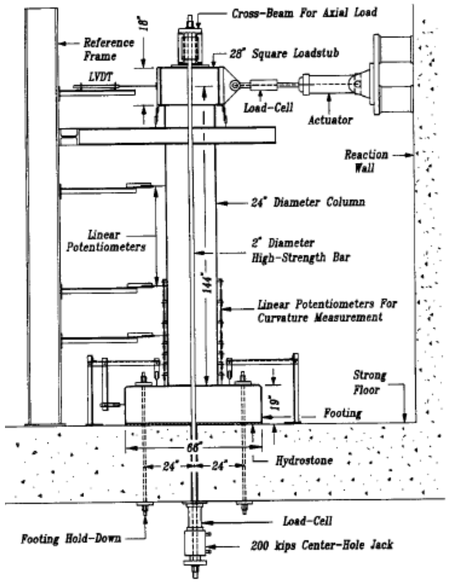
Loading/Column Images

Column designation	Column details Reinforcement details	Footing	Remarks	Concrete Strength (MPa)
1	20d$_b$ lap for long bars without steel jacket	weak footing	Reference	38.2
2	20d$_b$ lap for long bars with steel jacket	weak footing	Full retrofit	38.6
3	continuous column bars without steel jacket	strong footing	Reference	32.5
4	continuous column bars with steel jacket	strong footing	Full retrofit	38
5	20d$_b$ lap for long bars. 1/4 in styrofoam wrap	strong footing	Partial retrofit	35.1
6	20db lap for long bars with steel jacket	strong footing	Full retrofit	37.4

Details of Column Reinforcement



Test Setup



Column Properties:

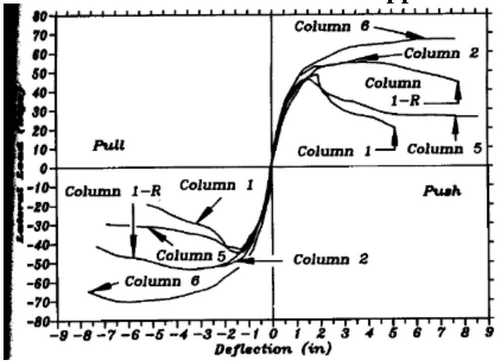
Column Height:	3660 mm
Column Diameter:	610 mm
Yield strength of longitudinal steel:	315 MPa
Yield strength of Transverse steel:	350 MPa
Ultimate tensile strength of longitudinal steel:	500 MPa

Retrofit Properties:

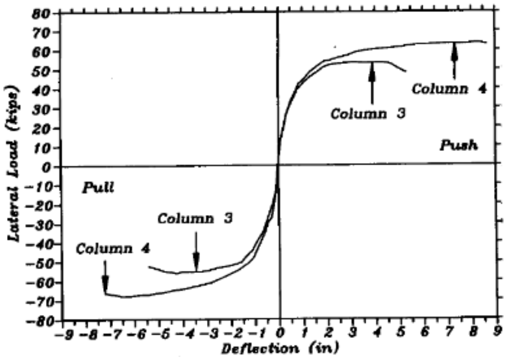
Thickness of steel jacket:	4.76 mm
Height of steel jacket:	1219 mm
Yield strength of steel jacket:	250 MPa
Ultimate strength of steel jacket:	400 MPa

Results

Load and deflection for columns with lapped starter bars



Load and deflection for columns with continuous reinforcement



Effectiveness of the Method

The apparent increase in the ultimate compressive strains of confined concrete is an indication of higher ductility capacity of column. Lapped starter bars in the potential plastic hinge region are likely to suffer bond failure less than their nominal flexural strength. Footings are susceptible to joint shear failure.

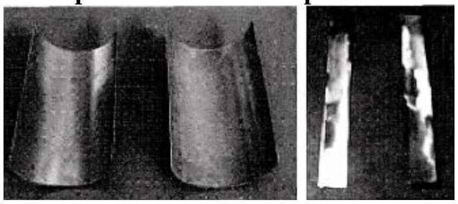
Choi, E., and Kim, M. C. (June 01, 2008). A New Steel Jacketing Method for Concrete Cylinders and Comparison of the Results with a Constitutive Model. International Journal of Railway, 1, 2, 72-81.

Significance

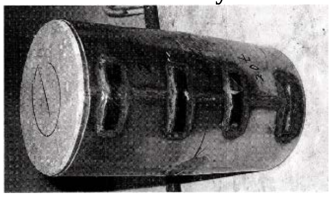
This paper examines adding steel jackets in the lap splice region of 45 reinforced concrete cylinders. The primary variables in this experiment are the strengths, the lateral confining pressure, the thickness of the jacket, adhesive presence, and welding quality. Additionally, the results are compared with a constitutive model.

Material and Retrofit Properties

Split Jackets and Strip Bands

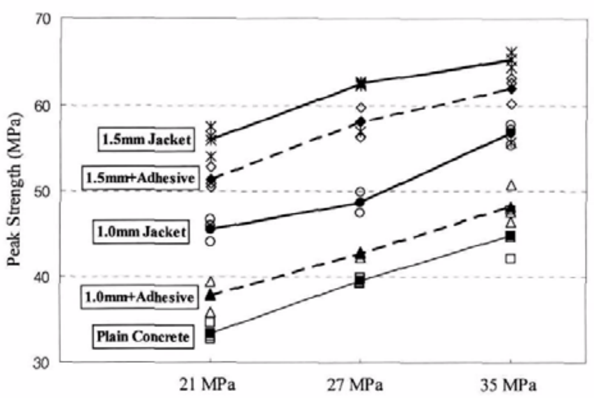


Whole Jacket Cylinder

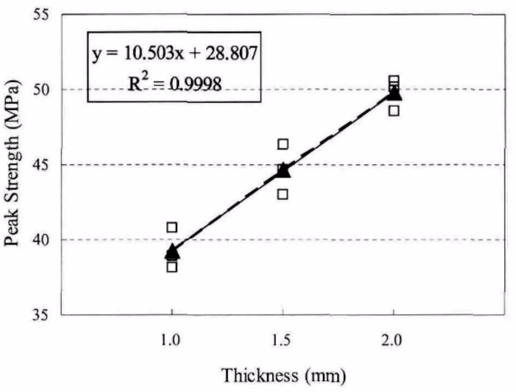


Results

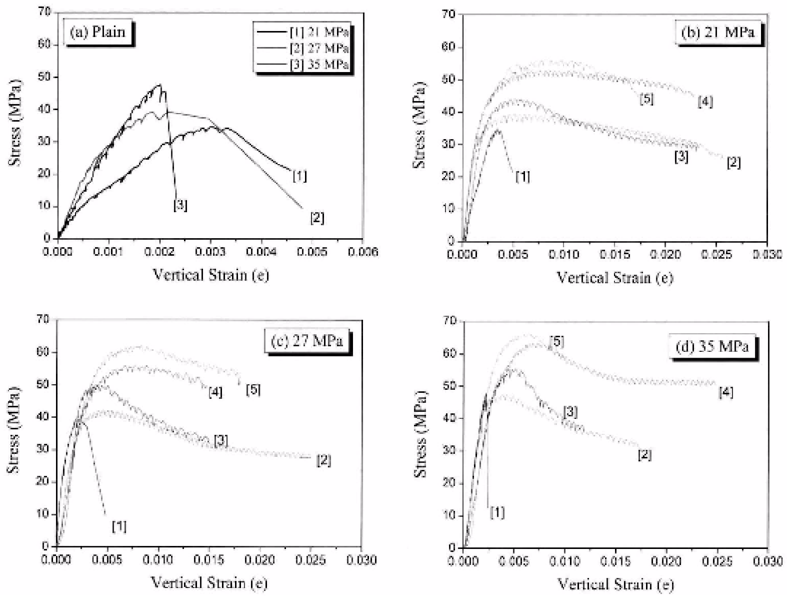
Peak Strength by Jacket for Split Jackets



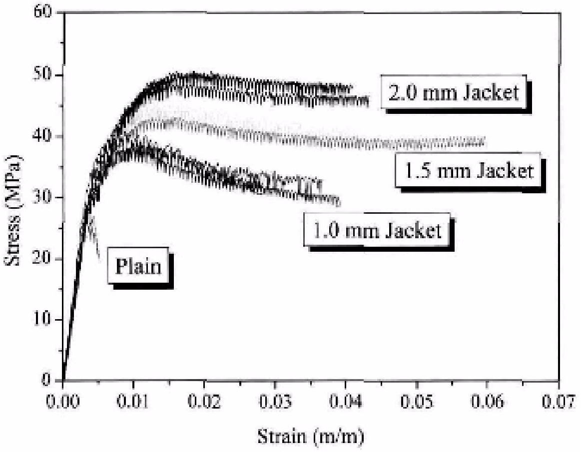
Peak Strength for Whole Jackets



Test Results for Plain and Split Jacket Cylinders. [1]: plain, [2]: 1.0mm + adhesive, [3]: 1.0 mm, [4]: 1.5 mm + adhesive, and [5]: 1.5 mm



Test Results for Whole Jacket Cylinders



Effectiveness of the Method

All methods were effective at improving the strength of the cylinders. Thicker jackets increase compressive strength, while adhesives reduce the confining effect, diminishing the compressive strength since the jackets already provide lateral pressure. The ductility of the jacket is dependent upon the welding quality. Whole jackets provide more ductility than split jackets. Double-layer and a single layer of equal thickness have the same effect. The improvement in strength is more significant for lower strength concrete. Peak strength vs. thickness follows a nearly linear trend.

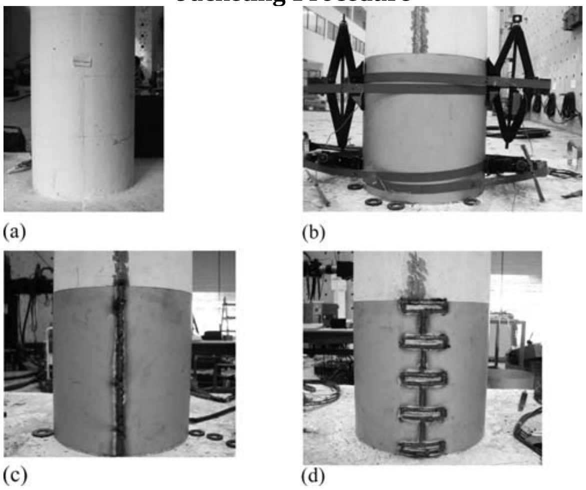
Choi, E., Chung, Y.S., Park, J., and Cho, B.S. 2010. "Behavior of Reinforced Concrete Columns Confined by New Steel-Jacketing Method,". ACI Structural journal, V.107, No.6, pp. 654-662

Significance

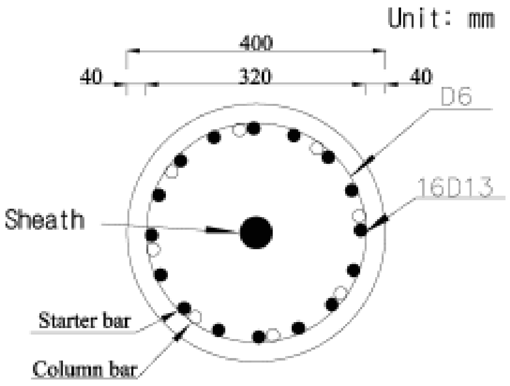
A state of the art jacketing technique is proposed wherein steel jackets are installed without the application of grout, entailing non composite behavior. Four test columns were subjected to lateral loading in which one is as built and the three are retrofitted with steel jackets. Of the three retrofitted jackets one used the application of pressure on steel jacket, the others were welded overlap and lateral strip bands. Other details are presented below.

Loading and Column Images

Jacketing Procedure



Cross-section of column

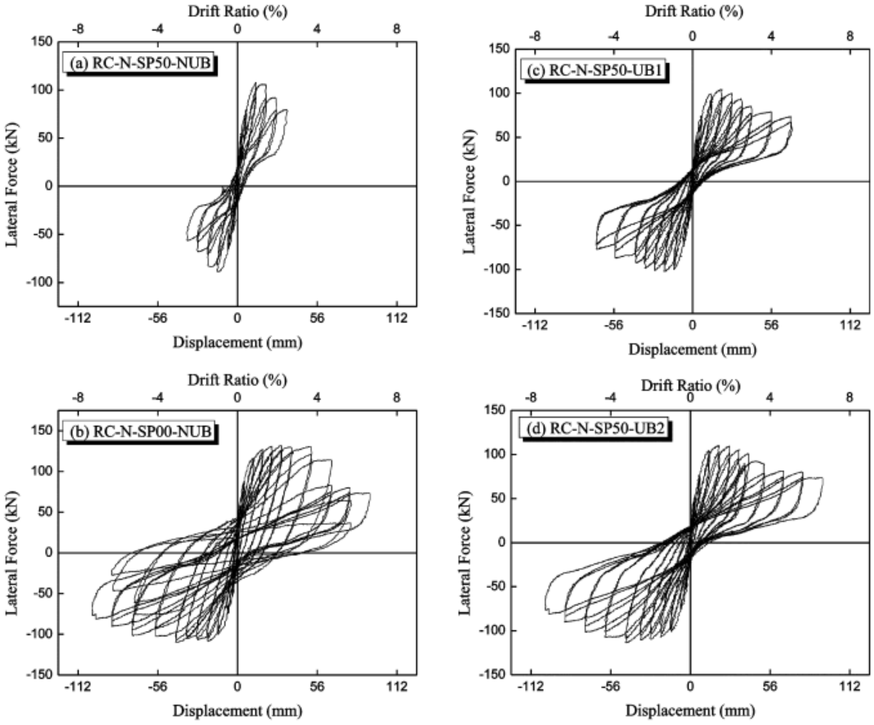


Results

Retrofit results

Column Designation	Peak Force (KN)	Peak Displ, mm	Displacement Ductility
RC-N-SP00-NUB	**112.4**/-93.3	**65.6**/-61.9	-
RC-N-SP50-NUB	**91.6**/-75.9	**27**/-23.3	**6.97**/5.01
RC-N-SP50-UB1	**88.4**/-86.7	39/**-54.5**	**3.19**/2.69
RC-N-SP50-UB2	93.5/**-96.5**	45.3/**-80**	4.08/**5.65**

Hysteresis diagram



Effectiveness of the Method

The construction process is accelerated since it does not require the application of grout. The performance of double layered jacket in terms of ductility and energy dissipation was better than the equivalent single layered jacket. Also this method offers easy installation of steel jacket at the desired location and has reduced cross section.

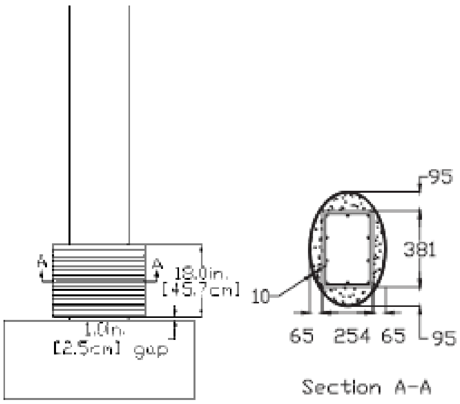
ElGawady, M., Endeshaw, M., McLean, D and Sack R. 2010. "Retrofitting of Rectangular Columns with Deficient Lap Splices," Journal of Composites for Construction, V.14, No.1, pp. 22-35.

Significance

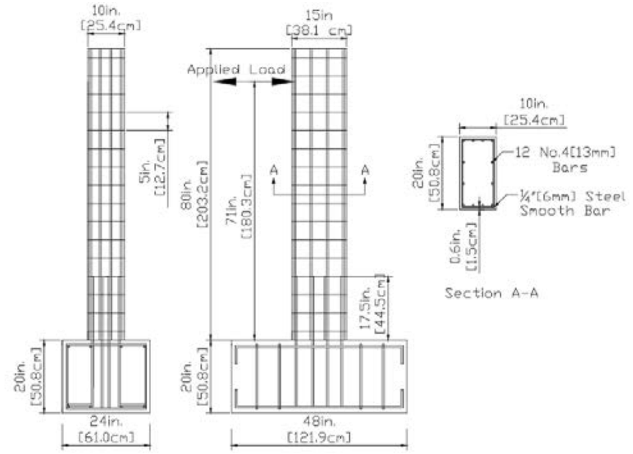
The research paper investigates the effect of confining the plastic hinge region of a column by CFRP and steel jackets. Two as built specimen and five retrofitted specimens were used, one of which was steel jacketing. Test specimens were subjected to reverse cyclic loading maintaining constant axial force. Results of the test reported that the failure of the retrofitted specimen was due to low cycle fatigue of longitudinal bars and that of original specimen due to lap splice failure. The failure occurred at the gap between footing and the steel jacket.

Loading/Column Images

Details of steel jacket



Reinforcement Details



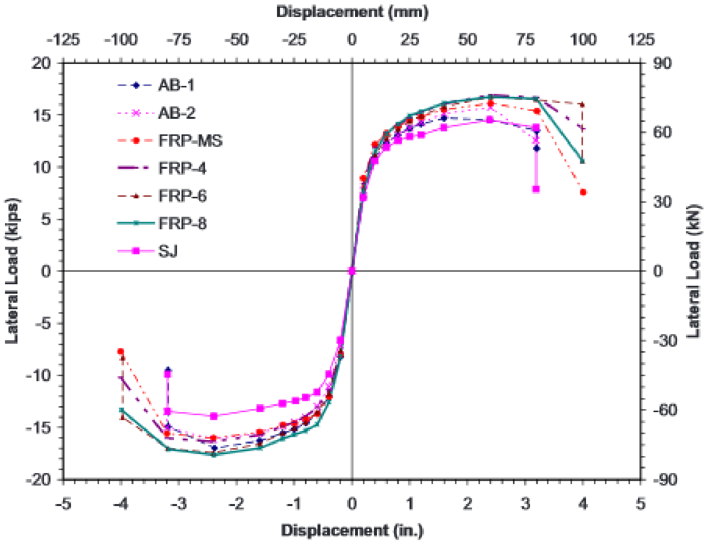
Summary of test specimen

Specimen	Test parameter	Retrofitting configuration	No. of FRP layers	Retrofit
AB-1	Control	NA	NA	None
AB-2	Control	NA	NA	None
FRP-MS	Retrofitting configuration	Oval	2	CFRP jacket
FRP-4	Retrofitting configuration	Rectangular	4	CFRP jacket
FRP-6	Retrofitting reinforcement ratio	Rectangular	6	CFRP jacket
FRP-8	Retrofitting reinforcement ratio	Rectangular	8	CFRP jacket
AR-2	Aspect ratio	Rectangular	5	CFRP jacket
SJ	Retrofitting material	Oval	NA	Steel jacket

Note: NA=not applicable.

Results

Envelope of hysteresis curves for the test specimen



Test results

Specimen	Yield displacement mm (in.)	Maximum displacement mm (in.)	Maximum % drift	Displacement ductility
AB-1	12.7 (0.50)	81(3.2)	4.5	6.4
AB-2	12.7 (0.50)	81 (3.2)	4.5	6.4
SJ	11.4 (0.45)	81 (3.2)	4.5	7.1
FRP-MS	11.9 (0.47)	86 (3.4)	4.5	7.2
FRP-4	12.7 (0.50)	94 (3.7)	5.2	7.4
FRP-6	11.2 (0.44)	102 (4.0)	5.6	9.1
FRP-8	12.2 (0.48)	89 (3.5)	4.9	7.3
AR-2	10.2 (0.40)	71 (2.8)	3.9	7.0

Effectiveness of the Method

Only one steel jacketed column was tested. The model improved displacement ductility, energy dissipation, and damping.

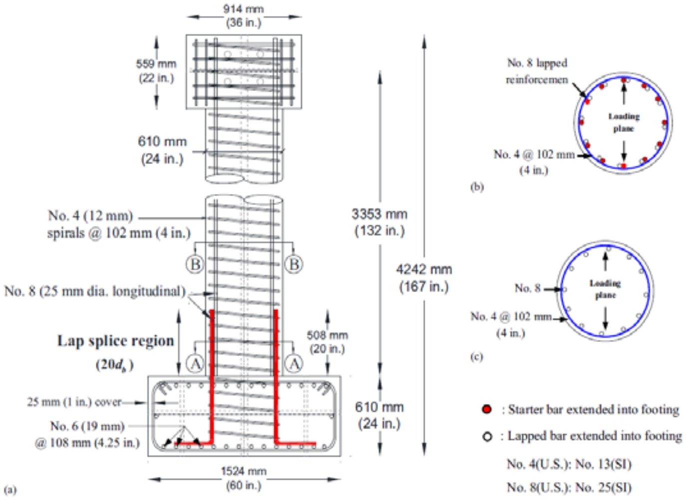
Fakharifar, M., Chen, G., Wu, C., Shamsabadi, A., ElGawady, M. A., and Dalvand, A. (April 01, 2016). Rapid Repair of Earthquake-Damaged RC Columns with Prestressed Steel Jackets. Journal of Bridge Engineering, 21, 4, 4015075.

