PARTIALLY CONFINED CONCRETE: VALUE ENGINEERING & PERFORMANCE ANALYSIS

A. R. Kotwal, CDT
Y. J. Kim, PhD, PE, LEED AP

Texas State University-San Marcos
Department of Engineering Technology

ABSTRACT

To promote the sustainable use of materials in the precast/prestressed concrete industry, this research initiative analyzed the performance and cost effectiveness of partially confined cylindrical concrete specimens wrapped with carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP). Variables that were manipulated include the fiber (CFRP vs. GFRP), confinement (25%, 50%, 75%, 100%) and layers (One, Two, Three). Specimens were subjected to uniaxial compression to measure ultimate compressive strength. An analysis of variance was then conducted to determine the variation in the performance of the specimens and to assess the contribution of each variable to the variation. By also taking a value engineering approach, the relation of function to cost was quantitatively compared for each scenario. Results of the study indicated that specimens confined with GFRP outperformed their CFRP counterparts at confinement levels of 50% and greater; however, the opposite was observed for 25% confinement ($p < 0.01$). Significant increases in compressive strength were measured for partially confined specimens when compared to unconfined control specimens, and the strength increased with higher levels of confinement ($p < 0.01$). In addition to the increased value realized by partially confining specimens with GFRP, it was also found that, in many cases, partial confinement of concrete can provide considerable structural strengthening while maintaining economic feasibility.

Keywords: concrete, confinement, glass fiber reinforced polymer, carbon fiber reinforced polymer, value engineering

INTRODUCTION

Confining existing concrete columns with FRP (a composite material made of a polymer matrix reinforced with fibers) has become an increasingly popular method of strengthening concrete, thereby, providing a means to increase the longevity of antiquated structures. Confined concrete is defined as reinforced concrete with restraints implemented perpendicular to the applied load's force. Foundational research on confined concrete began in the 1920s, discovering that radial confinement of concrete effectively increases its ultimate compressive strength.[1] Furthermore, as a result of the need for improved ductility in concrete columns for seismic engineering, studies performed in the 1980s developed stress-strain models which established that steel confinement significantly enhances ductility once ultimate strength is achieved.[2,3,4] More recent research has provided insight regarding the behavioral differences between steel and FRP confinement, including the fact that FRP confining stress increases linearly until rupture in lieu of having a constant confining stress similar to steel. The linear relationship is caused by the elastic nature of FRP which, in experimental studies, has been confirmed by observing a continuous increase in axial strain as the confining pressure increases.[5] In light of this key difference in confinement materials, there are a number of theoretical and empirical studies that have focused strictly on the behavior and modeling of concrete confined with FRP.[6,7,8]

In recent years, external confinement of concrete through the use of FRP has become increasingly popular for civil infrastructure applications, including the seismic retrofitting of columns in earthquake prone areas, offshore structures, large mining equipment and buildings. Sufficient reinforcement is accomplished by wrapping existing columns or encasing concrete with FRP for preventive maintenance or protective repair. These techniques have considerable advantages over alternative practices such as external post tensioning and strengthening using steel plates due to steel's corrosive nature. Due to its ease of use and high strength to weight ratio, FRP has become the leader in concrete confinement in the past decade. CFRP and GFRP allow for greater design flexibility, previously prohibited by the limitations of traditional building materials. The materials are also noncorrosive, strong, lightweight, maintenance free and can be erected efficiently and economically. Per unit weight, CFRP and GFRP are among the strongest commercially available materials, exhibiting structural properties greater than any concrete, steel or aluminum. However, in many cases, there is a considerable difference in the cost of the fibers depending on the dimensions and design pattern.[9]

In the scientific literature regarding confined concrete, procedures have varied as there are no explicit standards for wrapping specimens. Furthermore, confined concrete does not have an American Society for Testing and Materials (ASTM) standard for its application. Hence, materials used for confined concrete can be anything that will improve strength. Fiber wrapping may vary from one to twelve layers depending on the diameter and length of the specimens, and there are numerous methods of wrapping. In most cases, higher strength results from applying more layers to a specimen. Still, many researchers are trying to find the most respectable model for improving strength, which makes it difficult to specify standards for FRP confinement.[10]

A recent study was conducted to evaluate the performance of partially confined concrete, considering the need to repair partially deteriorated structures while also aspiring to reduce construction materials, labor and duration. Researchers at Dalian University of Technology performed an experimental study on the strength of concrete columns that were only partially deteriorated to test this theory. By wrapping short rectangular columns with CFRP, results of the study indicated that partial confinement in deteriorated regions can significantly enhance ultimate strength.[11]