Significance

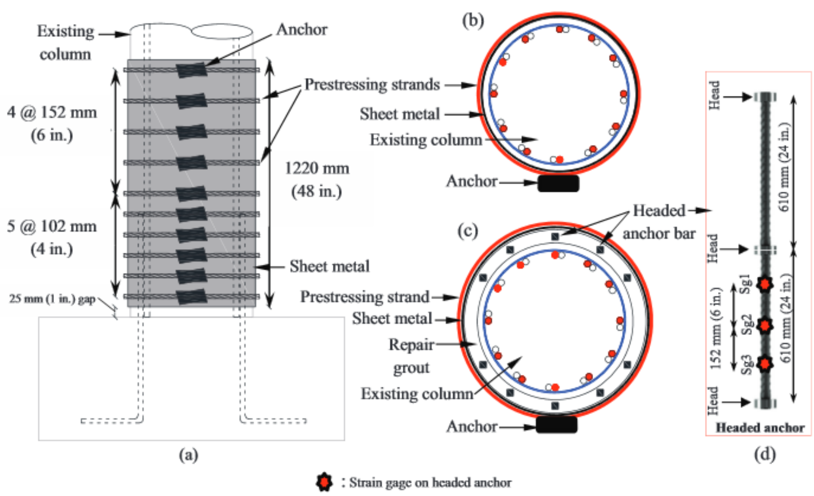
Fakharifar et al. designed a rapid and cost-effective repair of severely damaged circular reinforced concrete columns by using a lightweight prestressed steel jacket. The jacket has a thin steel sheet wrapped around the column restrained by several prestressed strands. The strands prevent steel sheet buckling while the sheet prevents the strands from damaging the concrete. With two workers, this can be completed in 12 hours. The authors tested two half-scale columns under pseudostatic cyclic reversed horizontal loads. Following testing, the columns were repaired and retested. Column 1 was repaired to restore stiffness, strength and ductility, while Column 2 was repaired to increase strength.

Loading and Column Images

As built columns



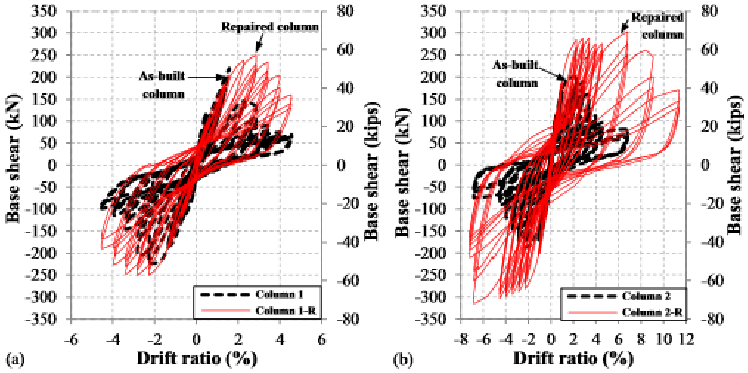
Retrofitted columns Column 1 (b), Column 2(c)



Column rotation was measured with 10 LVDTs and LPTs at the base of each column as a result of separation, anchorage slip, or steel slip of the column.

Results

Hysteresis Loops



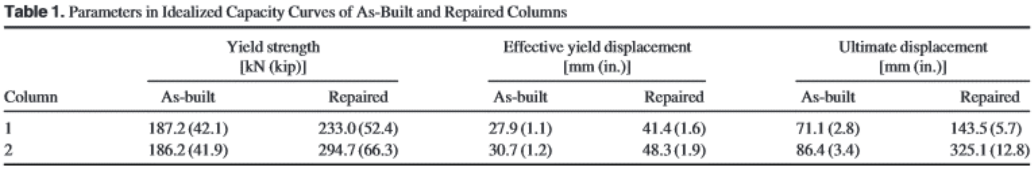


Table 1. Parameters in Idealized Capacity Curves of As-Built and Repaired Columns

Column	Yield strength [kN (kip)]		Effective yield displacement [mm (in.)]		Ultimate displacement [mm (in.)]	
	As-built	Repaired	As-built	Repaired	As-built	Repaired
1	187.2 (42.1)	233.0 (52.4)	27.9 (1.1)	41.4 (1.6)	71.1 (2.8)	143.5 (5.7)
2	186.2 (41.9)	294.7 (66.3)	30.7 (1.2)	48.3 (1.9)	86.4 (3.4)	325.1 (12.8)

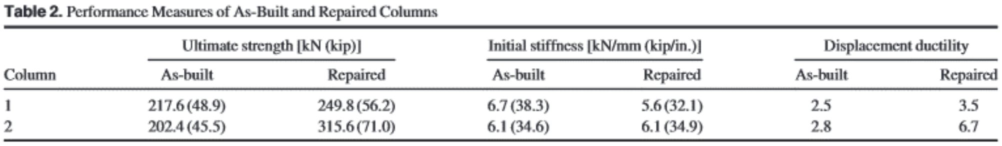


Table 2. Performance Measures of As-Built and Repaired Columns

Column	Ultimate strength [kN (kip)]		Initial stiffness [kN/mm (kip/in.)]		Displacement ductility	
	As-built	Repaired	As-built	Repaired	As-built	Repaired
1	217.6 (48.9)	249.8 (56.2)	6.7 (38.3)	5.6 (32.1)	2.5	3.5
2	202.4 (45.5)	315.6 (71.0)	6.1 (34.6)	6.1 (34.9)	2.8	6.7

Effectiveness of the Method

For long-term performance or aesthetics, a protective or architectural layer could be added to the proposed PSJ. When restoring stiffness is a concert, effective load transfer can be achieved by embedding headed bars anchored to the footing in grout added significant stiffness. Passive and active confinement were sufficient to prevent spalling and minimize cracks within the PSJ region. These methods are particularly useful when time and cost are a concern, since the column 1 method only requires 12 hours to repair, and the column 2 method requires 24 hours while remaining less expensive than other conventional repair techniques.

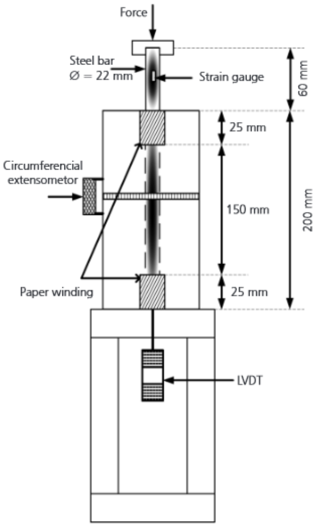
Lee, H., Choi, E., Cho, S.-C., and Park, T. (March 01, 2012). Bond and Splitting Behaviour of Reinforced Concrete Confined by Steel Jackets without Grouting. Magazine of Concrete Research, 64, 3, 225-237.

Significance

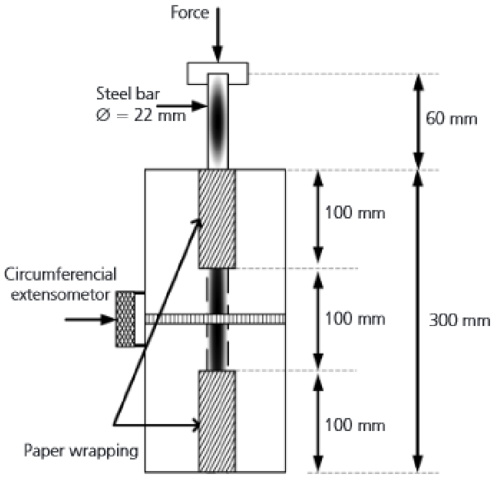
Lee et al. examined improving bond behavior and splitting stress for steel jackets in this experiment. A model is suggested relating the circumferential strain to bond stress. The main goals of this experiment were to analyze the performance of a steel jacketing method to increase bond strength while further understanding splitting stress and steel jacket failure modes.

Loading/beam Images

100 mm x 200 mm Steel Jacket Test



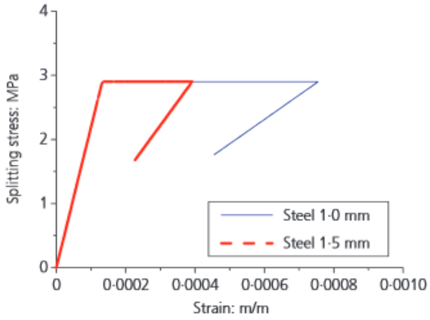
150 mm x 300 mm Steel Jacket Test



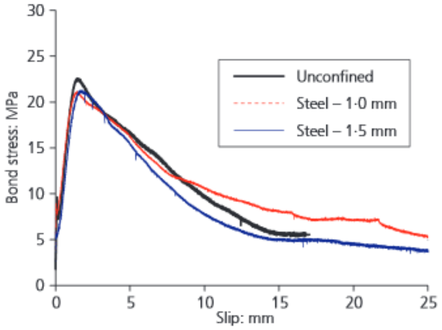
Completed Steel Jacket

Results

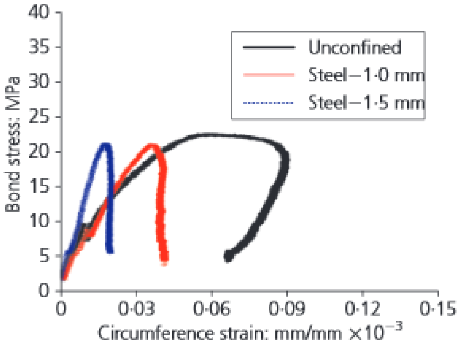
Splitting Stress as a Function of Slip Stress-Strain



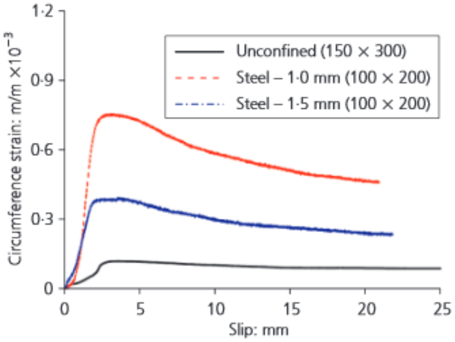
Bond Stress of 150 mm x 300 mm Comparison



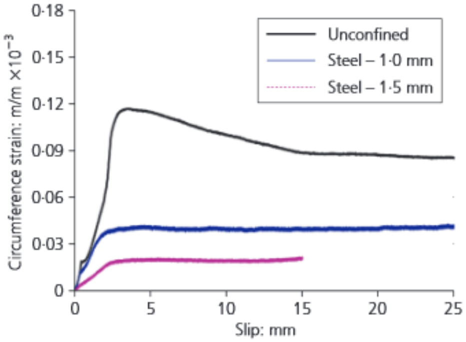
Bond Stress-Circumferential Strain Curves



Circumferential Strain-Slip Curves Comparison



Circumferential Strain-Slip Curves for 150 mm x 300 mm



Effectiveness of the Method

This new steel jacketing method transfers the bond failure mode from splitting to pull-out while increasing bond strength and toughness. If bond pull-out failure had already developed, more confinement did not increase bond strength, although more confinement reduced circumferential strain effectively. The relationship of bond stress and circumferential strain for pull-out bond failure showed a hook shaped behavior, but this may disappear if the confinement gets too heavy.

Li, Y.-F., Chen, S.-H., Chang, K.-C., and Liu, K.-Y. (February 01, 2005). A Constitutive Model of Concrete Confined by Steel Reinforcements and Steel Jackets. Canadian Journal of Civil Engineering, 32, 1, 279-288.

Significance

Li et al. tested 60 concrete cylinders while varying the concrete strength, jacket thickness, and type of lateral steel reinforcement in this experiment. A model applied to the different stress-strain curves was developed. During testing, the cylinders have a uniaxial force applied uniformly to the top and bottom of the cylinder.

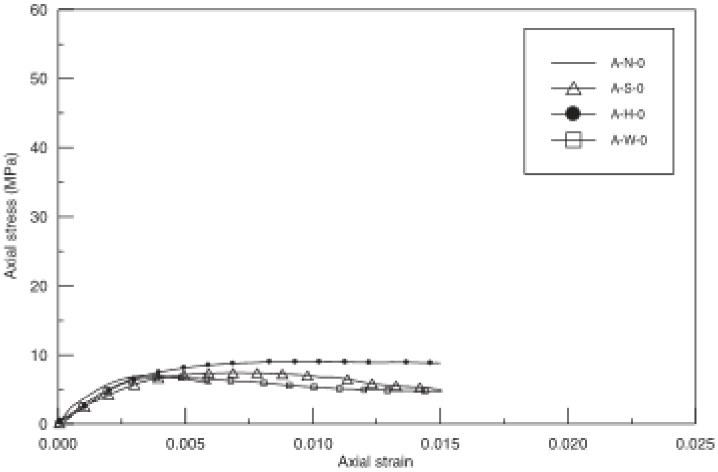
Loading/beam Images

Design Parameters of Concrete Cylinders

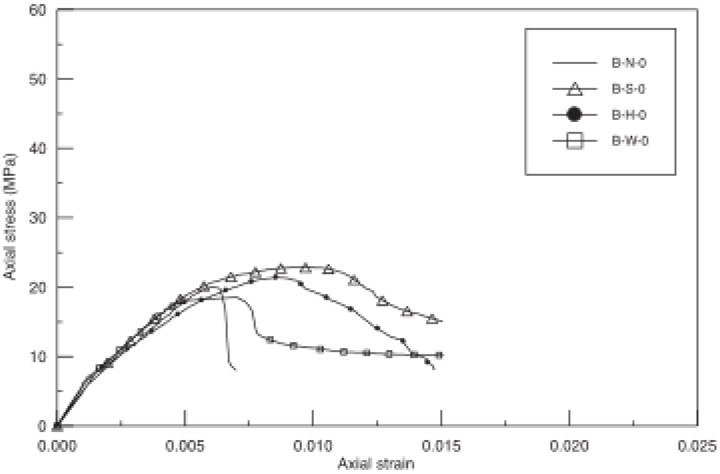
Parameter	Group A	Group B
Strength of unconfined concrete (MPa)	7.06	19.91
Type of lateral reinforcement	Nil (N), circular (H), spiral (S), wire (W)	Nil (N), circular (H), spiral (S), wire (W)
Thickness of steel jacket (mm)	0, 2, 5	0, 2, 5
No. of cylinders	3	2

Results

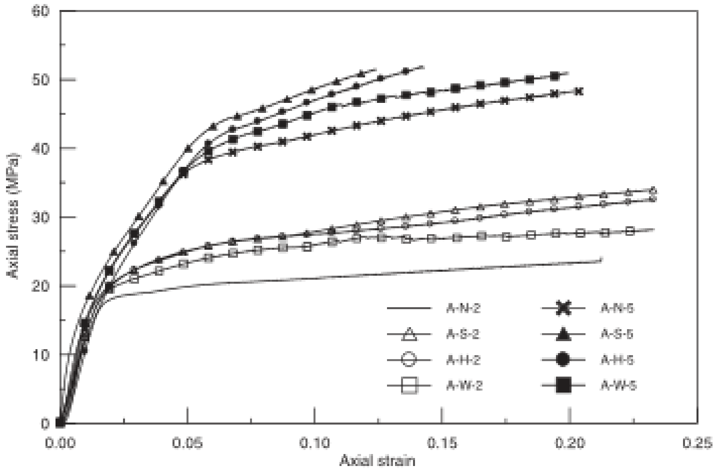
Stress-Strain for Group A with Lateral Steel Reinforcement



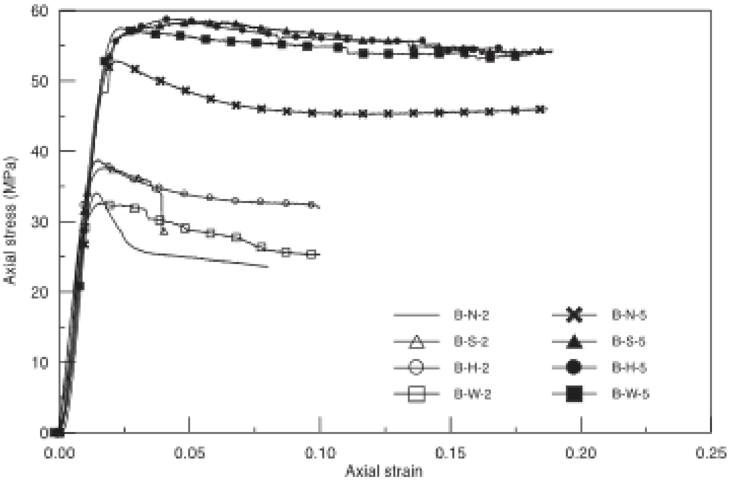
Stress-Strain for Group B with Lateral Steel Reinforcement



Stress-Strain for Group A with 2mm Steel Jacket and Lateral Reinforcement



Stress-Strain for Group B with 2mm Steel Jacket and Lateral Reinforcement



Effectiveness of the Method

Steel Jackets effectively improve the strength and ductility of concrete. Concrete compressive strength is highly dependent on the type of steel reinforcement. Spiral steel reinforcement resulted in the largest compressive strength, followed by circular/hoop steel reinforcement, and steel wire cable. Increasing jacket thickness can increase the stress of the confined concrete. The proposed model fits the test well, but can be fine-tuned more following further experiments.

Lin, M.N., 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 and Structural Dynamics, 39, 1687-1710.

Significance

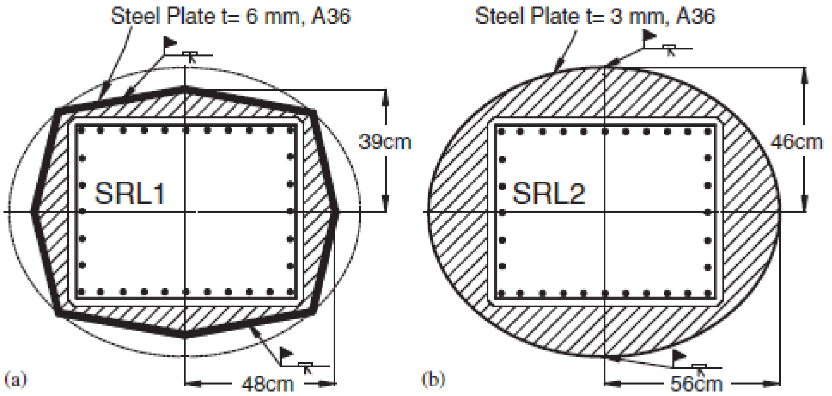
This paper investigates the behavior of lap splice deficient column subjected to cyclic lateral loads. Of the three specimens, two were retrofitted by steel jackets of elliptical and octagonal cross section. Test results reported that the octagonal steel jackets performed a little better than the elliptical steel jacket in terms of energy dissipation and lateral capacity. As anticipated, as built specimen showed brittle failure, while the retrofitted specimen exhibited ductile performance with low cycle fatigue failure of longitudinal reinforcement.

Loading/Column Images

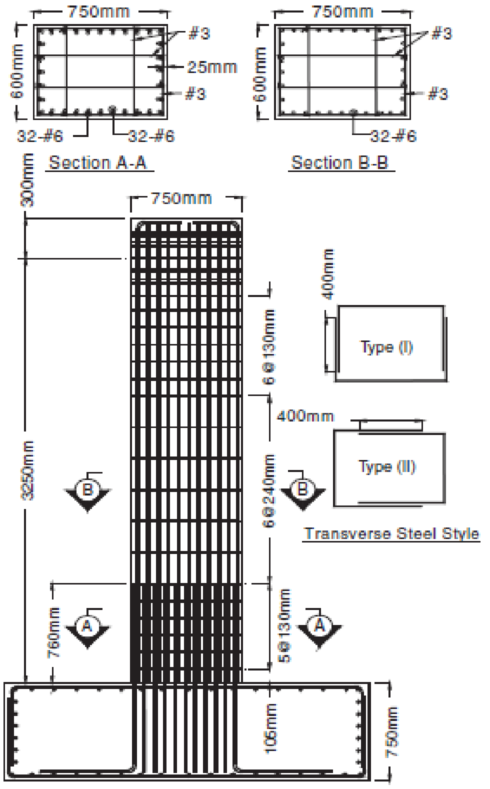
Material and retrofit properties

Specimen	Description	Yield Strength of Steel (Mpa)		Yield Strength of Steel Jacket (Mpa)
		#6 rebar	#3 rebar	
BMRL 100	As built column	440	423	-
SRL1	Octagonal steel jacket	440	423	262
SRL2	Elliptical steel jacket	440	423	412

Jacket details

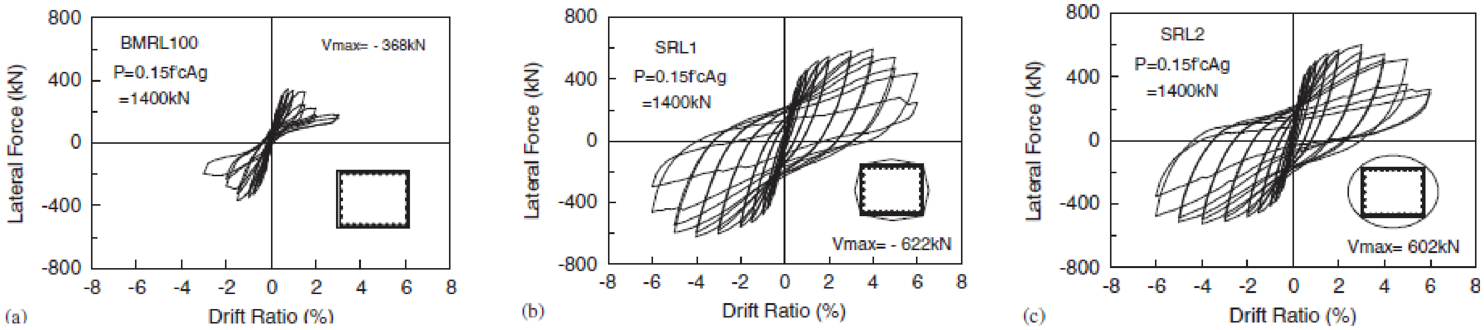


Test setup



Results

Lateral force versus deformation



Specimen	Maximum Lateral Load (kN)	Displacement Ductility
BMRL 100	368	-
SRL1	622	6.6
SRL2	602	8.9

Effectiveness of the Method

Octagonal Steel Jackets are excellent at preventing lap-splice failure and enhancing ductility. Octagonal Steel Jackets could be cost-effective and space-saving. They provide lateral confinement to mitigate against seismic failures of rectangular RC bridge columns from improper lap splices of vertical reinforcement. Octagonal Steel jackets have a smaller cross-section area requirement while improving strength and energy dissipation slightly versus elliptical jackets

Priestley, N, M. J., Seible, F., Xiao, Y., and Verma, R. (January 01, 1994). Steel Jacket Retrofitting of Reinforced Concrete Bridge Columns for Enhanced Shear Strength - Part 1: Theoretical Considerations and Test Design. ACI Structural Journal, 91, 4.

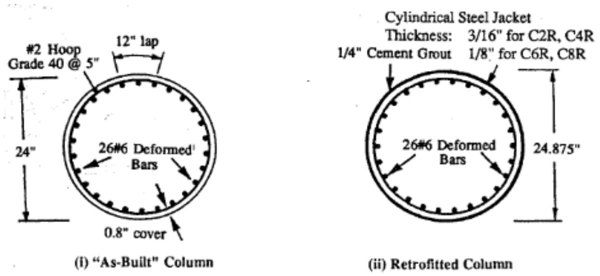
Priestley, N. M. J., Seible, F., Xiao, Y., and Verma, R. (January 01, 1994). Steel Jacket Retrofitting of Reinforced Concrete Bridge Columns for Enhanced Shear Strength - Part 2: Test Results and Comparison with Theory. ACI Structural Journal, 91, 5, 537.

Significance

Priestley et al. examined how effective full height steel jackets are at enhancing the seismic shear strength of reinforced concrete columns. Steel jackets were applied to circular and rectangular columns with different loads applied, aspect ratio's, reinforcing, jacket thickness, and jacket strength. A model was developed to compare the experimental results.

Loading/beam Images

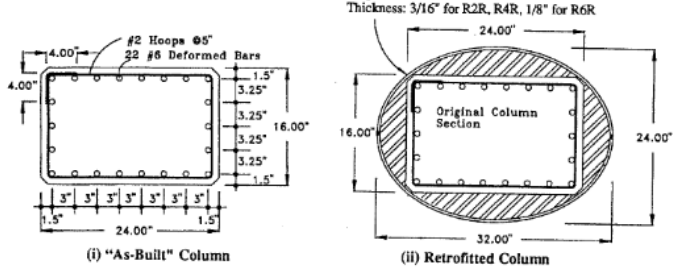
Circular Column Details



(i) "As-Built" Column

(ii) Retrofitted Column

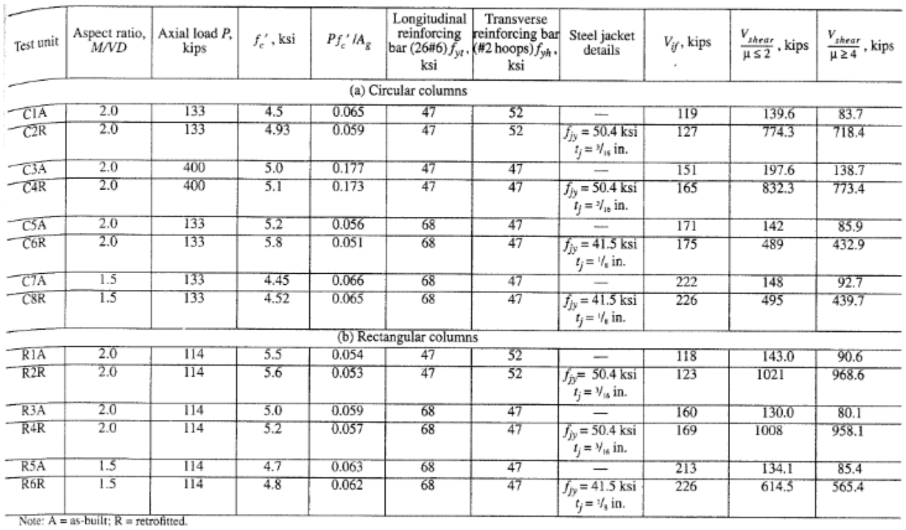
Rectangular Column Details



(i) "As-Built" Column

(ii) Retrofitted Column

Test Column Details

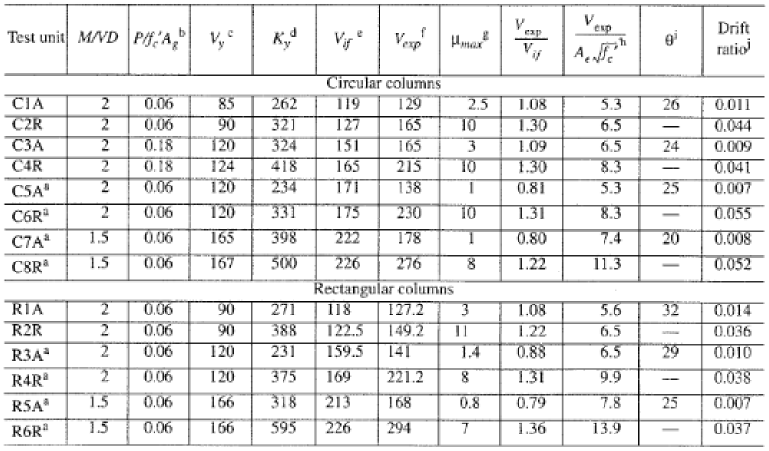


Test unit	Aspect ratio, M/VD	Axial load P, kips	f_c', ksi	Pf_c'/A_g	Longitudinal reinforcing bar (26#6) f_{yt}, ksi	Transverse reinforcing bar (#2 hoops) f_{yh}, ksi	Steel jacket details	V_{if}, kips	$\frac{V_{shear}}{\mu \le 2}$, kips	$\frac{V_{shear}}{\mu \ge 4}$, kips
					(a) Circular columns					
C1A	2.0	133	4.5	0.065	47	52	—	119	139.6	83.7
C2R	2.0	133	4.93	0.059	47	52	f_{jy} = 50.4 ksi t_j = 3/16 in.	127	774.3	718.4
C3A	2.0	400	5.0	0.177	47	47	—	151	197.6	138.7
C4R	2.0	400	5.1	0.173	47	47	f_{jy} = 50.4 ksi t_j = 3/16 in.	165	832.3	773.4
C5A	2.0	133	5.2	0.056	68	47	—	171	142	85.9
C6R	2.0	133	5.8	0.051	68	47	f_{jy} = 41.5 ksi t_j = 1/8 in.	175	489	432.9
C7A	1.5	133	4.45	0.066	68	47	—	222	148	92.7
C8R	1.5	133	4.52	0.065	68	47	f_{jy} = 41.5 ksi t_j = 1/8 in.	226	495	439.7
					(b) Rectangular columns					
R1A	2.0	114	5.5	0.054	47	52	—	118	143.0	90.6
R2R	2.0	114	5.6	0.053	47	52	f_{jy}= 50.4 ksi t_j = 3/16 in.	123	1021	968.6
R3A	2.0	114	5.0	0.059	68	47	—	160	130.0	80.1
R4R	2.0	114	5.2	0.057	68	47	f_{jy} = 50.4 ksi t_j = 3/16 in.	169	1008	958.1
R5A	1.5	114	4.7	0.063	68	47	—	213	134.1	85.4
R6R	1.5	114	4.8	0.062	68	47	f_{jy} = 41.5 ksi t_j = 1/8 in.	226	614.5	565.4

Note: A = as-built; R = retrofitted.

Results

Summary of Experimental Results



Test unit	M/VD	$P/f_c'A_g$ [b]	V_y [c]	K_y [d]	V_{if} [e]	V_{exp} [f]	μ_{max} [g]	$\frac{V_{exp}}{V_{if}}$	$\frac{V_{exp}}{A_e\sqrt{f_c'}}$ [h]	θ [i]	Drift ratio[j]
					Circular columns						
C1A	2	0.06	85	262	119	129	2.5	1.08	5.3	26	0.011
C2R	2	0.06	90	321	127	165	10	1.30	6.5	—	0.044
C3A	2	0.18	120	324	151	165	3	1.09	6.5	24	0.009
C4R	2	0.18	124	418	165	215	10	1.30	8.3	—	0.041
C5A[a]	2	0.06	120	234	171	138	1	0.81	5.3	25	0.007
C6R[a]	2	0.06	120	331	175	230	10	1.31	8.3	—	0.055
C7A[a]	1.5	0.06	165	398	222	178	1	0.80	7.4	20	0.008
C8R[a]	1.5	0.06	167	500	226	276	8	1.22	11.3	—	0.052
					Rectangular columns						
R1A	2	0.06	90	271	118	127.2	3	1.08	5.6	32	0.014
R2R	2	0.06	90	388	122.5	149.2	11	1.22	6.5	—	0.036
R3A[a]	2	0.06	120	231	159.5	141	1.4	0.88	6.5	29	0.010
R4R[a]	2	0.06	120	375	169	221.2	8	1.31	9.9	—	0.038
R5A[a]	1.5	0.06	166	318	213	168	0.8	0.79	7.8	25	0.007
R6R[a]	1.5	0.06	166	595	226	294	7	1.36	13.9	—	0.037

Effectiveness of the Method

For this test set-up, jackets of 1/8 in thickness were not able to provide enough confinement for the column in the plastic hinge region and at large ductility factors. Jacketed circular and rectangular columns increased in elastic stiffness by 30% and 64%, respectively, compared to the un-retrofitted columns. On the other hand, shear strength decreased as ductility increased – flexural ductility must be accounted for in seismic response.

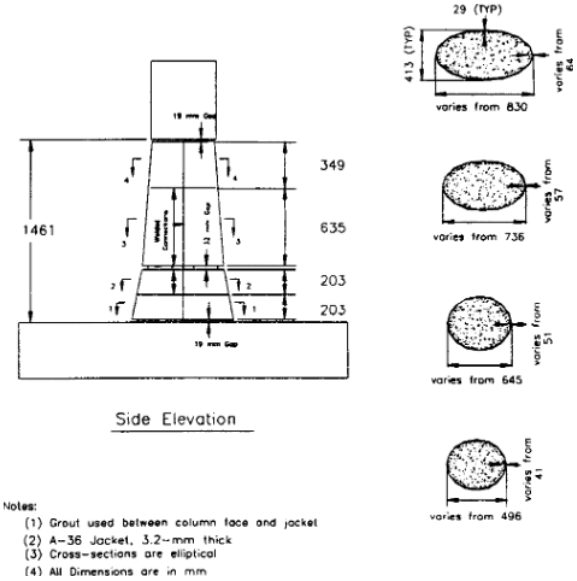
Saiid, S. M., Gordaninejad, F., Martinovic, F., McElhaney, B., and Sanders, D. (April 01, 2004). Assessment of Steel and Fiber Reinforced Plastic Jackets for Seismic Retrofit of Reinforced Concrete Columns with Structural Flares. Journal of Structural Engineering, 130, 4, 609-617.

Significance

This experiment focused on retrofitting reinforced concrete flared bridge columns to improve shear capacity under earthquake loads with a steel jacket, glass FRP, and carbon FRP. Four 0.3 scale irregular octagonal columns were tested on a shake table. The shifted plastic hinge was desired, so a gap was left at the current plastic hinge location to prevent any further movement. Results were compared to current models to compare results.

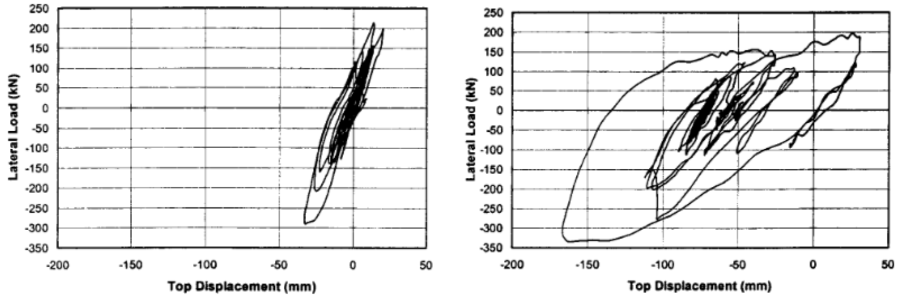
Loading/beam Images

Steel Jacket Details



Results

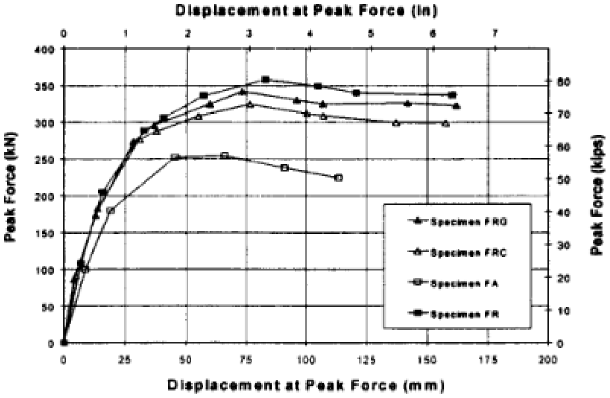
Measured Hysteresis Curves for Steel Jacket (Sylmar = Peak Ground Acceleration, 0.6 g)



(a) 0.75 x Sylmar

(b) 2.25 x Sylmar

Load-Deflection Envelopes for All Specimens



Effectiveness of the Method

The gap in the jacket kept the plastic hinge location still, prevent end damage. All the jackets had similar effectiveness by improving shear and displacement ductility capacity, while changing the failure mode from shear/flexure to flexure. The Caltrans and its modified version provided a reasonable estimate, while the FHWA seismic retrofit manual method significantly overestimated the capacity.

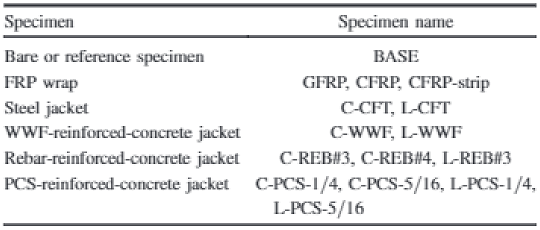
Sezen, H., and Miller, E. A. (March 01, 2011). Experimental Evaluation of Axial Behavior of Strengthened Circular Reinforced-concrete Columns. Journal of Bridge Engineering, 16, 2, 238-247.

Significance

Sezen et al. test steel jacketing, Fiber-reinforced polymer (FRP) composites, concrete jackets reinforced with spril rebar, welded wire fabric (WWF), and a new steel reinforcement method called PCS methods to retrofit reinforced concrete columns. Fifteen columns are tested under different axial-load applications.

Loading/beam Images

Reference and Strengthened Specimen

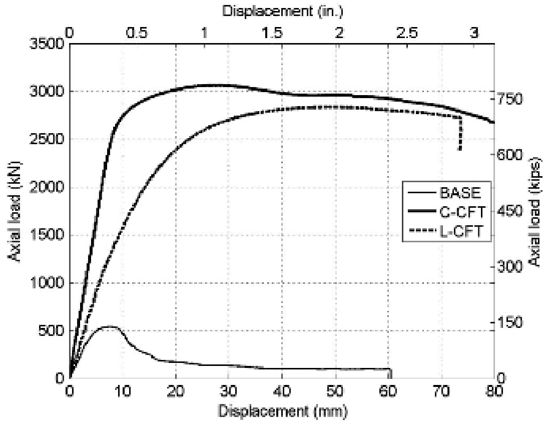


Specimen	Specimen name
Bare or reference specimen	BASE
FRP wrap	GFRP, CFRP, CFRP-strip
Steel jacket	C-CFT, L-CFT
WWF-reinforced-concrete jacket	C-WWF, L-WWF
Rebar-reinforced-concrete jacket	C-REB#3, C-REB#4, L-REB#3
PCS-reinforced-concrete jacket	C-PCS-1/4, C-PCS-5/16, L-PCS-1/4, L-PCS-5/16

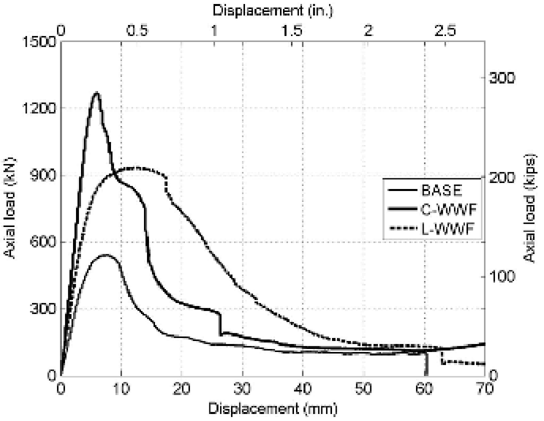
Results

The steel jacket improved initial stiffness, strength, and deformation of the retrofitted columns. When axial load was only applied to the concrete at the base, and not the jacket, the confinement provided by the steel jacket was adequate. At around the maximum axial capacity of the base column, concrete spalling occurred in the WWF columns. This method only increased deformation capacity slightly, while only providing moderate stiffness and strength increases. The concrete jacket with rebar had similar spalling. Thinner PCS reinforcement resulted in better post peak behavior. After spalling, longitudinal PCS buckled.

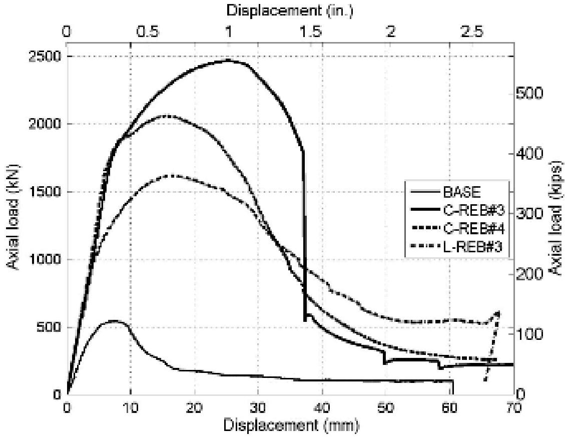
Experimental Axial Load-Displacement for BASE and SJ



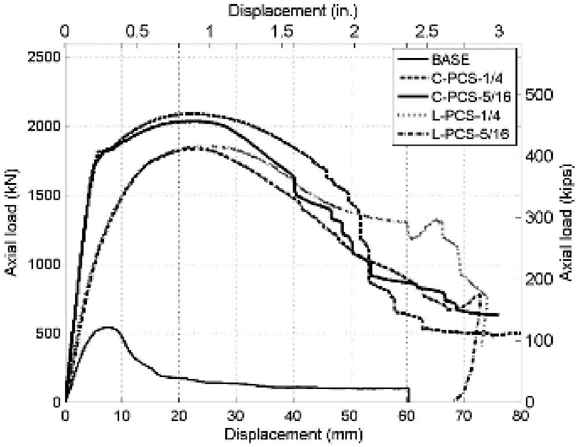
Experimental Axial Load-Displacement for BASE and WWF



Experimental Axial Load-Displacement for BASE and Rebar



Experimental Axial Load-Displacement for BASE and PCS



Effectiveness of the Method

The jacket should be extended to the top and bottom face of the column, so load is applied across the new cross-section. WWF and FRP improved capacity greatly (140%) but brittle failure occurred right after the peak capacity. FRP strips were less effective and ruptured earlier. Rebar and WWF methods had similar stiffnesses before cracking. Rebar and PCS had similar load-displacement behavior until the peak. Steel jackets improved strength, stiffness, and displacement the most. PCS was as effective until the concrete cracked.

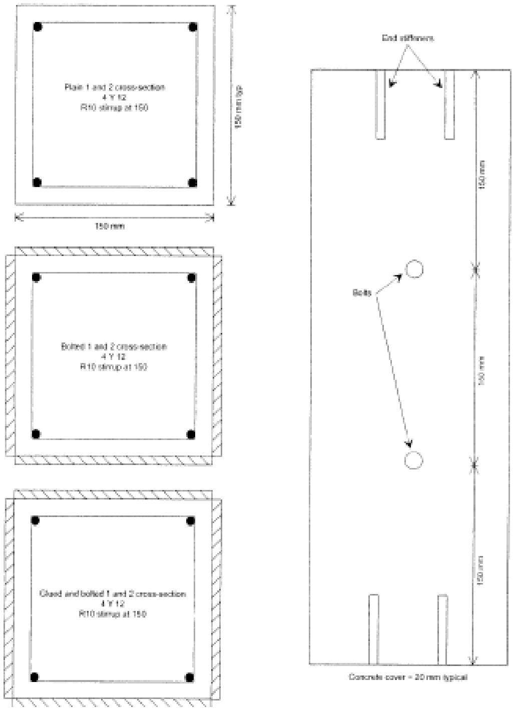
Uy, B. 2002. "Strength of Reinforced Concrete Columns Bonded with External Steel Plates," Magazine of Concrete Research, 54, 1, 61-76.