Limited research has been conducted with regards to the sustainable use of material for confined concrete; however, there is a growing need to reduce the consumption of resources in the construction industry while still achieving desired results. Prior to World War II, General Electric developed a technique called value engineering to define objectives and develop means to achieve them. Value engineering is a systematic method that defines and analyzes the function of a product then compares the function to the product's cost. This process can be especially useful when investigating the value of construction materials. The value of a product is defined as the ratio of its function to cost. Therefore, the value of a product increases with improved function and decreases with higher cost. To approach this matter in a laboratory setting, performance was measured for multiple FRP material types and confinement levels. The objective was to investigate the value of the various confinement scenarios in order to determine how the function of FRP is related to its cost.[12]

METHODOLOGY

The following experimental program was executed in order to contribute to the empirical research regarding partially confined concrete. To determine the effect of several confinement related variables, 50x100mm (2x4") cylindrical concrete specimens were prepared utilizing a MP75 SICOMA Laboratory Mixer and cured in accordance with ASTM C192.[13] Table 1 presents the mix design, which remained constant for all specimens. Type 3 cement was obtained from Ingram Ready Mix in San Marcos, Texas, and aggregates were obtained from a local quarry. Glenium 7700 super plasticizer was also utilized to improve the flow characteristics and workability of the fresh concrete. The specimens were allowed to age 7 days before the confinement procedure commenced.

Table 1. Mix Design for Cylindrical Concrete Specimens.

Component	kg/m^3 (lb/yd^3)
Cement (Type 3)	443.15 (746.95)
Water (Tap)	177.61 (299.37)
Course Aggregate (Pea Gravel)	975.28 (1643.88)
Fine Aggregate (Limestone Sand)	176.91 (298.19)
Super Plasticizer (Glenium 7700)	1.32 (2.22)

EFFECT OF SPLICE OVERLAP

As per Table 2, the first experimental design was prepared to determine the effect of different FRP splice overlaps for 100% confined specimens, i.e., to assess how much circumferential overlap is required to prevent the FRP from premature failure at the overlap. As one of the main focuses of this study is sustainability, this process was followed to discover how less material can be used to still achieve desired results. The levels of overlap that were examined were 1/8, 1/4 and 1/2 of the cylindrical circumference, meaning that one full layer of confinement was applied plus the additional overlap.

Table 2. Experimental Design for Splice Overlap.

	FIBER					
	CFRP			GFRP		
OVERLAP	1/8	1/4	1/2	1/8	1/4	1/2

The effect of splice overlap was evaluated for CFRP (Sikawrap 230C) and GFRP (Sikawrap 100G) obtained from the Sika Corporation. Table 3 presents the physical properties of the structural strengthening fibers. First, the FRP was measured and cut to ensure that, when it was applied, it would be the same height as the specimens and cover the designated circumferential distance. Second, as per Sika recommendations, the epoxy adhesive (Sikadur 330) was prepared using a 4:1 mixing ratio by weight for components A and B, respectively. The adhesive was mixed for five minutes before applying it to a single side of two transparency sheets. Third, the FRP was sandwiched between the transparencies and rolled with a rolling pin in every direction until it was fully saturated with the adhesive. Finally, the FRP was used to wrap and, thereby, confine the specimens, ensuring that the woven structural fibers were aligned horizontally at a zero degree angle with respect to the circumference. Excess adhesive was removed from the FRP so that the remaining adhesive was smooth and evenly distributed. The adhesive cured for 5 days at an ambient room temperature of 23°C (73°F).

Table 3. Physical Properties of Fiber Fabrics.

	Sikawrap 230C	**Sikawrap 100G**
Description	Woven Carbon Fiber Fabric	Woven Glass Fiber Fabric
Orientation	Unidirectional	Unidirectional
Tensile Strength	3850 MPa (558 ksi)	2276 MPa (330 ksi)
Tensile Modulus	235000 MPa (34084 ksi)	72413 MPa (10503 ksi)
Elongation	1.6%	4%

EFFECT OF FIBER LOCATION

Before proceeding to the primary experimental design, a small group of 75% confined specimens was also prepared to determine the effect of fiber location. The performance of partial confinement was investigated for two scenarios. In one case, cylinders were wrapped with one 3” wide CFRP strip that was centered vertically, covering 75% of the circumferential surface area. In the other case, cylinders were wrapped with one 2” wide CRFP strip that was centered vertically and two 1/2" wide CFRP strips that were located on each end, also covering 75% of the circumferential surface area.