Significance

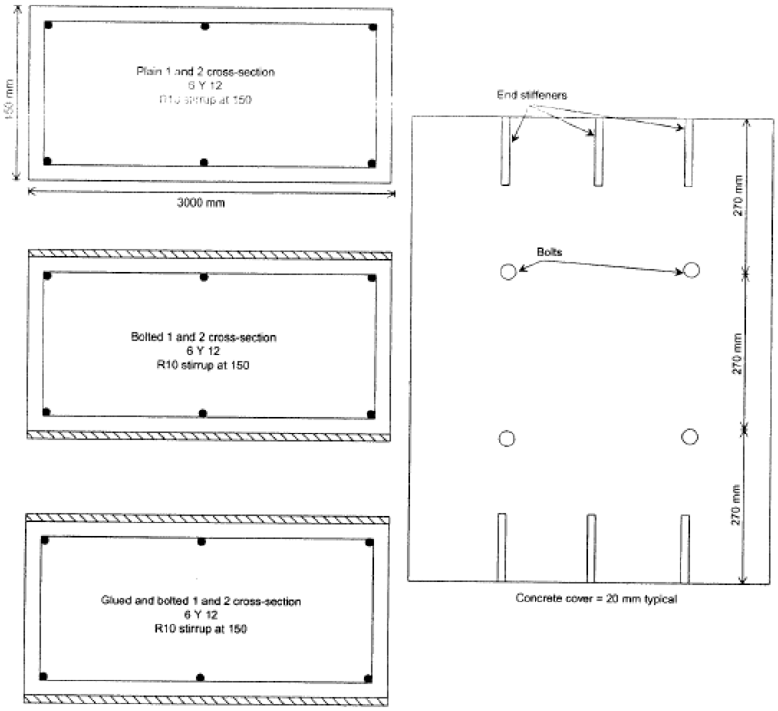
The experimental paper investigates the effect of external steel plating on column either on two or four sides of the columns. The variables included were the aspect ratio, column height and the anchorage technique. Steel plates were anchored to the columns by either bolts or 'glue and bolt' procedure. Test specimens were subjected to axial force till failure and the results showed that 'glue and bolt' technique was the most effective technique in mitigating local slip buckling thus providing complete composite action between original column and steel plate.

Properties and Results

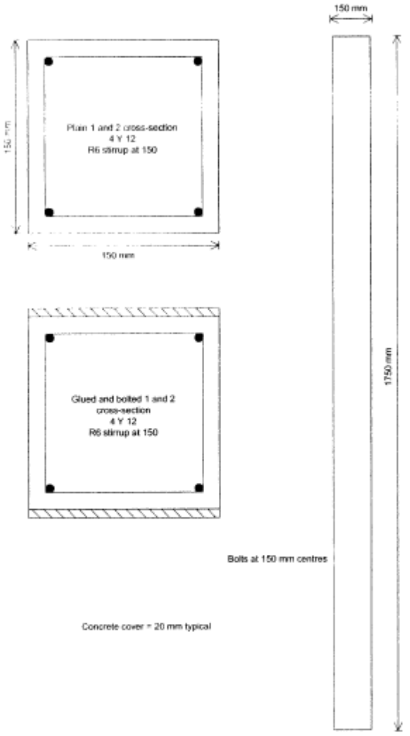
Series 1 column details



Series 2 column details



Series 3 Column Details



Test Results

Specimen		Axial Capacity N_u (kN)
Series 1	Plain 1	1031
	Plain 2	1125
	Bolted 1	1251
	Bolted 2	1255
	G & B 1	1359
	G & B 2	1476
Series 2	Plain 1	2214
	Plain 2	1828
	Bolted 1	2374
	Bolted 2	2476
	G & B 1	2252
	G & B 2	2229
Series 3		Axial & Flexural
	Plain 1	242.8
	Plain 2	220.5
	Bolted 1	485.8
	Bolted 2	441

Effectiveness of the Method

This is an accelerated method of construction and the degree of labor required is basic. The' glue and bolt' method finds application in elevated water tanks for which the columns are slender.

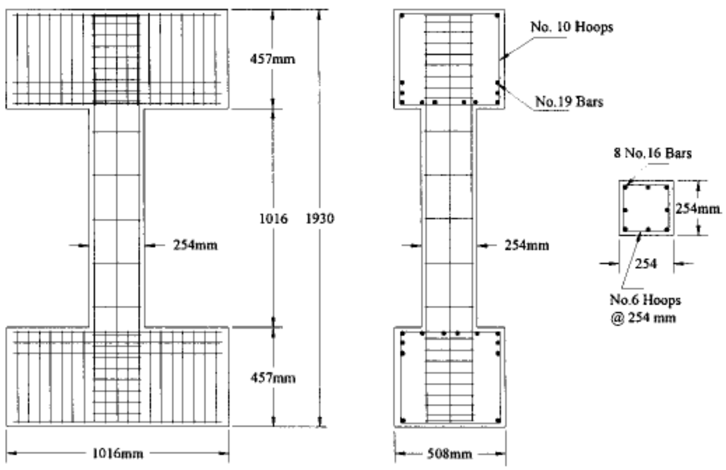
Xiao, Y and Wu H. 2003. "Retrofit of Reinforced Concrete Columns Using Partially Stiffened Steel Jackets," Journal of Structural Engineering, 129, 6, 725-732.

Significance

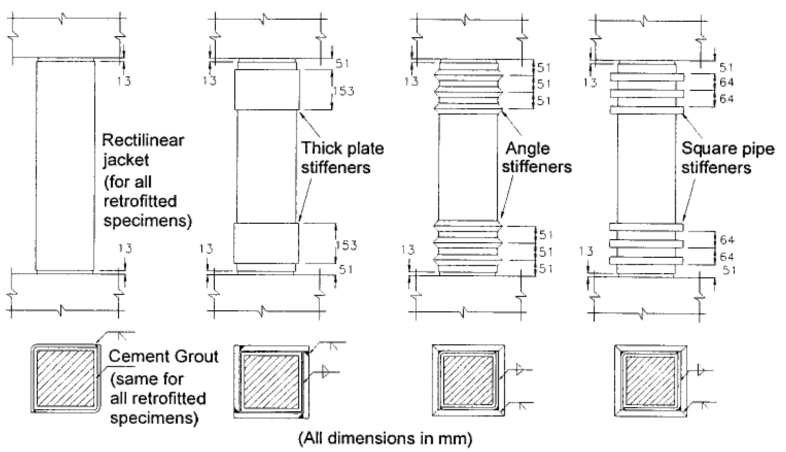
This research paper emphasizes on providing end stiffeners at the potential plastic hinge regions of the columns in addition to steel jackets provided throughout its length. Test specimens were subjected to lateral cyclic loading and the test result showed that strength and stiffness was highest for the specimen with steel tube stiffeners, followed by angle stiffeners and plate stiffeners. However, ductility remained the same for all the three specimen. In addition for the specimen with steel jackets only, stiffness degradation was observed and the ductility was poor.

Loading/Column Images

Details of as built specimen



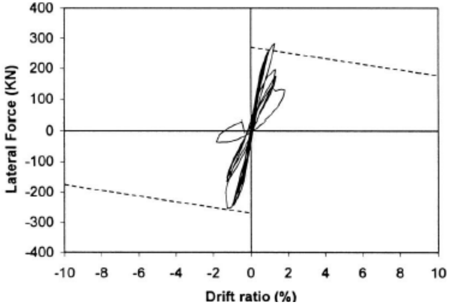
Details of retrofitted specimen



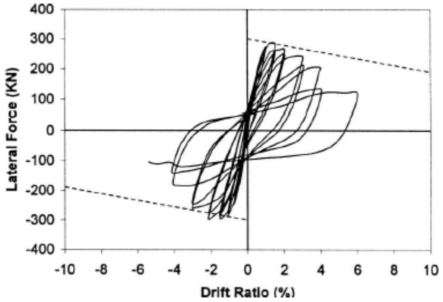
Results

Test Unit	f_c' (Mpa)	Axial Load (kN)	Retrofit Details	Peak Load (kN)
RC-1A	45	930	As built	280
RC-2R	57	1112	3.175 mm rec. jacket fyj = 393 Mpa	280
RC-3R	57	1112	3.175 mm rec. jacket with 15.9mm plate fyj = 328 Mpa	320
RC-4R	57	1112	3.175 mm rec. jacket with 31.8 x 31.8 x 6.4 mm angles as stiffeners, fyj = 367 Mpa	320
RC-5R	60	1157	3.175 mm rec. jacket with 31.8 x 31.8 x 6.4 mm square tubes as stiffeners, fyj = 491 Mpa	320

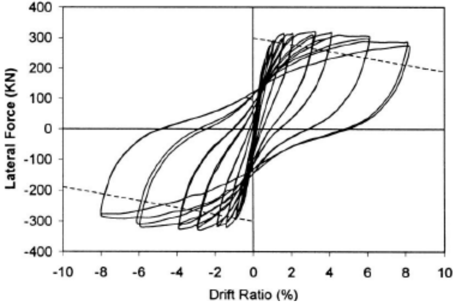
Hysteretic response (RC-1A)



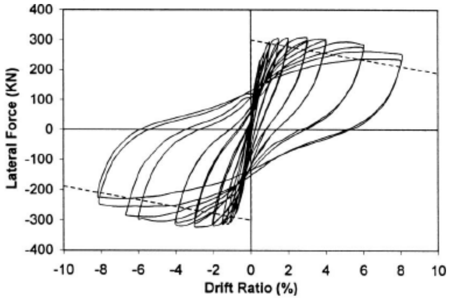
Hysteretic response (RC-2R)



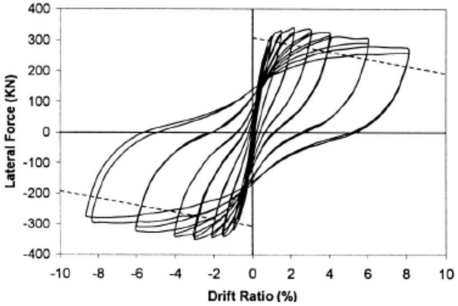
Hysteretic response (RC-3R)



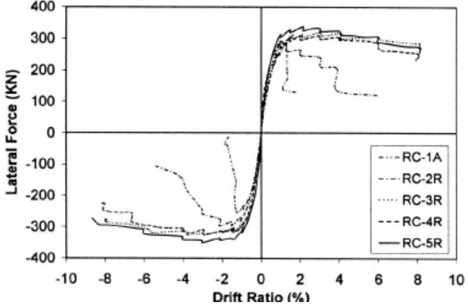
Hysteretic response (RC-4R)



Hysteretic response (RC-5R)



Comparison of envelopes



Effectiveness of the Method

In terms of applicability, angle stiffeners are most viable since it is commercially produced in large scale and easy to weld. Partially stiffened rectilinear steel jacket prevents brittle shear failure and greatly improves the ductility of the columns with smaller ultimate drift ratio.

Appendix C: Steel Cage One-Pagers

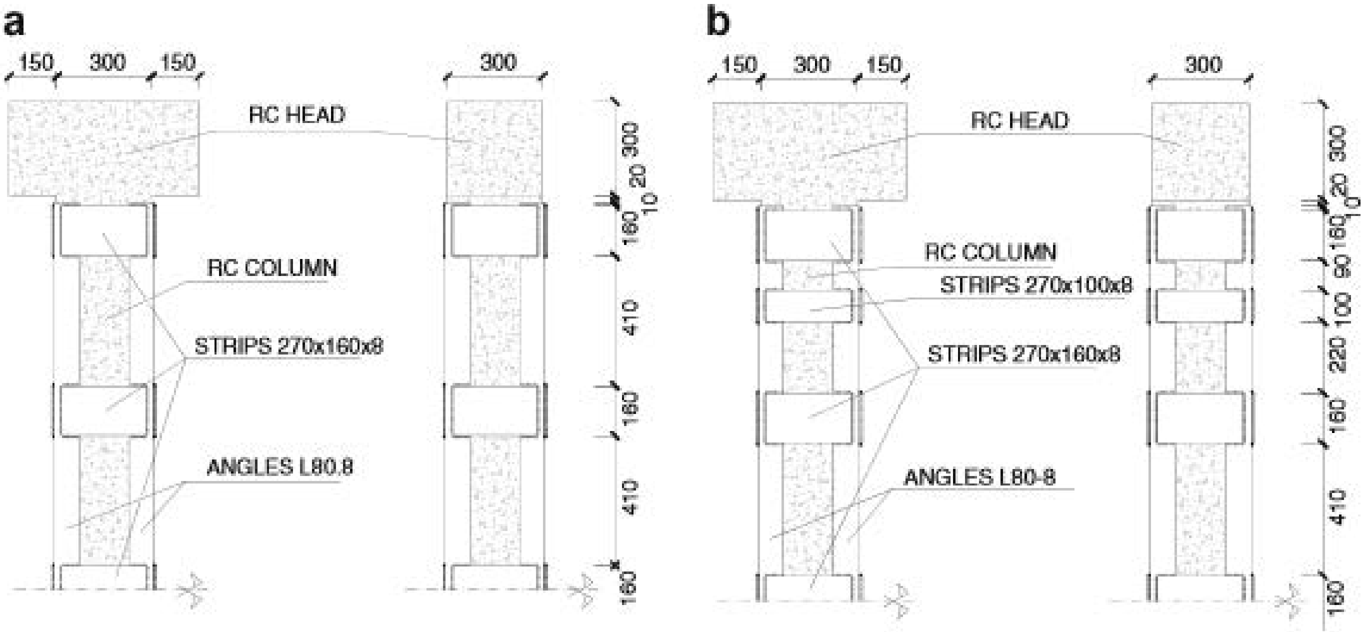
Adam, J. M., Ivorra, S., Pallarés, F. J., Giménez, E., and Calderón, P. A. (January 01, 2009). Axially Loaded RC Columns Strengthened by Steel Caging. Finite element modelling. Construction and Building Materials, 23, 6, 2265-2276.

Significance

Adam et al. looked at the effects of different angles sizes, steel strength, compressive concrete strength, strip sizes, friction between mortar and steel cage, and the presence of steel strips at the column ends. Columns were designed to represent full scale columns of a building. Each of the columns had at least 14 strain gauges and 8 LVDTs. Two specimens for each of five types of columns were tested, resulting in 10 columns overall. Finite Element Modeling is a major component of this study.

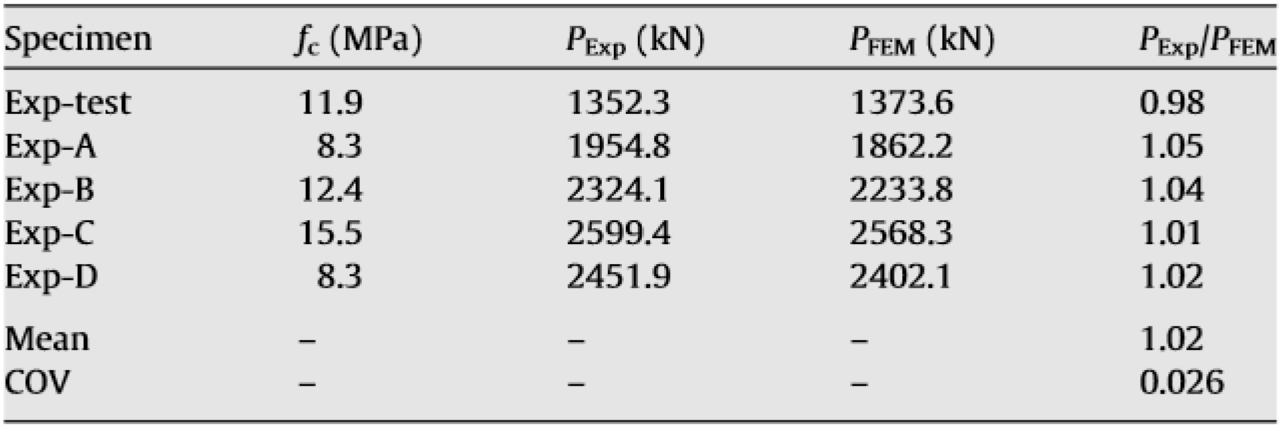
Loading/beam Images

Columns Tested: (a) Exp-A, Exp-B and Exp-C and (b) Exp-D



Results

Column Properties and Result Comparison with Finite Element Analysis



Specimen	f_c (MPa)	P_{Exp} (kN)	P_{FEM} (kN)	P_{Exp}/P_{FEM}
Exp-test	11.9	1352.3	1373.6	0.98
Exp-A	8.3	1954.8	1862.2	1.05
Exp-B	12.4	2324.1	2233.8	1.04
Exp-C	15.5	2599.4	2568.3	1.01
Exp-D	8.3	2451.9	2402.1	1.02
Mean	–	–	–	1.02
COV	–	–	–	0.026

Effectiveness of the Method

Increasing the size of angles increases confinement effectiveness, although it decreases the how effectively loads between the cage and column are transferred. Increasing yield stress slightly increases ultimate load, but decreases load transfer effectiveness. Increasing concrete compressive strength decreases the strengthening effectiveness and load transfer between the cage and column because the retrofit will take less load. Larger strips improve confinement and load transmission due to shear stress transfer. Having closer spaced strips near the ends can move the failure point towards the center of the column. Improving the friction coefficient corresponds to greater strength.

Belal, M. F., Mohamed, H. M., and Morad, S. A. (August 01, 2015). Behavior of Reinforced Concrete Columns Strengthened by Steel Jacket. HBRC Journal, 11, 2, 201-212.

Significance

The primary focus of this experiment was testing different cross sections of steel jackets on reinforced concrete columns using angles, channels, and plate cross sections. Additionally, the size and number of batten plates varied. Seven columns were tested, two unstrengthened ones, two with angles, two with channels, and 1 with plates. All jackets had the same vertical cross section area. Finite element models were created to compare the behavior between experimental and theoretical tests. Vertical load was applied using a load cell, while the columns have LVDT's and strain gauges along them.

Loading/beam Images

Concrete strength: 34 MPa (4931 psi)

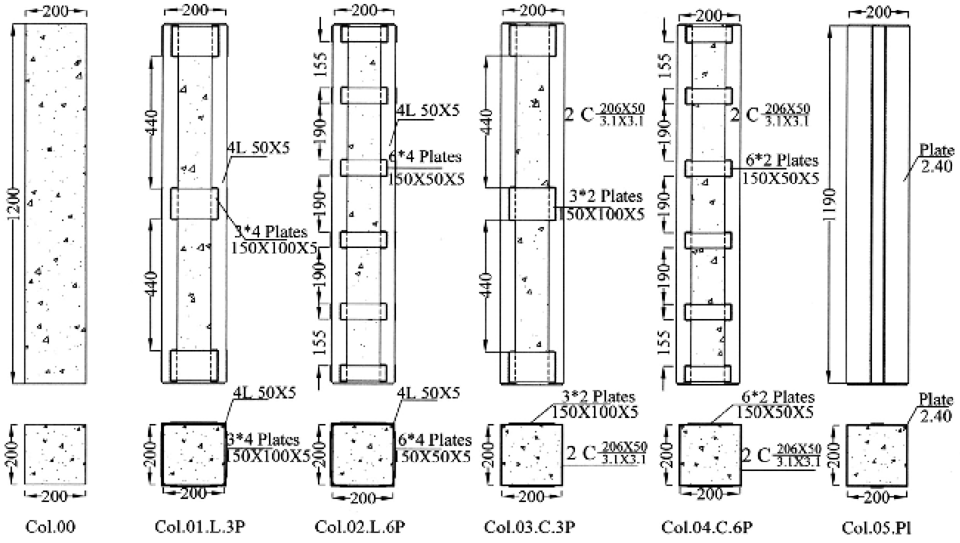
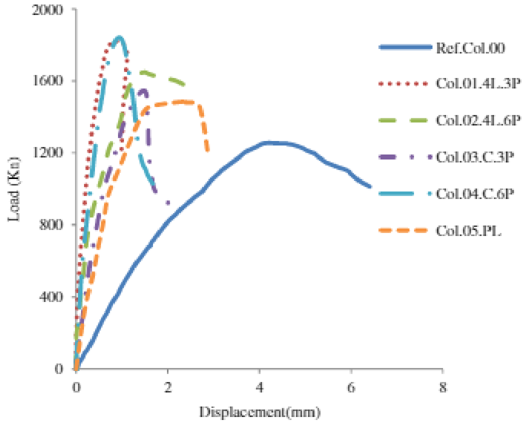


Fig. 1 Specimen dimensions and steel jacket configuration.

Results

Failure loads, displacements, and modes					
Specimen	Failure Load P_u (kN)	$P_u/P_{u(ref)}$	Disp. δ (mm)	δ/δ_{ref}	Failure mode
Col.00 (Ref.)	1255	1.00	4.24	1.00	Buckling (reinforcement) and spalling
Col.01.L.3P	1821	1.45	.89	.21	Spalling, buckling (reinf., L), weld failure
Col.02.L.6P	1649	1.31	1.55	.37	Spalling, weld failure
Col.03.C.3P	1545	1.23	1.46	.35	Buckling (Channel), spalling
Col.04.C.6P	1841	1.47	.93	.22	Spalling, minor buckling (batten, C flange)
Col.05.Pl	1489	1.19	2.45	.58	Significant buckling

Larger battens improved confining stress and column capacity with using angles vertically, while more battens improved the continuity and confinement for the columns with channel jackets.



Effectiveness of the Method

All methods tested improved the strength by at least 20%. Different strengthening methods, including angles, channels, and plates, have a significant impact on the failure load of columns. The effectiveness of using angles versus channels is minor; meanwhile, steel plates had significantly less capacity due to the thinness of the plates. The number of batten plates has variable results since more plates was better with channels, but worse when using angles. Steel jackets helped the columns have a more ductile failure mode. Experimental and modelled behavior had a good match.

Gimenez E., Adam J.M., Ivorra S., and Calderon P.A. 2009. "Influence of strips configuration on the behavior of axially loaded RC columns strengthened by steel angles and strips," Materials and Design, Vol.30, pp.4103-4111.

Significance

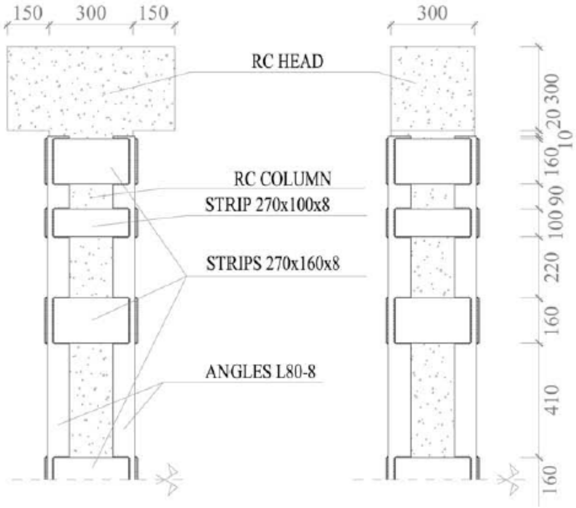
This research signifies the experimental tests conducted on columns strengthened with angles and strips. All specimen were subjected to axial load till failure. Of the seven steel strips used in strengthening, two were installed near the column ends with smaller height. Test results were compared with an identical arrangement of specimen with the only difference being that the smaller steel strips were not present.

Loading/Column Images

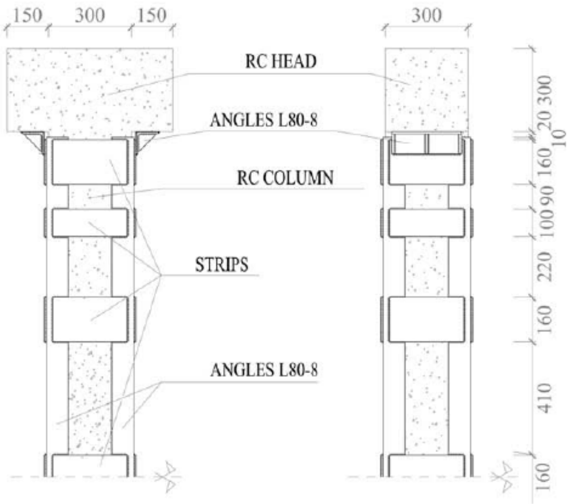
Specimen	Loading Condition	Type of Capital	Ultimate Load N_{exp} (kN)
Hx	Control	-	814
Hy	Control	-	814
PADx	Unloaded	A	2432
PADy	Unloaded	A	2451
PBDx	Unloaded	B	2206
PBDy	Unloaded	B	2648
PACx	Loaded	A	2256
PACy	Loaded	A	1961
PBCx	Loaded	B	2108
PBCy	Loaded	B	2524

Material and Retrofit Properties	
Column dimensions:	300 mm x 300 mm x 2500 mm
Concrete compressive strength	8.3 MPa
Pre-load magnitude	900 kN
Reinforcement	4φ12 with φ6 stirrup every 200mm
Reinforcement yield strength	400 MPa
Strip dimensions	270 x 160 x 8mm
Angle classification	L80-8
Angle yield stress	275 MPa

Columns strengthened without capitals (7 strips) (type A)

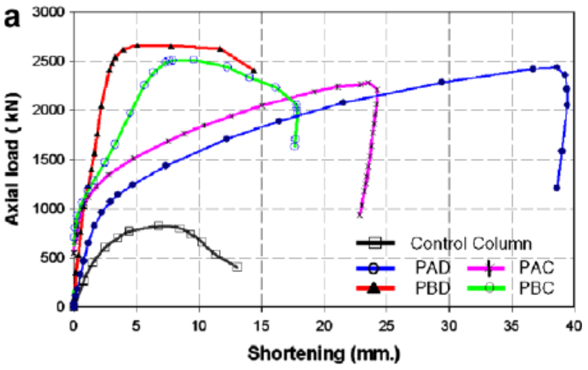


Columns strengthened with capitals (5 strips) (type B)

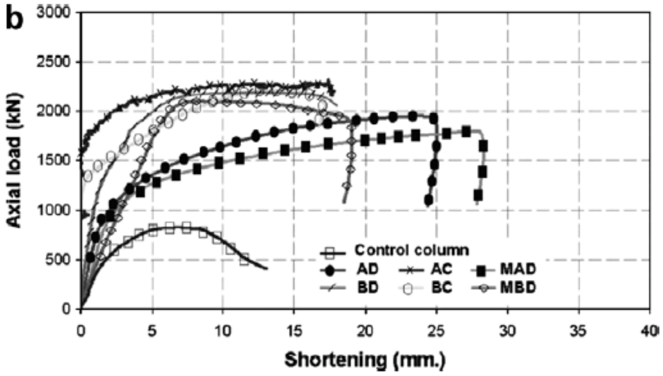


Results

Load versus deflection for 7 strip arrangement



Load versus deflection for 5 strip arrangement



Effectiveness of the Method

Results revealed that '7 strip arrangement' had better ductility and ultimate load than the '5 strip arrangement'. For columns with capitals, the failure was at the centre of columns, while for columns without capitals, the failure was at RC Head.

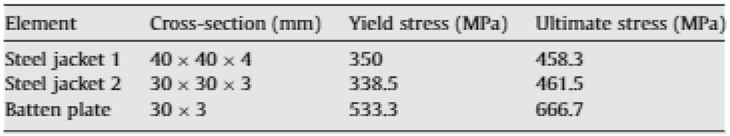
Li, J., Gong, J., and Wang, L. (July 01, 2009). Seismic Behavior of Corrosion-damaged Reinforced Concrete Columns Strengthened Using Combined Carbon Fiber-reinforced Polymer and Steel Jacket. Construction and Building Materials, 23, 7, 2653-2663.

Significance

Li et al. tested using CFRP and steel jackets to retrofit corrosion-damaged reinforced concrete columns. 14 columns were tested under lateral cyclic displacement and a constant axial force. 4 columns were unstrengthened, 2 columns had just a steel jacket, 2 had just a CFRP sheet, and 6 had both a steel jacket and CFRP sheet(s).

Loading/beam Images

Mechanical Properties of Steel Angle and Batten Plate

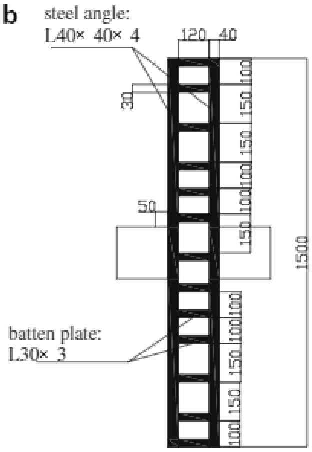


Element	Cross-section (mm)	Yield stress (MPa)	Ultimate stress (MPa)
Steel jacket 1	40 × 40 × 4	350	458.3
Steel jacket 2	30 × 30 × 3	338.5	461.5
Batten plate	30 × 3	533.3	666.7

Mechanical Properties of Steel Bars

Bars	Diameter (mm)	Yield stress (MPa)	Ultimate stress (MPa)
Longitudinal bar	14	384.77	604.87
Stirrups	8	326.95	510.7

Steel Jacket Details (mm)



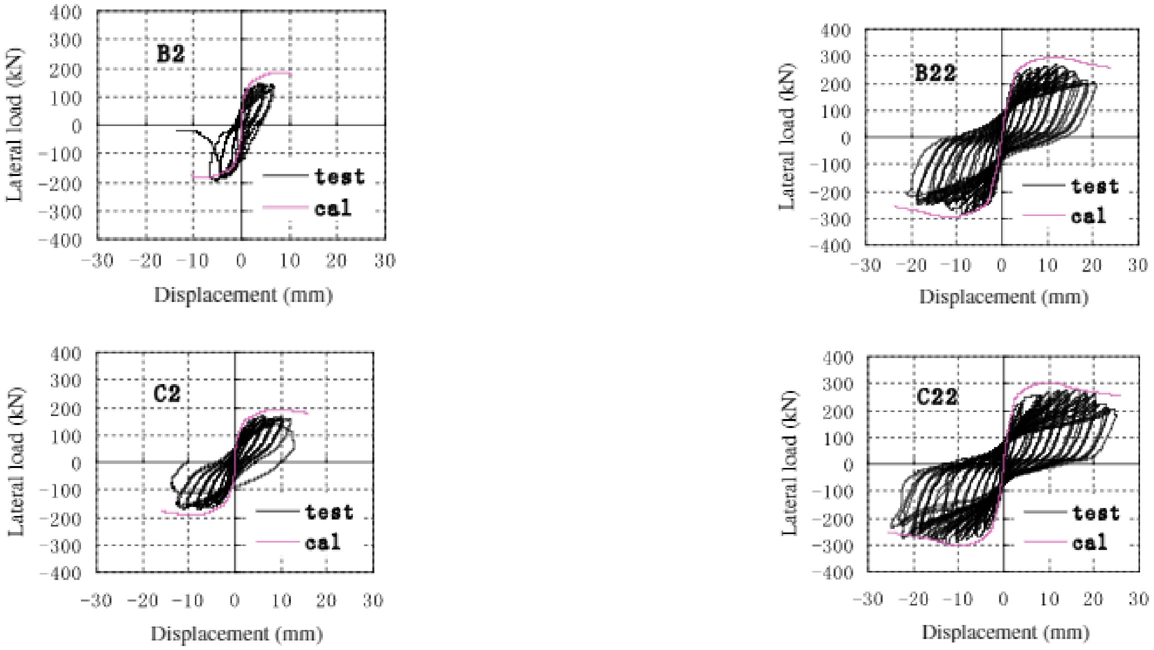
Configuration of Specimen

Specimen	Corrosion loss (%)	Axial load (kN)	Axial load ratio	Strengthening Method
B2	19.17	300	0.25	None
B22	16.5	300	0.24	Steel jacket
C2	11.49	300	0.25	None
C22	9.9	300	0.24	Steel Jacket

Results

Specimen	P_y (kN)	Δ_y (mm)	P_{max} (kN)	Δ_{max} (mm)	P_u (kN)	Δ_u (mm)	μ_A
B2	153.1	1.9	164.91	6.3	140.17	6.8	3.58
B22	220.21	2.75	265.79	8.17	225.92	18.02	6.55
C2	135.42	2.6	167.8	8.1	142.63	12.23	4.7
C22	230.58	3.6	279.62	10.33	237.68	22.9	6.36

Load Against Displacement Curves for Unstrengthened Columns and Those with Steel Jackets



Effectiveness of the Method

Strengthening corroded RC columns with steel jacket is effective and significantly increases the strength and ductility of the column. Strengthening with both CFRP and SJ is more effective than using either individually. The degree of corrosion has a major influence on the behavior—more corrosion results in more significant strengthening effects. The steel jacket alone did not have as large an improvement in seismic behavior as CFRP did. Higher axial load considerably reduces the ductility of strengthened columns.

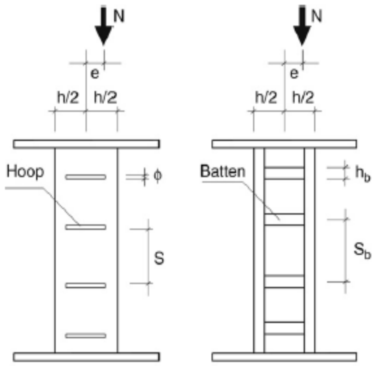
Montuori .R, and Piluso V. 2009. Reinforced Concrete Columns Strengthened with Angles and Battens Subjected to Eccentric Load, Engineering Structures, 31, 539-550

Significance

This paper compares the increase in axial capacity and enhancement in ductility of column between unstrengthened and strengthened specimen. Results of the test indicate that the strengthened specimen had load capacity nearly twice that of the unstrengthened specimen and with higher buckling resistance. Peak axial load with less displacement is exhibited for angles resisting load in both compression and tension, while highest ductility is obtained for specimen with angles as confinement elements only.

Loading/Column Images

Specimen models



Retrofit properties

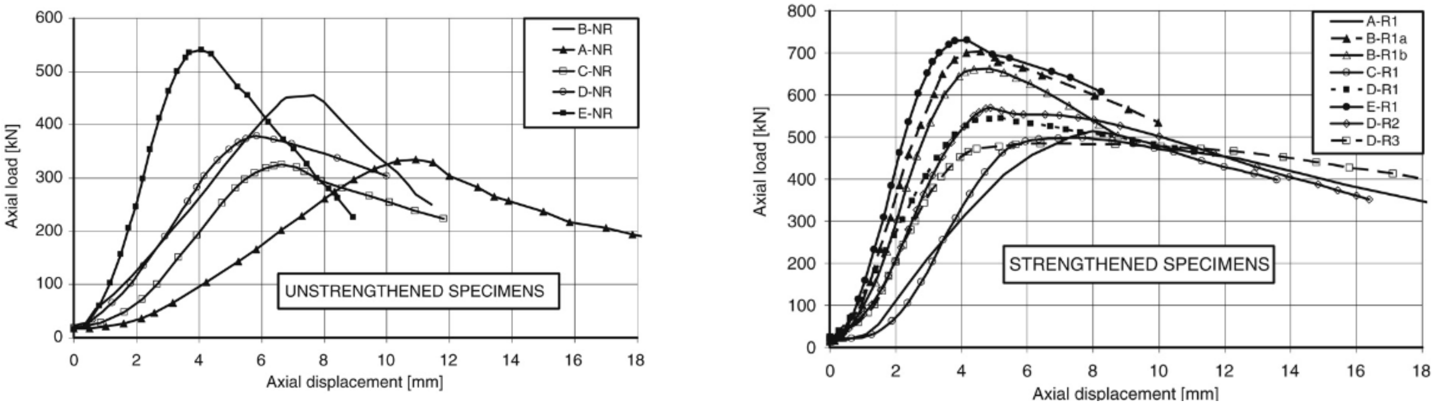
Steel type	f_y (MPa)	f_u (MPa)	Concrete Specimen	$f_{c}'{}_{cube}$(MPa)
Bar ϕ 10	491	593	1	25.02
Bar ϕ 16	539	655	2	27.57
Hoops	350	454	3	32.37
Angles	353	508	4	26.49
Battens	291	465	5	26.68

CT = angles resisting both compression and tensions
CO = angels resisting in compression
CA = angles acting as confinement only

Results

Beam Name	Long Bars	Angles (mm)	Battens (mm)	Ties (mm)	Eccentricity, e (mm)	Hoop Spacing, s (mm)	c/c Battens, b (mm)	Ultimate Experimental Load (kN)	Disp (mm) at Peak Load
A-NR	8 ϕ10	-	-	-	71	125	-	335.11	11
B-NR	8 ϕ10	-	-	-	44.5	101.3	-	455.14	7.5
C-NR	8 ϕ10	-	-	6	73	102.5	-	324.81	6.5
D-NR	4 ϕ16	-	-	-	80	102.5	-	379.45	5.5
E-NR	4 ϕ16	-	-	-	44	116	-	541.12	4
A-R1 (CT)	8 ϕ10	30 x 30 x 3	15 x 3	-	73	111.2	135	513.95	8
B-R1a (CT)	8 ϕ10	30 x 30 x 3	15 x 3	-	47.5	106	130	703.23	4
B-R1b (CT)	8 ϕ10	30 x 30 x 3	15 x 3	-	50.7	100	130	662.71	4.5
C-R1 (CT)	8 ϕ10	30 x 30 x 3	15 x 3	6	79.3	105	130	498.74	7
D-R1 (CT)	4 ϕ16	30 x 30 x 3	15 x 3	-	78.6	100	127	545.19	5
E-R1 (CO)	4 ϕ16	30 x 30 x 3	15 x 3	-	54.7	116.5	130	713.24	4
D-R2 (CA)	4 ϕ16	30 x 30 x 3	15 x 3	-	71.2	105	130	568.98	5
D-R3 (CT)	4 ϕ16	30 x 30 x 3	15 x 3	-	69.7	105	130	483.63	5

Load versus deflection curves



Effectiveness of the Method

This method provides effective lateral restraint to columns thus preventing buckling of bars. The technique is most suitable for a corner column of a building with poor lateral confinement for longitudinal bars.

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

Significance

Three reinforced concrete columns were tested for failure; One was as built and the two were strengthened ones. The strengthening scheme involved the application of external steel cage which are made of angles and battens. The columns were subjected to a constant axial load with gradually increasing lateral loads. The results of the experiments revealed that the strengthened columns had better energy dissipation, ductility and lateral stiffness as compared to original specimen. The wider batten at the end of column provided better confinement thus increasing the compressive strength and also in preventing buckling of steel angles.

Loading/Column Images

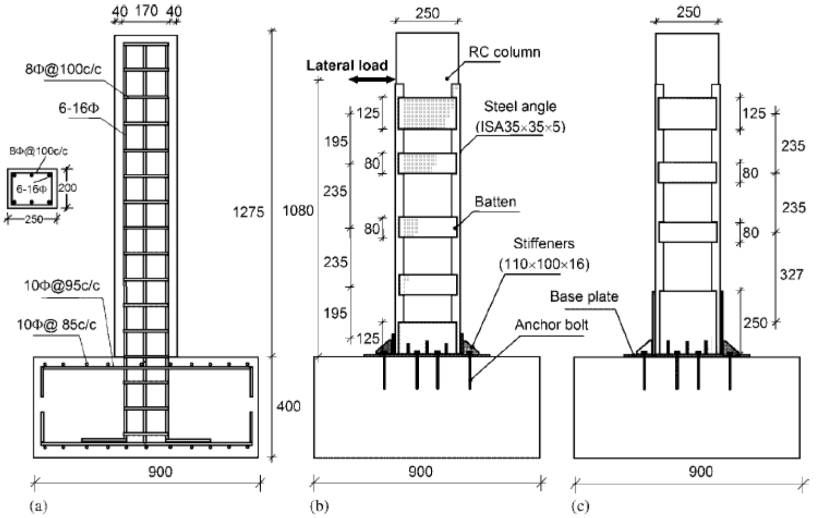
Material properties

Specimen	Conc Compressive Strength (MPa)	Yield Strength of Rebars (MPa)		Tensile Strength of Rebars (MPa)
RCO	32.5	8mm	438.5	542
RCS1	37.7	10mm	489	668
RCS2	34.7	16mm	468.4	623.2

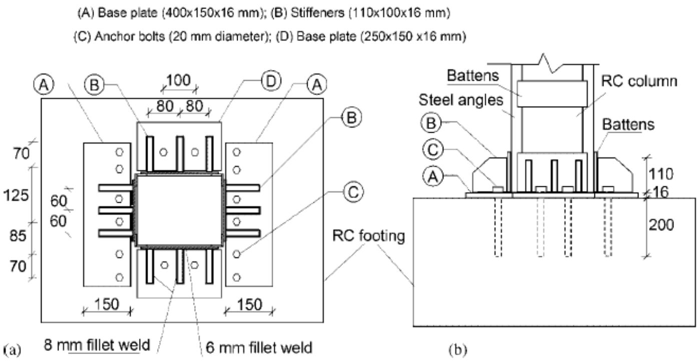
Retrofit properties

Specimen	Yield strength of Rebar (MPa)	Tensile Strength of Rebar (MPa)
Angle section	353	498
Batten plate	330	518

Details of test specimens



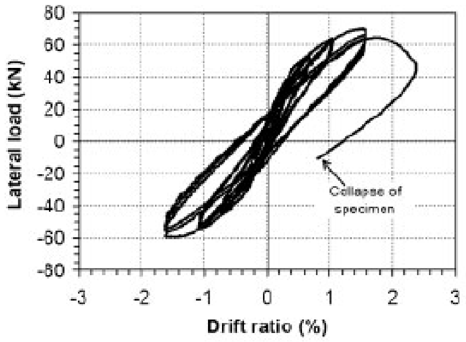
Steel cage to foundation connection



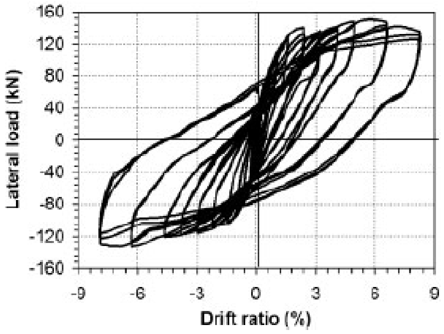
Results

Specimen	Max Disp Δ_{max} (mm)	Yield Disp Δ_y (mm)	Disp Ductility	Drift Ratio (%)	Peak Moment (kNm)	Lateral stiffness (kN/mm)
RCO	17.1	8.5	2.012	1.5	69.0	11.9
RCS1	70.9	14.5	4.89	2.5	133.2	20.5
RCS2	87	13.5	6.444	4.2	141.1	16.6

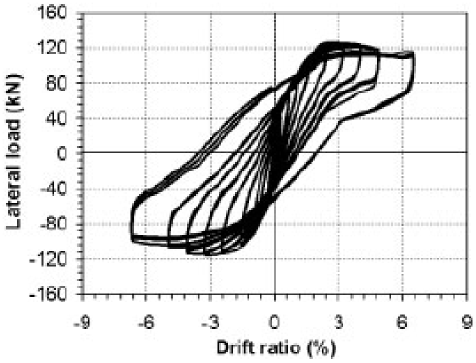
RCO hysteretic response



RCS2 hysteretic response



RCS1 hysteretic response



Effectiveness of the Method

This method is best suitable for project sites where encroachment of floor area is a hindrance, as this technique occupies negligible floor space. For the post-earthquake effects, this method is very much suitable. However, this method requires intermediate level of skilled labor since it demands drilling of holes in the foundation.

Roca, J.G., Adam, J.M. and Calderon, P.A. 2011. "Behavior of RC columns Strengthened by Steel Caging Under Combined Bending and Axial Loads," Construction and Building Materials, 25, 2402-2412.

Significance

This research focused on strengthening of columns by steel caging subjected to axial loads and bending moments. Two types of strengthening were used. In the first technique, capitals were welded to the steel cage in contact with beam. In the second technique, steel tubes were used joining the cage on both sides of beam. Test results indicate that steel tube technique had higher shear resistance and ductility as compared to specimen strengthened with capitals.