EFFECT OF FIBER, CONFINEMENT & LAYERS

As per Table 4, the primary experimental design was built upon the aforementioned procedures but encompassed many more variable manipulations. The program was designed to investigate the effect of fiber (CFRP vs. GFRP), confinement (25%, 50%, 75%, 100%) and layers (One, Two, Three). The methodology utilized previously was adopted for the preparation of the additional specimens required for completion of the study. The only key difference in the preparation process was the type and amount of fiber utilized for confinement. Figure 1 illustrates the various levels of confinement and types of fiber in this empirical study. Although the results of the previous experimental designs will be discussed in further detail, it was determined that a 1/4 overlap should be utilized for wrapping specimens and multiple strips should be used for partial confinement.

Table 4. Primary Experimental Design.

		FIBER							
		CFRP				GFRP			
	CONFINEMENT	25%	50%	75%	100%	25%	50%	75%	100%
LAYERS	One								
	Two								
	Three								

Figure 1. Cylindrical Concrete Specimens Confined with CFRP (left) and GFRP (right).

Following preparation and curing of the specimens, compression testing was performed with a Test Mark CM400 Concrete Compressive Machine in accordance with ASTM C39.[14] The maximum load was recorded for each specimen to determine compressive strength and, thereby, measure the performance of partially confined concrete.

VALUE ENGINEERING ANALYSIS

With the understanding that value is the ratio of function to cost, a systematic method was implemented to assess the value of FRP materials with respect to the performance measured during compressive testing. It is important to note that the epoxy adhesive costs approximately \$26/L (\$97/gal); however, since the concrete and the adhesive remained constant, their costs were not included in the value engineering analysis. The cost of the CFRP is \$16.35/m^2 (\$19.56/yd^2), and the cost of the GFRP is \$6.45/m^2 (\$7.72/yd^2). Also, the additional compressive strength obtained from confining specimens with FRP was established as the baseline for comparing performance. Thus, the following equation was utilized to determine the value of each confinement scenario in the primary experimental design:

$$\text{Value} = \frac{\text{Function}}{\text{Cost}} = \frac{\text{Compressive Strength (MPa)} - 23.96\text{ MPa}}{\text{Material (m}^2\text{)} \times \text{Cost (\$/m}^2\text{)} \times 1000}$$

Where, compressive strength is the compressive strength for a confined cylindrical concrete specimen, 23.96 MPa is the average compressive strength of an unconfined specimen and material is the amount of material utilized for confinement.

RESULTS

EFFECT OF SPLICE OVERLAP

The results of the study regarding the performance of single layer 100% confined specimens with circumferential splice overlaps of 1/8, 1/4 and 1/2 provides evidence indicating that a 1/4 overlap or more is adequate for preventing premature failure. As per Table 5, 50% of the specimens with a 1/8 overlap failed at the overlap; whereas, all other specimens failed in a portion of the continuous woven fiber opposite the overlap. However, as half of each overlap group was reinforced with CFRP and the other half with GFRP, the specimens that failed at the overlap were both, in fact, confined with GFRP. The premature failure of the GFRP with 1/8 overlap may be due to an inability of the epoxy adhesive to hold the smaller surface area. This finding also indicates that the CFRP may provide adequate confinement with a mere 1/8 circumferential overlap; however, to keep this characteristic constant, a 1/4 overlap was utilized for both types of fiber in the primary experimental design. Although a splice overlap of 1/2 the cylindrical circumference could also be used, employing less material was the main focus of this study.

Table 5. Effect of Splice Overlap on Premature Failure.

	FIBER					
	CFRP			GFRP		
OVERLAP	1/8	1/4	1/2	1/8	1/4	1/2
	Pass	Pass	Pass	Fail	Pass	Pass

EFFECT OF FIBER LOCATION

The specimens that were tested to determine the effect of fiber location only varied slightly with respect to their compressive strength. Cylinders that were wrapped with one 3” wide CFRP strip centered vertically, covering 75% of the circumferential surface area, had an average strength of 72.37 MPa (10.50 ksi) when subjected to an uniaxial compressive load. However, cylinders that were wrapped with one 2” wide CFRP strip centered vertically and two 1/2" wide CFRP strips located on each end, also covering 75% of the circumferential surface area, had a slightly higher average strength of 76.10 MPa (11.04 ksi). Therefore, it appears that the fiber location may have a slight effect on the mechanical behavior of partially confined concrete and, for this reason, the primary study utilized specimens with multiple fiber strips for partial confinement.