Properties and Results

Material Properties

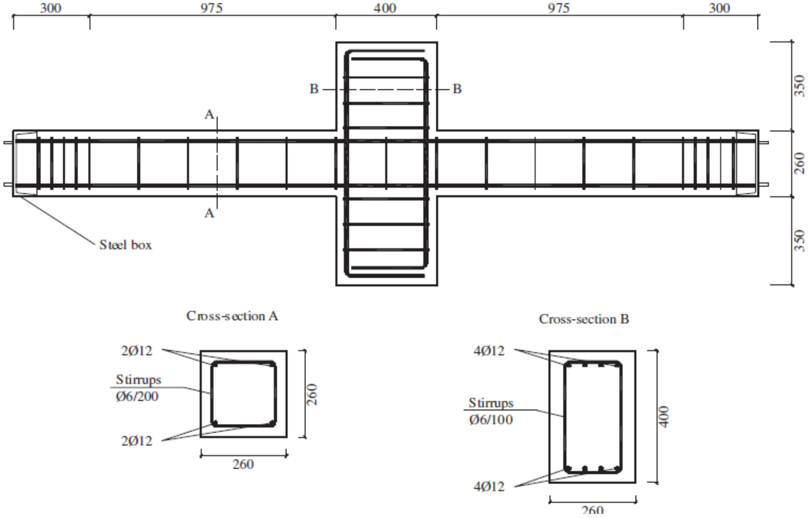
Concrete compressive strength	12 MPa
Reinforcement yield strength	500 MPa
Steel cage yield strength	275 MPa

Specimen	Beam-Column Joint Connection Type	Axial Load (kN)
Ref	-	-
C-1000	Capital	1000
C-300	Capital	300
T-1000	Tube	1000
T-300	Tube	300

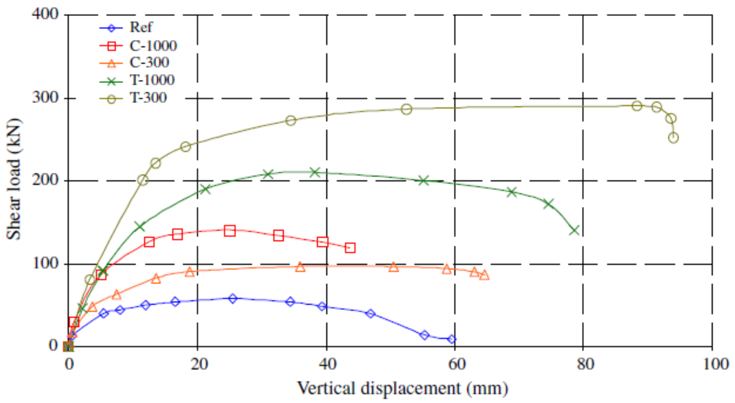
Test results

Specimen	Maximum shear Load (kN)	Maximum Bending Moment (kNm)
Ref	60.5	44
C-1000	143.3	104.3
C-300	101.7	74
T-1000	215.3	156.6
T-300	299.8	218.1

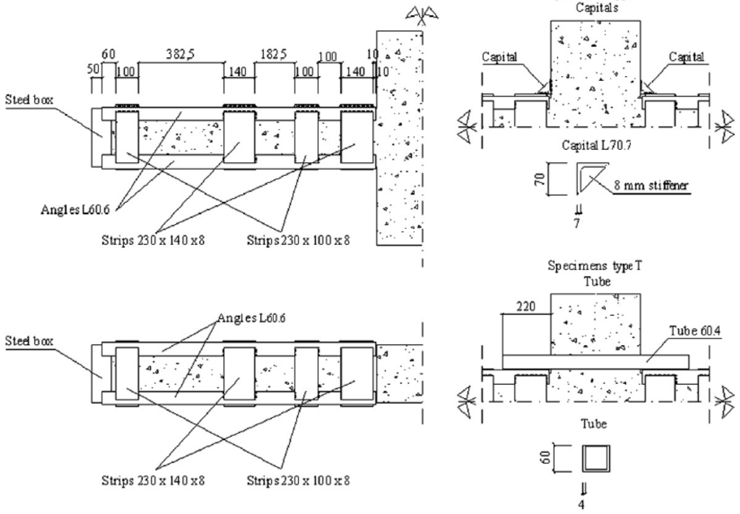
As built details of specimen



Shear load versus vertical displacement



Retrofit details of specimen



Effectiveness of the Method

Strengthening by capitals is more viable in terms of application since the procedure is easy to apply. However, failure of the specimen occurs in joints which is undesirable. Strengthening by tubes gives better ductility and shear capacity. However, the application is complicated since it requires drilling large holes in beams which reduces the beams capacity. One of the suggested solution for the two extremes is to join capitals on both lengths of column using steel bars passing through the joint. With this technique, the holes drilled are smaller whilst maintaining the beam capacity. Also the failure is shifted away from the joint onto the beam.

Appendix D: Precambered Steel Plating One-Pagers

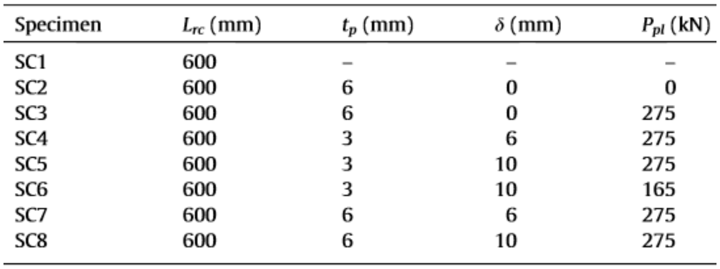
Su, R. K. L., and Wang, L. (May 01, 2012). Axial Strengthening of Preloaded Rectangular Concrete Columns by Precambered Steel Plates. Engineering Structures, 38, 42-52.

Significance

Precambered steel jackets are tested to improve the axial capacity of preloaded RC columns. A model was created to compare the experimental results. Eight columns were tested: one control column, and the others varied in the plate thickness, precambering, and preloading. LVDTs were attached on opposite sides of the column to measure axial shortening. Strain gauges were placed at four sections along the height to identify failure mode and assess axial load distribution.

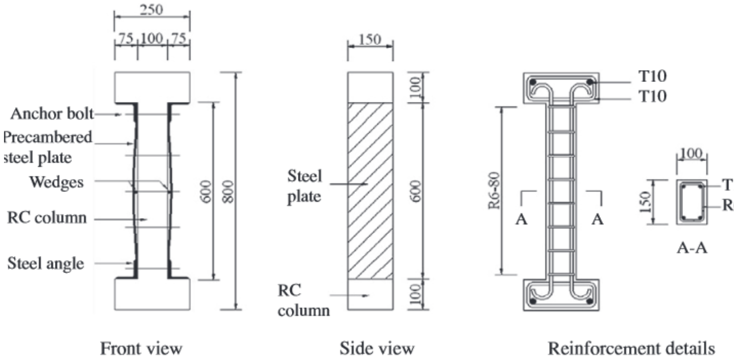
Loading/beam Images:

Strengthening Details



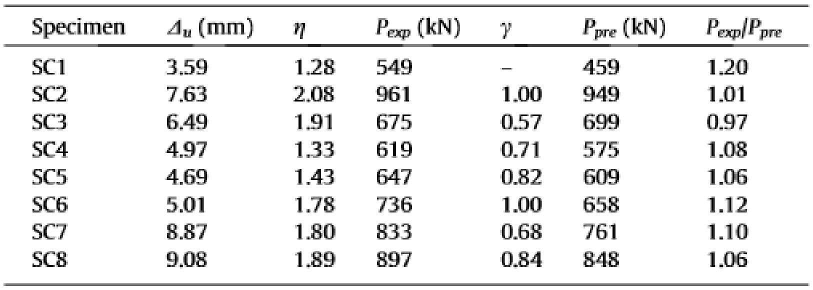
Specimen	L_{rc} (mm)	t_p (mm)	δ (mm)	P_{pl} (kN)
SC1	600	–	–	–
SC2	600	6	0	0
SC3	600	6	0	275
SC4	600	3	6	275
SC5	600	3	10	275
SC6	600	3	10	165
SC7	600	6	6	275
SC8	600	6	10	275

Reinforcement Details



Results:

Theoretical and Experimental Result Comparison



Specimen	Δ_u (mm)	η	P_{exp} (kN)	γ	P_{pre} (kN)	P_{exp}/P_{pre}
SC1	3.59	1.28	549	–	459	1.20
SC2	7.63	2.08	961	1.00	949	1.01
SC3	6.49	1.91	675	0.57	699	0.97
SC4	4.97	1.33	619	0.71	575	1.08
SC5	4.69	1.43	647	0.82	609	1.06
SC6	5.01	1.78	736	1.00	658	1.12
SC7	8.87	1.80	833	0.68	761	1.10
SC8	9.08	1.89	897	0.84	848	1.06

Stress-Lagging Effects (tp=6mm, d=0mm)

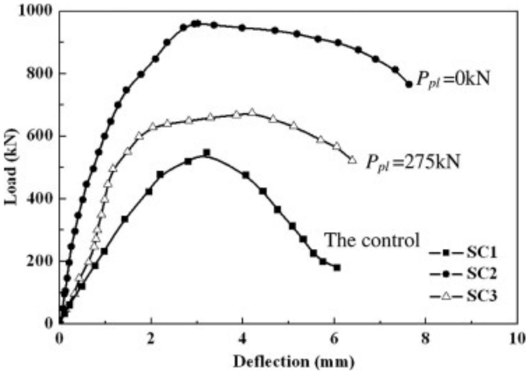
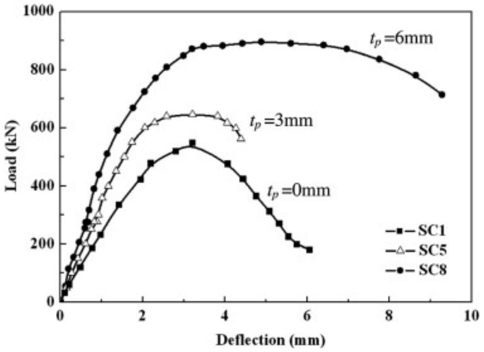
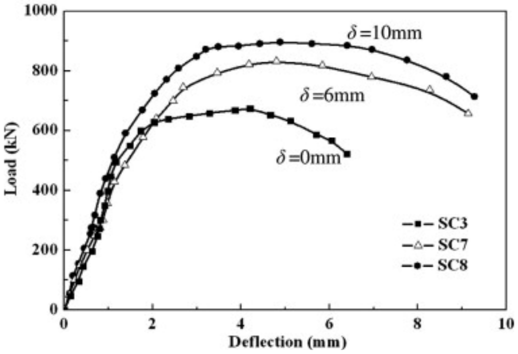


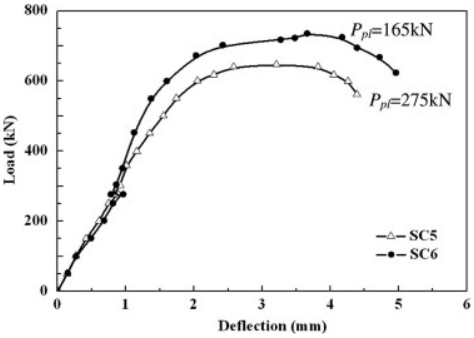
Plate Thickness Effects (d=10mm)



Precamber Effects (tp=6mm)



Preloading Effects (tp=3mm, d= 10mm)



Column SC3 had slightly lower load capacity due to the uneven packing of the steel angle packing at the top, preventing plates from reacing their full resistance. With no preloading, the precambered steel plates can reach their full capacity before cracks appear.

The presence of plates, and specifically larger plates, delayed the development of mid-height cracks. Axial load was nearly uniformly distributed across the plate height, resulting in effective load sharing between the column and the steel plates. Previous column loading does not transfer to the plates; stress-lagging causes premature failure. Thicker plates enhance strength and deformability of columns. Keeping design plate strength utilization coefficient less than 1 and increasing initial precamber results in greater axial load sharing and higher ultimate load capacity.

Effectiveness of the Method:

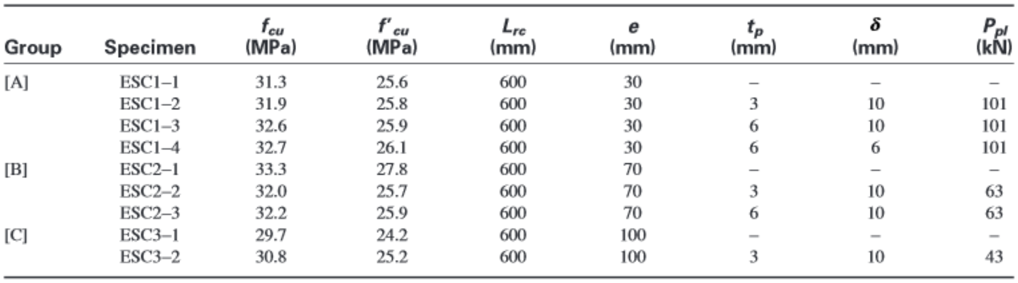
Controlling the initial precamber profile can alleviate stress-lagging effects. External steel plates can enhancew the strength, deformation, and ductility of strengthened columns under axial compressive loads. Using both the concrete column and steel plates to resist the load can produce higher axial load-carrying capacity.

Wang, L., and Su, R. K. L. (December 01, 2012). Experimental investigation of preloaded RC columns strengthened with precambered steel plates under eccentric compression loading. Advances in Structural Engineering, 15, 8, 1253-1264.

Significance:
Wang et al. evaluating using precambered steel plates to post-stress RC columns to alleviate stress-lagging effects and achieve higher axial strength and deformability. Nine columns with different eccentricities were tested, plate thicknesses and initial precamber displacements were tested under eccentric compression loads. Within each of 3 groups, one column acted as a control. The columns were tested with a hydraulic actuator. LVDTs were plated on opposite sides of the column vertically to measure axial and lateral deformations. Strain gauges at four sections along the height and middle of the vertical steel bars were placed to measure the deformation and internal stress distribution of the steel plates. The strain values were also used to determine the failure mode.

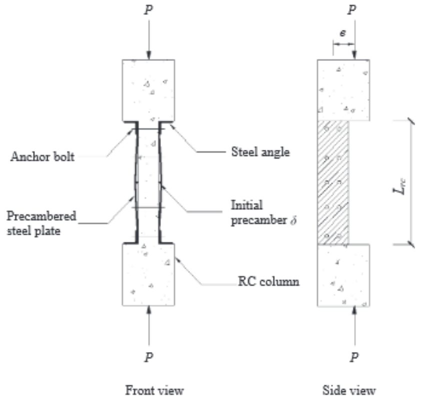
Loading/beam Images:

Strengthening Details Summary



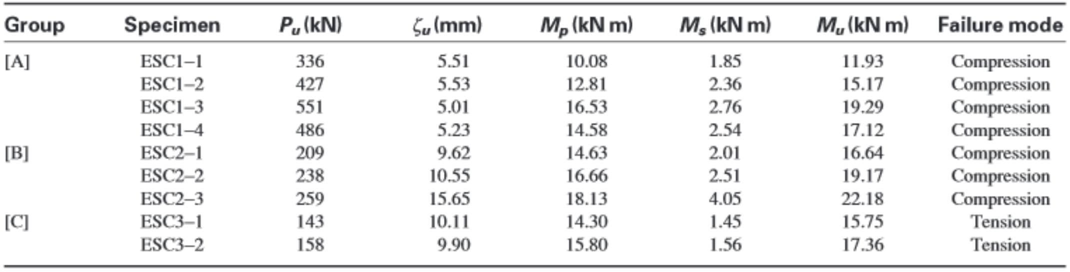
Group	Specimen	f_{cu} (MPa)	f'_{cu} (MPa)	L_{rc} (mm)	e (mm)	t_p (mm)	δ (mm)	P_{pl} (kN)
[A]	ESC1–1	31.3	25.6	600	30	–	–	–
	ESC1–2	31.9	25.8	600	30	3	10	101
	ESC1–3	32.6	25.9	600	30	6	10	101
	ESC1–4	32.7	26.1	600	30	6	6	101
[B]	ESC2–1	33.3	27.8	600	70	–	–	–
	ESC2–2	32.0	25.7	600	70	3	10	63
	ESC2–3	32.2	25.9	600	70	6	10	63
[C]	ESC3–1	29.7	24.2	600	100	–	–	–
	ESC3–2	30.8	25.2	600	100	3	10	43

Strengthening Method Configuration



Results:

Strengthening Results Summary



Group	Specimen	P_u (kN)	ζ_u (mm)	M_p (kN m)	M_s (kN m)	M_u (kN m)	Failure mode
[A]	ESC1–1	336	5.51	10.08	1.85	11.93	Compression
	ESC1–2	427	5.53	12.81	2.36	15.17	Compression
	ESC1–3	551	5.01	16.53	2.76	19.29	Compression
	ESC1–4	486	5.23	14.58	2.54	17.12	Compression
[B]	ESC2–1	209	9.62	14.63	2.01	16.64	Compression
	ESC2–2	238	10.55	16.66	2.51	19.17	Compression
	ESC2–3	259	15.65	18.13	4.05	22.18	Compression
[C]	ESC3–1	143	10.11	14.30	1.45	15.75	Tension
	ESC3–2	158	9.90	15.80	1.56	17.36	Tension

Eccentricity Effects (tp=3mm)

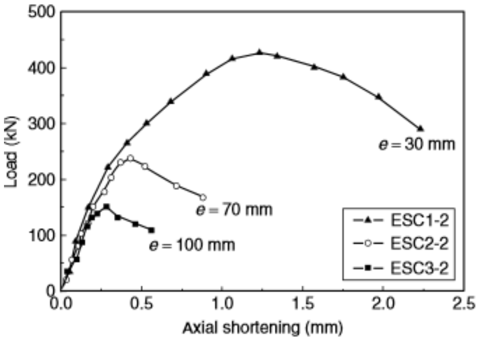
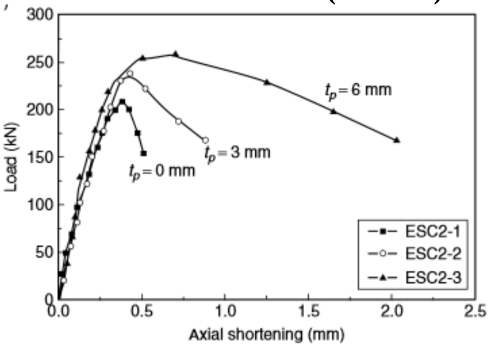
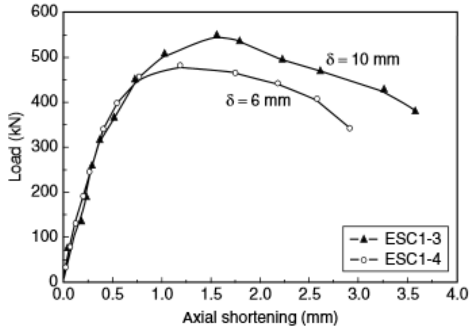


Plate Thickness Effects (e=70mm)



Initial Precamber Effects



Steel plates delayed the onset of the first cracking in concrete. Reinforcements yielded when reaching ultimate capacity in groups A and B, but Group C had tension reinforcement yield force, due to the eccentricity. Larger initial precamber can alleviate compressive strain by providing more resistance. The largest ultimate load capacity occurred in ECS1-2, which was 79.4% than the largest with a 70mm eccentricity, and 170.3% larger than one with a 100mm eccentricity. Thus, larger eccentricities produce smaller load capacities. Thicker precambered plates can increase the strength and deformability of columns. Increasing initial precamber produces more load sharing and higher ultimate load capacity from more post-compressive stress. For increasing deformability, plate thickness has an important role, but initial precamber and eccentricity do not.

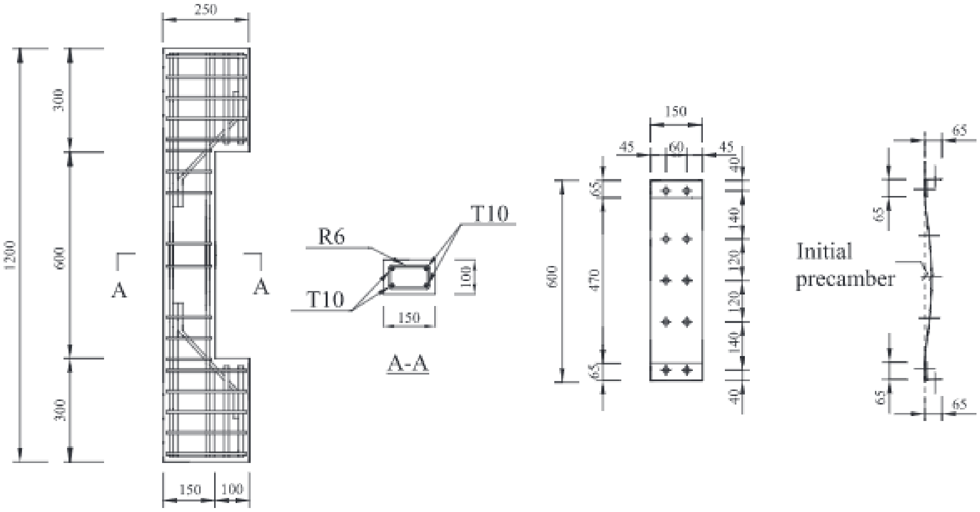
Effectiveness of the Method:
Precambered plates resulted in better post-yield deformation. Precambered steel plates were effective at increasing the axial strength and bending moment capacity of RC columns. Controlling initial precamber profile can mitigate stress-lagging effects. The maximum increase in load carrying capacity achieved by these columns was approximately 60%. Thicker plates and larger initial precamber can increase the ultimate load capacity of columns. Thicker plates also improve axial deformation capacity of columns significantly. Eccentricity affects the ultimate load capacity.