EFFECT OF FIBER, CONFINEMENT & LAYERS

The results of the testing conducted for the primary experimental design are presented in Table 6 and illustrated in Figure 2 to show the effect of fiber, confinement and layers. The average compressive strength of the unconfined control specimens was 23.96 MPa (3.48 ksi).

Table 6. Compressive Strength (MPa) of Confined Cylindrical Concrete Specimens.

		FIBER							
		CFRP				GFRP			
	CONFINEMENT	25%	50%	75%	100%	25%	50%	75%	100%
LAYERS	One	42.5	55.4	67.2	83.9	38.3	57.1	85.0	114.2
	Two	50.5	72.3	113.4	132.2	46.8	74.8	130.7	162.0
	Three	55.5	80.8	103.9	178.0	49.5	83.0	146.4	182.3

The experimental results were divided into several groups to evaluate the main effects and interaction effects of the manipulated variables. As per Table 7, an analysis of variance was utilized to determine the variation in the results of the experiment and to assess the contribution of each variable to the variation. An increase in the amount of confinement and number of layers corresponded with a statistically significant increase in compressive strength ($p < 0.01$). Also, GFRP outperformed CFRP at confinement levels of 50% and greater ($p < 0.01$).

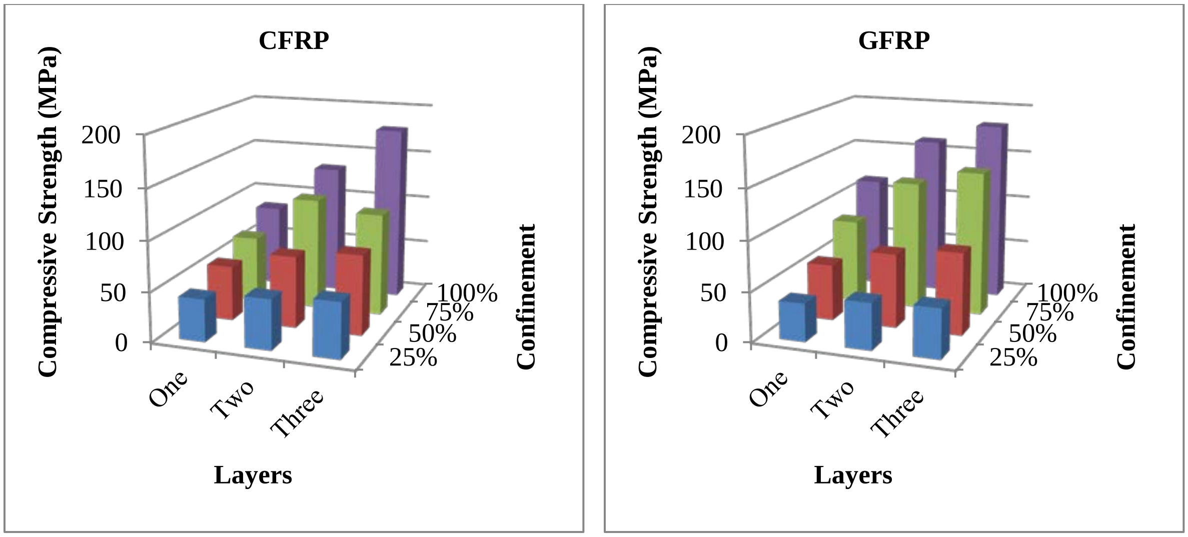
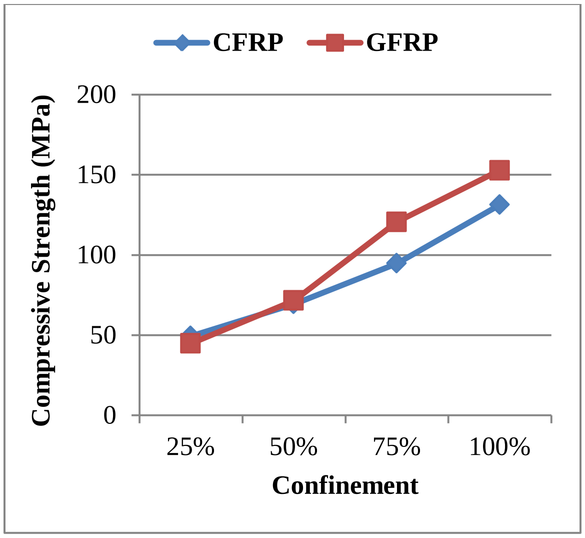


Figure 2. Effect of Fiber, Confinement and Layers on Compressive Strength.