Wang, L., and Kai-Leung, S. R. (March 01, 2013). Theoretical and Experimental Study of Plate-Strengthened Concrete Columns under Eccentric Compression Loading. Journal of Structural Engineering, 139, 3, 350-359.

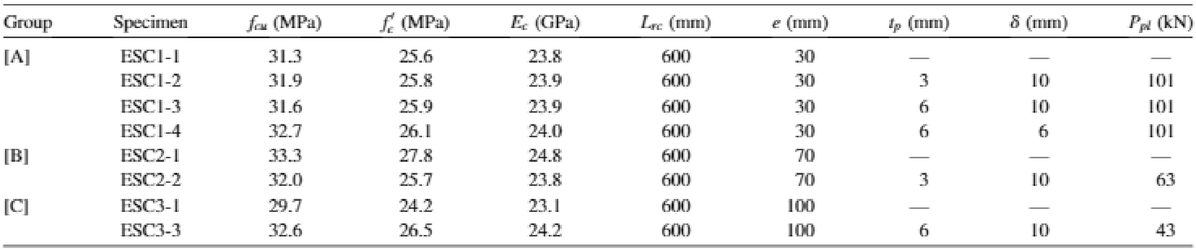
Significance
This study looks at alleviating the stress-lagging effects through precambered steel plates, which also improve axial strength and moment capacity of eccentrically preloaded RC columns. Eight columns were tested while varying their eccentricity, plate thickness, initial pre-cambering. Experimental results are compared with theoretical values by creating a model.

Loading/beam Images

Reinforcement and Precambered Steel Plate Details



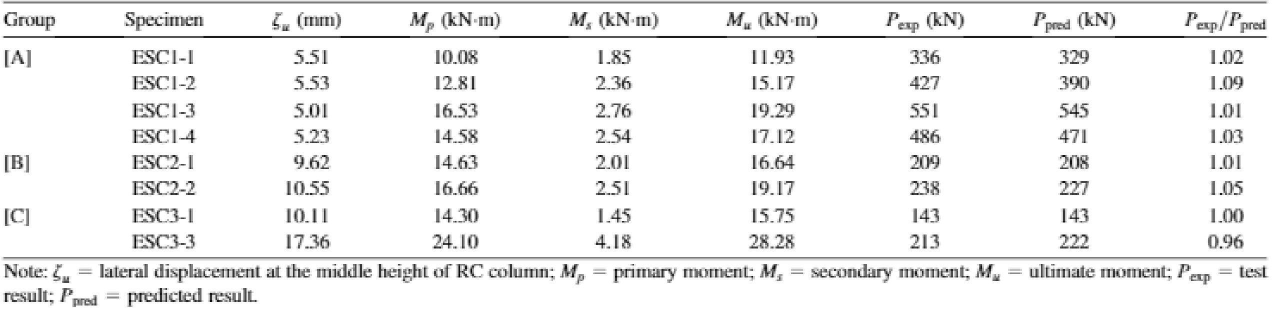
Summary of Strengthening Details



Group	Specimen	f_{cu} (MPa)	f'_c (MPa)	E_c (GPa)	L_{rc} (mm)	e (mm)	t_p (mm)	δ (mm)	P_{pl} (kN)
[A]	ESC1-1	31.3	25.6	23.8	600	30	—	—	—
	ESC1-2	31.9	25.8	23.9	600	30	3	10	101
	ESC1-3	31.6	25.9	23.9	600	30	6	10	101
	ESC1-4	32.7	26.1	24.0	600	30	6	6	101
[B]	ESC2-1	33.3	27.8	24.8	600	70	—	—	—
	ESC2-2	32.0	25.7	23.8	600	70	3	10	63
[C]	ESC3-1	29.7	24.2	23.1	600	100	—	—	—
	ESC3-3	32.6	26.5	24.2	600	100	6	10	43

Results

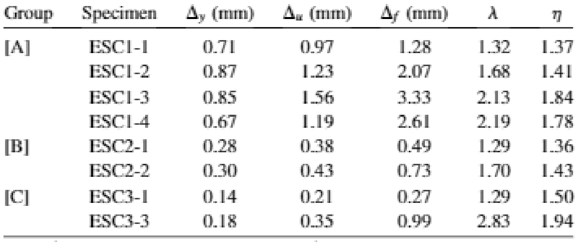
Comparison of Theoretical and Experimental Results



Group	Specimen	ζ_u (mm)	M_p (kN·m)	M_s (kN·m)	M_u (kN·m)	P_{exp} (kN)	P_{pred} (kN)	$P_{\mathrm{exp}}/P_{\mathrm{pred}}$
[A]	ESC1-1	5.51	10.08	1.85	11.93	336	329	1.02
	ESC1-2	5.53	12.81	2.36	15.17	427	390	1.09
	ESC1-3	5.01	16.53	2.76	19.29	551	545	1.01
	ESC1-4	5.23	14.58	2.54	17.12	486	471	1.03
[B]	ESC2-1	9.62	14.63	2.01	16.64	209	208	1.01
	ESC2-2	10.55	16.66	2.51	19.17	238	227	1.05
[C]	ESC3-1	10.11	14.30	1.45	15.75	143	143	1.00
	ESC3-3	17.36	24.10	4.18	28.28	213	222	0.96

Note: ζ_u = lateral displacement at the middle height of RC column; M_p = primary moment; M_s = secondary moment; M_u = ultimate moment; P_{exp} = test result; P_{pred} = predicted result.

Summary of Deformability and Ductility Factors



Group	Specimen	Δ_y (mm)	Δ_u (mm)	Δ_f (mm)	λ	η
[A]	ESC1-1	0.71	0.97	1.28	1.32	1.37
	ESC1-2	0.87	1.23	2.07	1.68	1.41
	ESC1-3	0.85	1.56	3.33	2.13	1.84
	ESC1-4	0.67	1.19	2.61	2.19	1.78
[B]	ESC2-1	0.28	0.38	0.49	1.29	1.36
	ESC2-2	0.30	0.43	0.73	1.70	1.43
[C]	ESC3-1	0.14	0.21	0.27	1.29	1.50
	ESC3-3	0.18	0.35	0.99	2.83	1.94

Effectiveness of the Method
Controlling the initial precamber profile can diminish stress lagging effects. Ultimate load capacity can be improved with thicker plates and larger initial precambering. Thicker plates can also improve the axial deformation capacity and ductility of the columns.

Appendix E: External Pre-stressed Steel One-Pagers

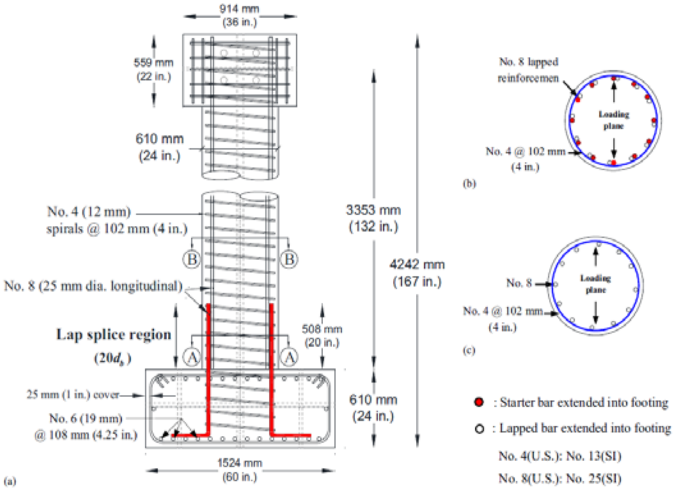
Fakharifar, M., Chen, G., Wu, C., Shamsabadi, A., ElGawady, M. A., and Dalvand, A. (April 01, 2016). Rapid Repair of Earthquake-Damaged RC Columns with Prestressed Steel Jackets. Journal of Bridge Engineering, 21, 4, 4015075.

Significance

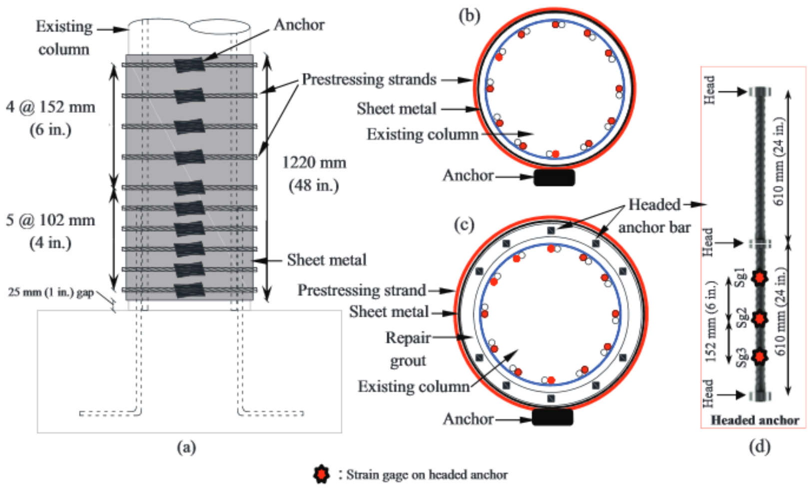
Fakharifar et al. designed a rapid and cost-effective repair of severely damaged circular reinforced concrete columns by using a lightweight prestressed steel jacket. The jacket has a thin steel sheet wrapped around the column restrained by several prestressed strands. The strands prevent steel sheet buckling while the sheet prevents the strands from damaging the concrete. With two workers, this can be completed in 12 hours. The authors tested two half-scale columns under pseudostatic cyclic reversed horizontal loads. Following testing, the columns were repaired and retested. Column 1 was repaired to restore stiffness, strength and ductility, while Column 2 was repaired to increase strength.

Loading and Column Images

As built columns



Retrofitted columns Column 1 (b), Column 2(c)



Column rotation was measured with 10 LVDTs and LPTs at the base of each column as a result of separation, anchorage slip, or steel slip of the column.

Results

Hysteresis Loops

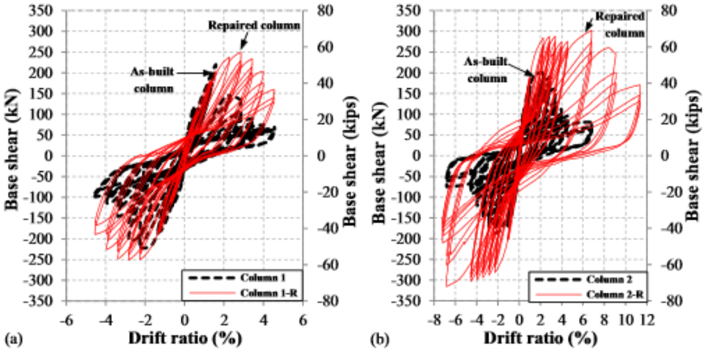
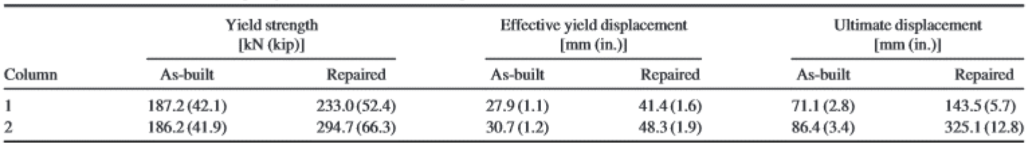
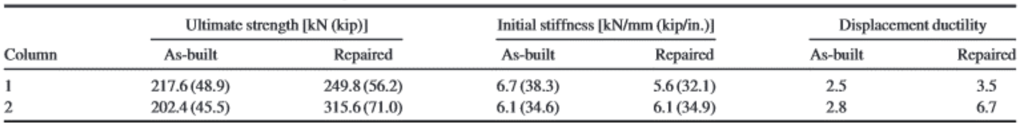


Table 1. Parameters in Idealized Capacity Curves of As-Built and Repaired Columns



	Yield strength [kN (kip)]		Effective yield displacement [mm (in.)]		Ultimate displacement [mm (in.)]	
Column	As-built	Repaired	As-built	Repaired	As-built	Repaired
1	187.2 (42.1)	233.0 (52.4)	27.9 (1.1)	41.4 (1.6)	71.1 (2.8)	143.5 (5.7)
2	186.2 (41.9)	294.7 (66.3)	30.7 (1.2)	48.3 (1.9)	86.4 (3.4)	325.1 (12.8)

Table 2. Performance Measures of As-Built and Repaired Columns



	Ultimate strength [kN (kip)]		Initial stiffness [kN/mm (kip/in.)]		Displacement ductility	
Column	As-built	Repaired	As-built	Repaired	As-built	Repaired
1	217.6 (48.9)	249.8 (56.2)	6.7 (38.3)	5.6 (32.1)	2.5	3.5
2	202.4 (45.5)	315.6 (71.0)	6.1 (34.6)	6.1 (34.9)	2.8	6.7

Effectiveness of the Method

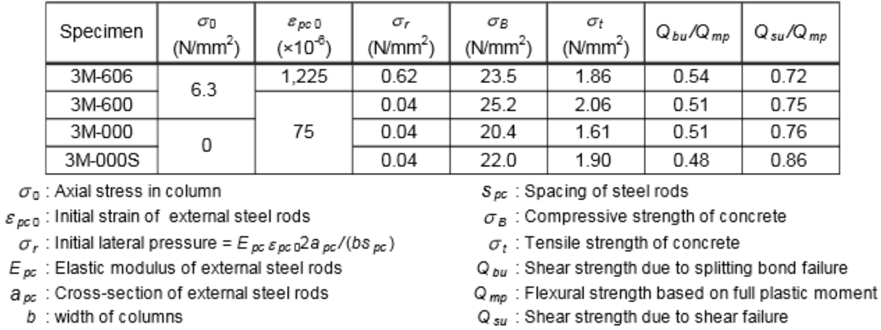
For long-term performance or aesthetics, a protective or architectural layer could be added to the proposed PSJ. When restoring stiffness is a concern, effective load transfer can be achieved by embedding headed bars anchored to the footing in grout added significant stiffness. Passive and active confinement were sufficient to prevent spalling and minimize cracks within the PSJ region. These methods are particularly useful when time and cost are a concern, since the column 1 method only requires 12 hours to repair, and the column 2 method requires 24 hours while remaining less expensive than other conventional repair techniques.

Ho, S. W., Kuroki, M., and Kikuchi, K. (August 25, 2010). Experimental Study on Splitting Bond Strength of RC Columns Retrofitted Laterally with Stressed External Steel Rods. CI-Premier PTE LTD.

Significance:
Ho et al. tested laterally strengthening columns with external steel rods. An equation was developed to predict shear strength. Four columns were tested under cyclic lateral loading and a constant axial load by oil jacks.

Loading/beam Images:

Summary of Specimens

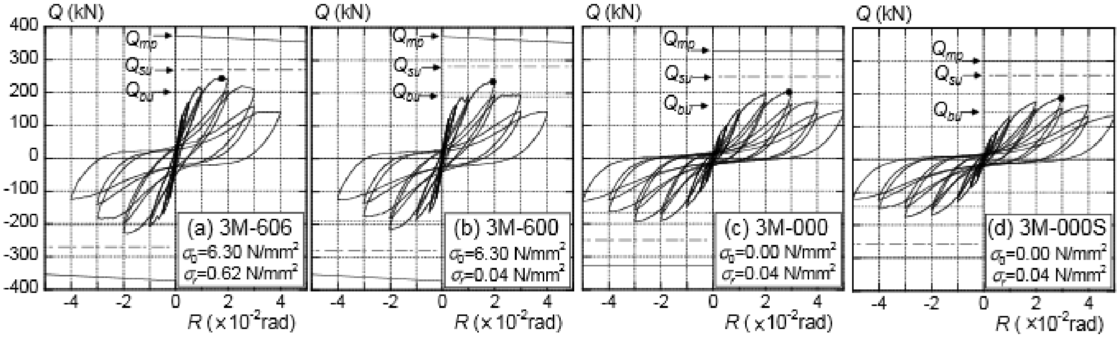


Specimen	σ_0 (N/mm^2)	ε_{pc0} ($\times10^{-6}$)	σ_r (N/mm^2)	σ_B (N/mm^2)	σ_t (N/mm^2)	Q_{bu}/Q_{mp}	Q_{su}/Q_{mp}
3M-606	6.3	1,225	0.62	23.5	1.86	0.54	0.72
3M-600		75	0.04	25.2	2.06	0.51	0.75
3M-000	0		0.04	20.4	1.61	0.51	0.76
3M-000S			0.04	22.0	1.90	0.48	0.86

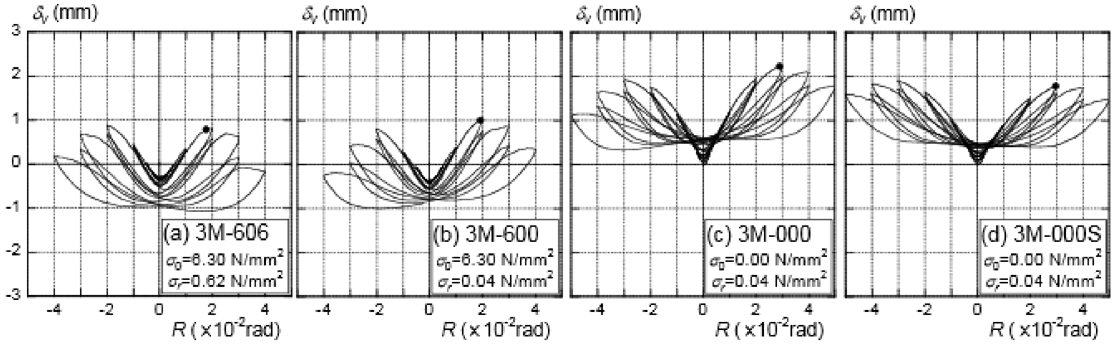
σ_0 : Axial stress in column
ε_{pc0} : Initial strain of external steel rods
σ_r : Initial lateral pressure = $E_{pc}\,\varepsilon_{pc0}\,2a_{pc}/(bs_{pc})$
E_{pc} : Elastic modulus of external steel rods
a_{pc} : Cross-section of external steel rods
b : width of columns
s_{pc} : Spacing of steel rods
σ_B : Compressive strength of concrete
σ_t : Tensile strength of concrete
Q_{bu} : Shear strength due to splitting bond failure
Q_{mp} : Flexural strength based on full plastic moment
Q_{su} : Shear strength due to shear failure

Results:

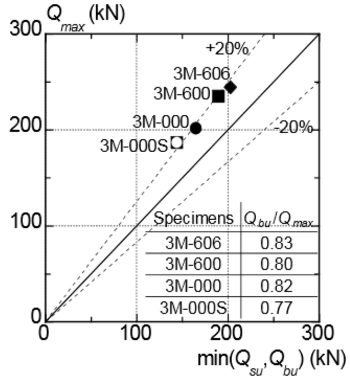
Lateral Forces (Q) and Deformation Angle (R) Relationships



Axial Deformation and Deformation Angle (R) Relations



Relation Between Experimental Maximum Strength and Calculated Shear Strength



Specimens	Q_{bu}/Q_{max}
3M-606	0.83
3M-600	0.80
3M-000	0.82
3M-000S	0.77

Effectiveness of the Method:
Columns failed in shear, splitting bond failure, or a mix. The shear strength was approximately 80% of the maximum strength from the experiment.

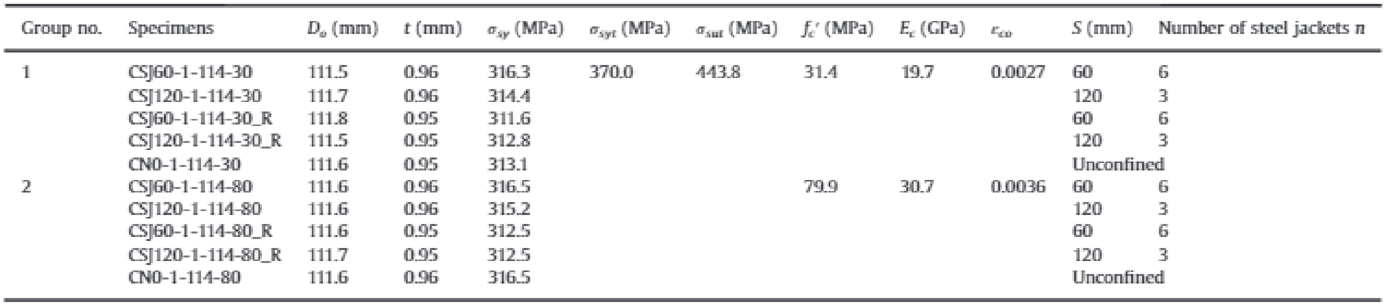
Lai, M. H., and Ho, J. C. M. (December 01, 2015). Axial strengthening of thin-walled concrete-filled-steel-tube columns by circular steel jackets. Thin-walled Structures, 97, 11-21.

Significance

Lai et al. tested the use of concrete-filled-steel-tube (CFST) columns for strengthening columns. The main parameters evaluated were cylinder strength, hoop spacing, and pre-compressed axial load level. The results were also compared against theoretical values. The 5 HST and 10 thin-walled CFST columns were tested under compressive uniaxial loads. Strain gauges and LVDT's were attached to each of the hoops.

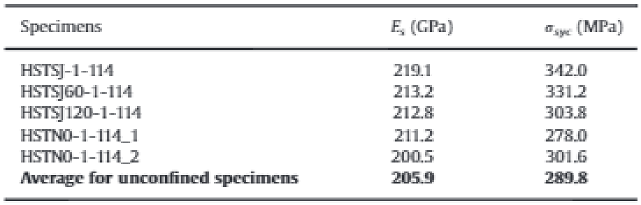
Test Properties and Loading

CFST Properties



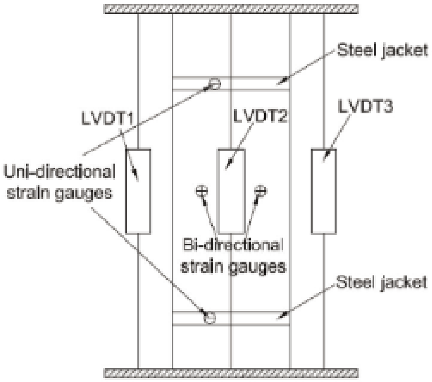
Group no.	Specimens	D_o (mm)	t (mm)	σ_{sy} (MPa)	σ_{syt} (MPa)	σ_{sut} (MPa)	f_c' (MPa)	E_c (GPa)	ε_{co}	S (mm)	Number of steel jackets n
1	CSJ60-1-114-30	111.5	0.96	316.3	370.0	443.8	31.4	19.7	0.0027	60	6
	CSJ120-1-114-30	111.7	0.96	314.4						120	3
	CSJ60-1-114-30_R	111.8	0.95	311.6						60	6
	CSJ120-1-114-30_R	111.5	0.95	312.8						120	3
	CN0-1-114-30	111.6	0.95	313.1						Unconfined	
2	CSJ60-1-114-80	111.6	0.96	316.5			79.9	30.7	0.0036	60	6
	CSJ120-1-114-80	111.6	0.96	315.2						120	3
	CSJ60-1-114-80_R	111.6	0.95	312.5						60	6
	CSJ120-1-114-80_R	111.7	0.95	312.5						120	3
	CN0-1-114-80	111.6	0.96	316.5						Unconfined	

HST Properties

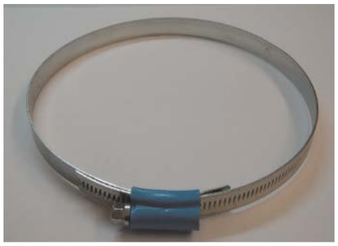


Specimens	E_s (GPa)	σ_{syc} (MPa)
HSTSJ-1-114	219.1	342.0
HSTSJ60-1-114	213.2	331.2
HSTSJ120-1-114	212.8	303.8
HSTN0-1-114_1	211.2	278.0
HSTN0-1-114_2	200.5	301.6
Average for unconfined specimens	**205.9**	**289.8**

Testing Configuration

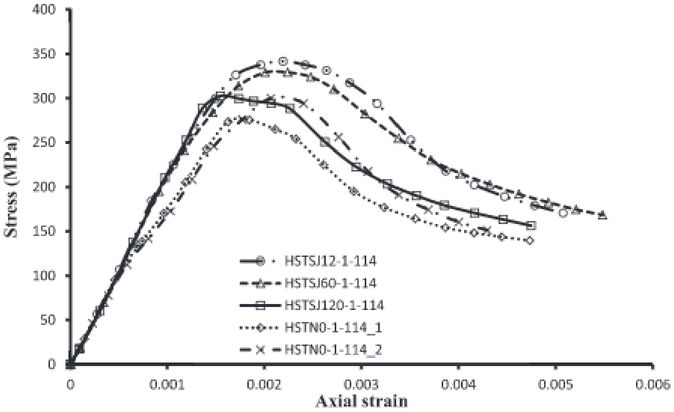


Steel Jacket Detail

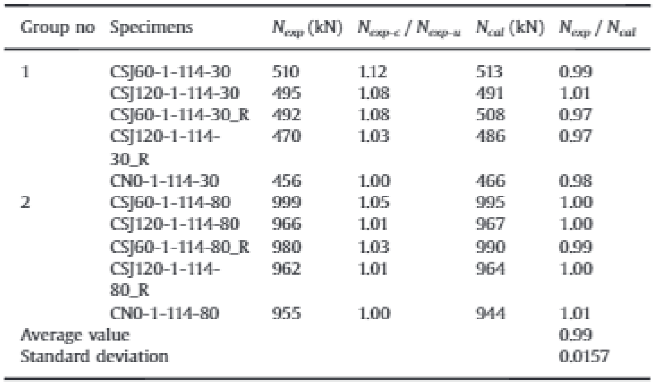


Results

Axial Stress-strain Curves for HST Columns



Theoretical and Experimental Result Comparison for CFST Columns



Group no	Specimens	N_{exp} (kN)	N_{exp-c} / N_{exp-u}	N_{cal} (kN)	N_{exp} / N_{cal}
1	CSJ60-1-114-30	510	1.12	513	0.99
	CSJ120-1-114-30	495	1.08	491	1.01
	CSJ60-1-114-30_R	492	1.08	508	0.97
	CSJ120-1-114-30_R	470	1.03	486	0.97
	CN0-1-114-30	456	1.00	466	0.98
2	CSJ60-1-114-80	999	1.05	995	1.00
	CSJ120-1-114-80	966	1.01	967	1.00
	CSJ60-1-114-80_R	980	1.03	990	0.99
	CSJ120-1-114-80_R	962	1.01	964	1.00
	CN0-1-114-80	955	1.00	944	1.01
Average value					0.99
Standard deviation					0.0157

Local buckling was the failure mode for all jacketed columns, while the unconfined HST column failed due to outward buckling at the top of the column. The confinement minimized end buckling while having bulging between hoop rows. The high strength column had a more brittle failure mode from brittle shear failure and irregular local buckling.

Effectiveness of the Method

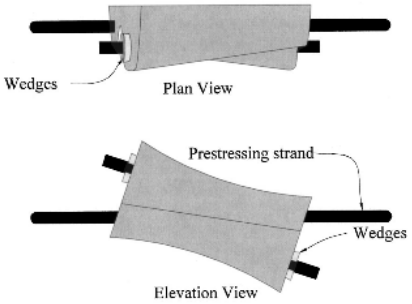
The steel hoops tested were highly effective at improving uni-axial behavior among HST and CFST columns. The columns pre-compressed had less significant strength enhancement due to the initial confining stress and stress-lagging effect. The hoops converted the end buckling failure mode for unconfined columns into bulging between rows of the steel hoops.

Saatcioglu, M., and Yalcin, C. (August 01, 2003). External Prestressing Concrete Columns for Improved Seismic Shear Resistance. Journal of Structural Engineering, 129, 8.

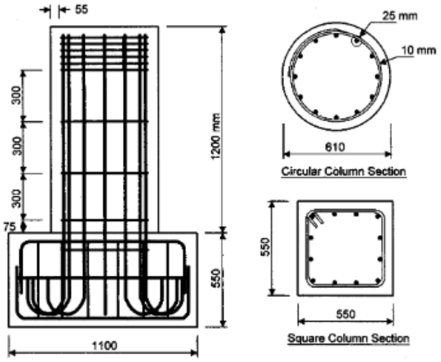
Significance:
Saatcioglu et al. tested retrofitting columns in the transverse direction with individual hoops with prestressing strands and anchors. Seven full-scale columns were tested under compression and incrementally loaded with increasing lateral deformation. LVDTs are on opposite sides of the columns to measure displacements. Strain gauges are on prestressing strand. A procedure is presented to design columns using this retrofit method.

Loading/beam Images:

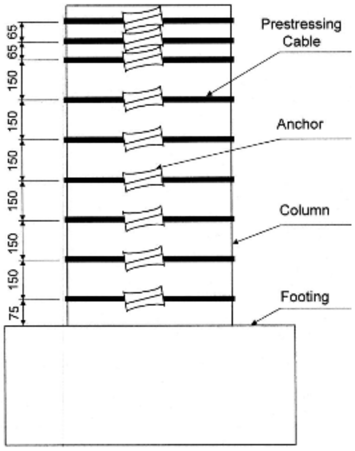
Anchors for Prestressing



Geometry of Test Columns



Hardware for Retrofitting Columns

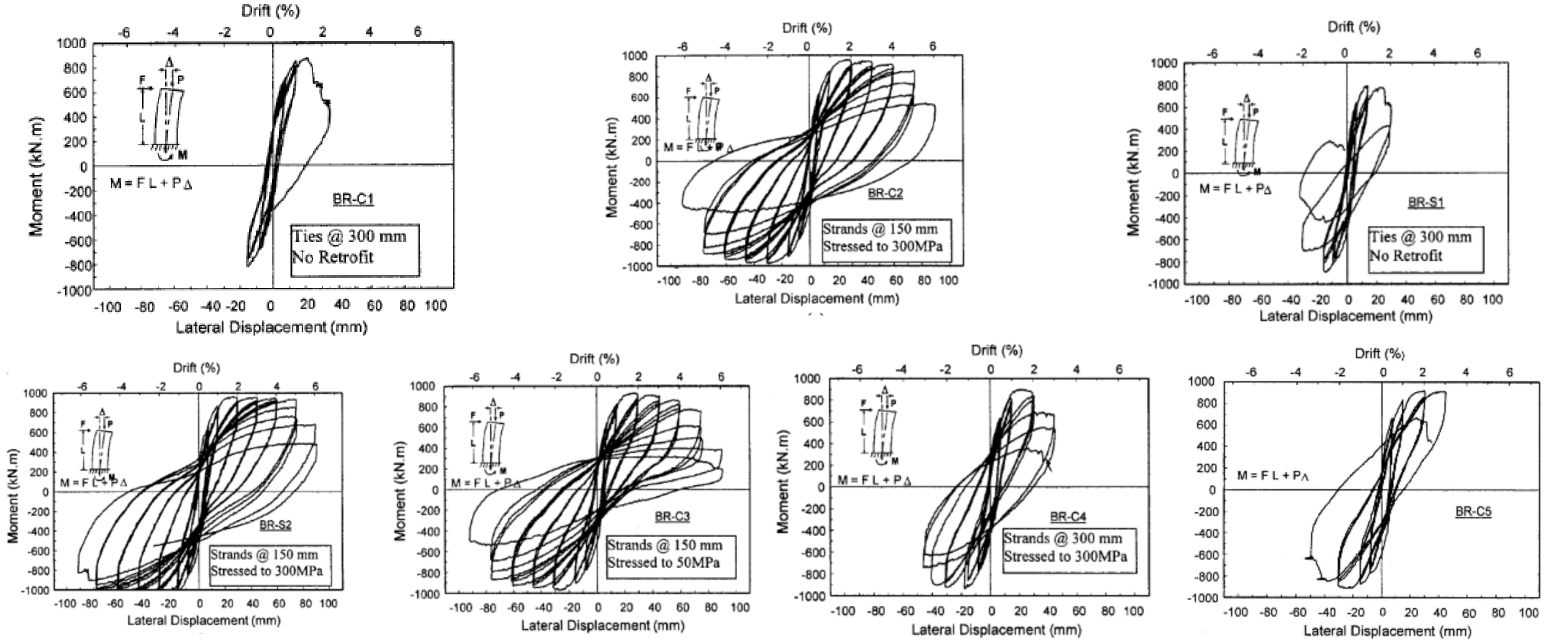


Test Parameters

Test column	Cross section	Retrofitting by external hoops: Hoop steel	Hoop spacing	Initial prestress
BR-S1	550 mm square	—	—	—
BR-S2	550 mm square	Seven-wire strand	150 mm	300 MPa
BR-C1	610 mm circular	—	—	—
BR-C2	610 mm circular	Seven-wire strand	150 mm	300 MPa
BR-C3	610 mm circular	Seven-wire strand	150 mm	50 MPa
BR-C4	610 mm circular	Seven-wire strand	300 mm	300 MPa
BR-C5	610 mm circular	Steel strap	150 mm	50 MPa

Results:

Hysteresis Curves



Effectiveness of the Method:
The columns improved in lateral drift capacity from 1% to 5% in the retrofitted columns relative to the shear-critical columns. Wider spacing of strands may not produce sufficient column deformability or may cause a significant reduction in effectiveness.

Appendix F: Other Retrofit Methods

Ozbulut, O., Hurlebaus, S., and Desroches, R. (January 01, 2011). Seismic Response Control Using Shape Memory Alloys: A Review. Journal of Intelligent Material Systems and Structures, 22, 14, 1531-1549.

Significance

Shape memory alloys (SMAs) can offer shape recovery after structures have experienced large strain, provide energy dissipation, have great resistance to corrosion and fatigue, and are high strength. As a result, they have particularly useful applications for structures under seismic loading.

Effectiveness of the Method

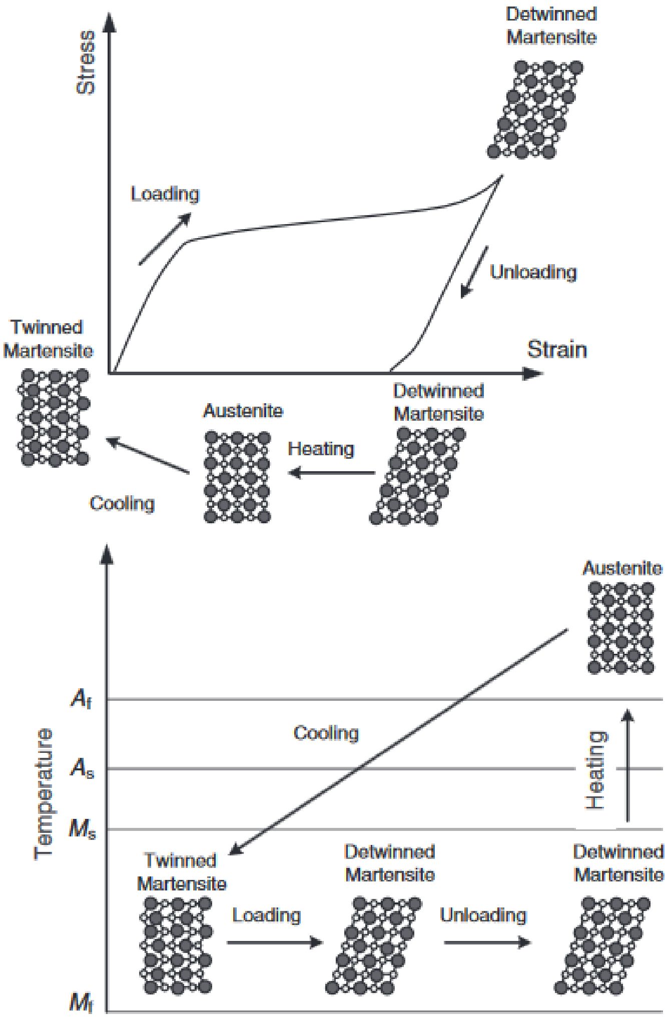
SMAs have two phases: martensite, which is stable at low temperatures and high stress; and austentite, which is stable at high temperatures and low stress. SMAs can move between these phases due to application of stress or heat.

The SMAs demonstrate a shape memory effect by being loaded beyond a critical level, where it will keep its shape in the detwinned martensite phase after unloading. When heat is applied it can return to the austentite phase. Upon cooling, it will return to the twinned martensite phase and its original shape before loading.

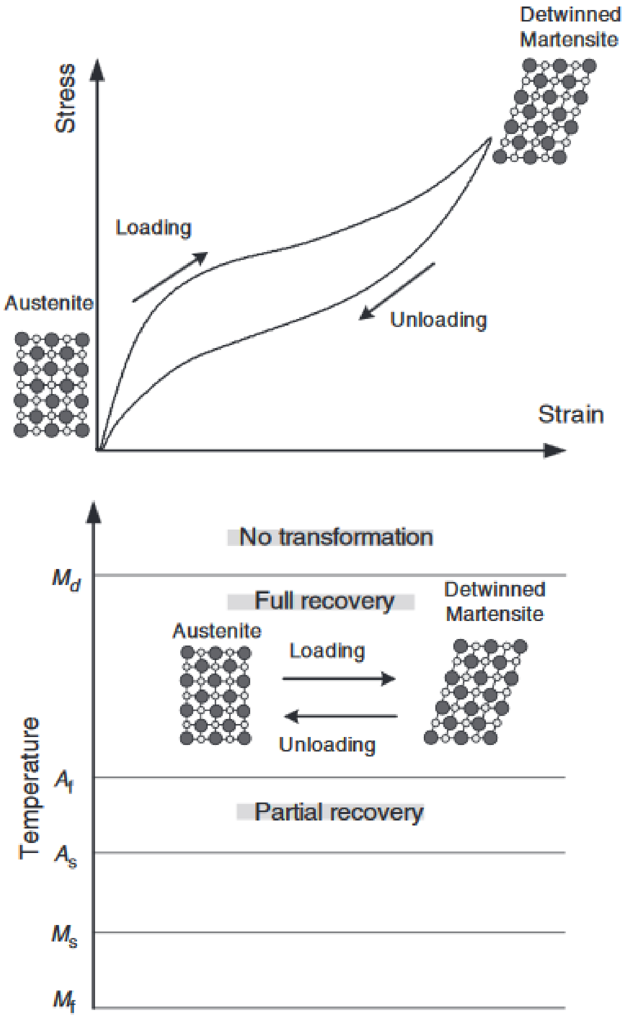
The superelastic effect can be exhibited when the alloy is at a high enough temperature initially to be in the austentite phase. When a high stress is induced, the alloy will move to the detwinned martensite phase, in which it can return to the austentite phase and original shape upon unloading.

SMAs are frequently composed of either a nickel-titanium or a coppery based alloy. The NiTI alloy is best when nickel and titanium are present in equal amounts. More nickel results in less transformation temperature. Copper alloys are less expensive and easier to create, however NiTi alloys have decreased in cost recently. However, CU-based alloys can only reach 2-4% strain levels, while NiTi can recover strains up to 8%.

SMAs also have greater energy dissipation and recovery capacity. However, their high cost and limited amount of research has resulted in their lack of implementation.



Shape memory effect



Superelastic effect

Triantafillou, T. C. (January 01, 2001). Seismic Retrofitting of Structures with Fibre-reinforced Polymers. Progress in Structural Engineering and Materials, 3, 1, 57-65.

Significance

Triantafillou describe the key behavior and design aspects for fiber-reinforced polymers (FRP), particularly in reference to seismic strengthening. FRP's are used in a variety of reinforced concrete or masonry structures. Retrofit issues including shear strengthening, and plastic-hinge behavior are summarized. Externally bonded FRP strengthening can be composed of carbon, glass or aramid fibers in a matrix with an epoxy.

Effectiveness of the Method

Flexural Members:

The shear strengthening capacity of FRP members is controversial with some researchers describing the capacity of FRP to resist tensile forces from a constant strain equal or less than the FRP ultimate tensile strain. However, other studies have described the strain as dependent on the FRP failure mode, type of jacket, axial rigidity of the jacket, and strength of the substrate material.

Confinement:

As shown in the figure, the concrete demonstrates bilinear behavior with a transition zone near the capacity of unconfined concrete. The effectiveness of confinement depends on the jacket characteristics and increases as stiffness and ultimate strain increase. The confinement is less effective for rectangular columns, due to the confining stress being transferred through the corners of the cross-section.

Plastic-hinge:

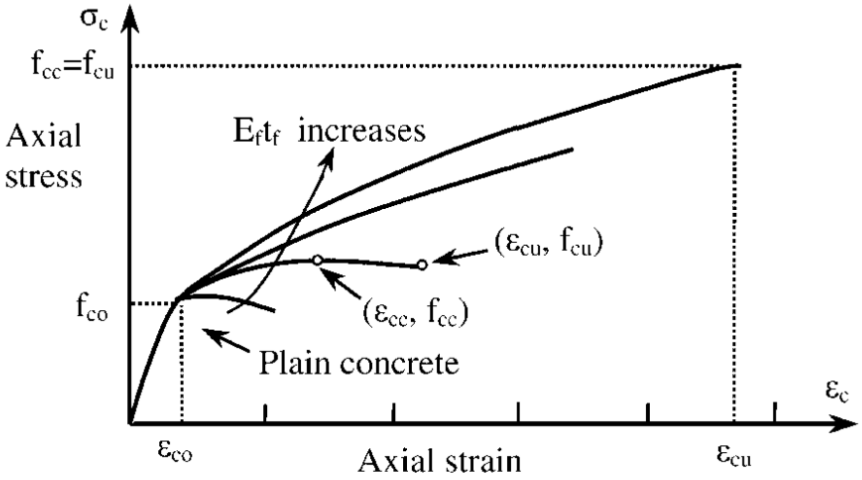
Proper design of the FRP jackets can lead to sufficient ductility enhancement.

Lap splice clamping:

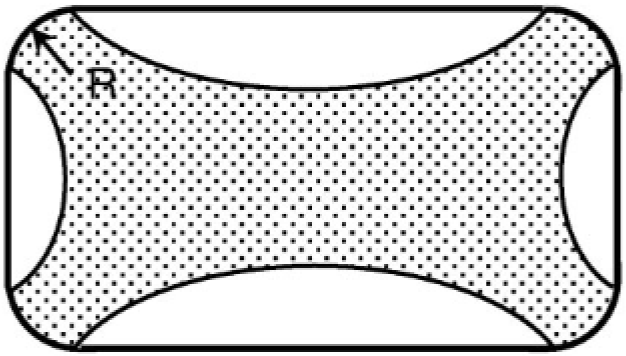
FRP is effective at preventing lap splice failures if sufficient lateral pressure is applied in the lap splice region.

Practicality:

FRP wrapping techniques can be performed quickly and take up little space.



Axial stress-strain response of FRP-confined concrete versus plain concrete



Confined area in a rectangular column