Table 7. Analysis of Variance for Compressive Strength.

Source	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	p (significance)
F (Fiber)	1505.1	1	1505.1	11.47	< 0.01
C (Confinement)	62742.5	3	20914.2	159.43	< 0.01
L (Layers)	14928.6	2	7464.3	56.90	< 0.01
F × C	1961.2	3	653.7	4.98	< 0.01
F × L	1.1	2	0.6	0.00	0.996
C × L	6076.8	6	1012.8	7.72	< 0.01
F × C × L	861.8	6	143.6	1.09	0.394
Error	3148.2	24	131.2	-	-
Total	91225.3	47	-	-	-

Manipulated variables interact if the effect of one of the variables differs depending on the level of the other variable. The interaction effect of fiber and confinement was found to be statistically significant ($p < 0.01$). Figure 3 illustrates how compressive strength varies in relation to these interaction effects. Although CFRP outperformed GFRP at the 25% confinement level, the opposite was observed for 50% confinement and greater. At 75% and 100% confinement levels, the structural strengthening ability of GFRP is even more pronounced. The interaction effect of confinement and layers was also found to be statistically significant ($p < 0.01$). At 25% and 50% confinement levels, there is only slight distinction between the compressive strength measurements of different layers of confinement. However, at 75% confinement, there is a larger increase in compressive strength for both two and three layers. Finally, at 100% confinement, there is a substantial increase in compressive strength and clear differentiation between all layers.



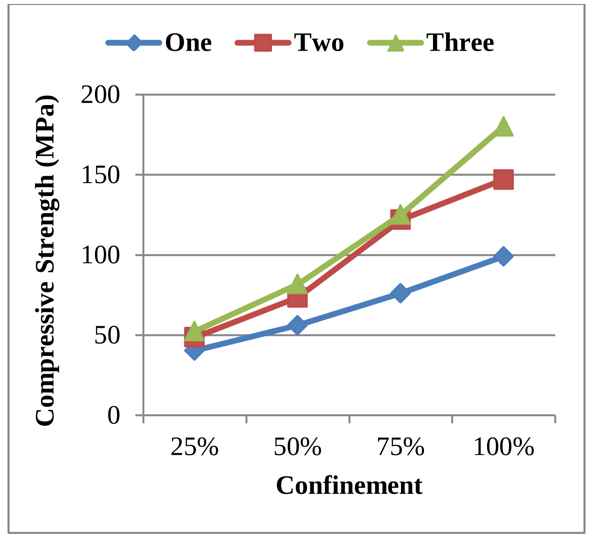


Figure 3. Interaction Effects of Fiber × Confinement (left) and Confinement × Layers (right) on Compressive Strength.

VALUE ENGINEERING ANALYSIS

The results of the value engineering analysis are presented in Table 8 and illustrated in Figure 4 to show the effect of fiber, confinement and layers. A higher value indicates that the FRP has high performance in relation to its cost; whereas, a lower value indicates that the FRP has low performance in relation to its cost. The value of the FRP increases with greater compressive strength and decreases with higher cost. Despite the differences exposed during the performance testing, CFRP and GFRP are still considered to be in the same class of structural strengthening materials. However, when also incorporating material usage and cost into this scenario, it is clear that there is a large divergence between the values of the materials.

Table 8. Value Engineering Analysis of Confined Cylindrical Concrete Specimens.

		FIBER							
		CFRP				GFRP			
	CONFINEMENT	25%	50%	75%	100%	25%	50%	75%	100%
LAYERS	One	237	200	184	205	463	535	657	729
	Two	188	171	211	192	410	456	638	619
	Three	155	139	131	189	317	367	507	492

Not only do the specimens confined with GFRP outperform their CFRP counterparts more often, the GFRP specimens provide a considerable cost advantage as well. It also appears that specimens confined with one layer of FRP have an economic advantage over specimens with multiple layers. The GFRP scenarios with the greatest value include (One/100%), (One/75%) and (Two/75%), while the CFRP scenario with the greatest value is (One/25%). Therefore, partial confinement of concrete with FRP can provide considerable structural strengthening while maintaining economic feasibility. It is important to emphasize the fact that these values or lack of values would be magnified when translated into an industrial setting.

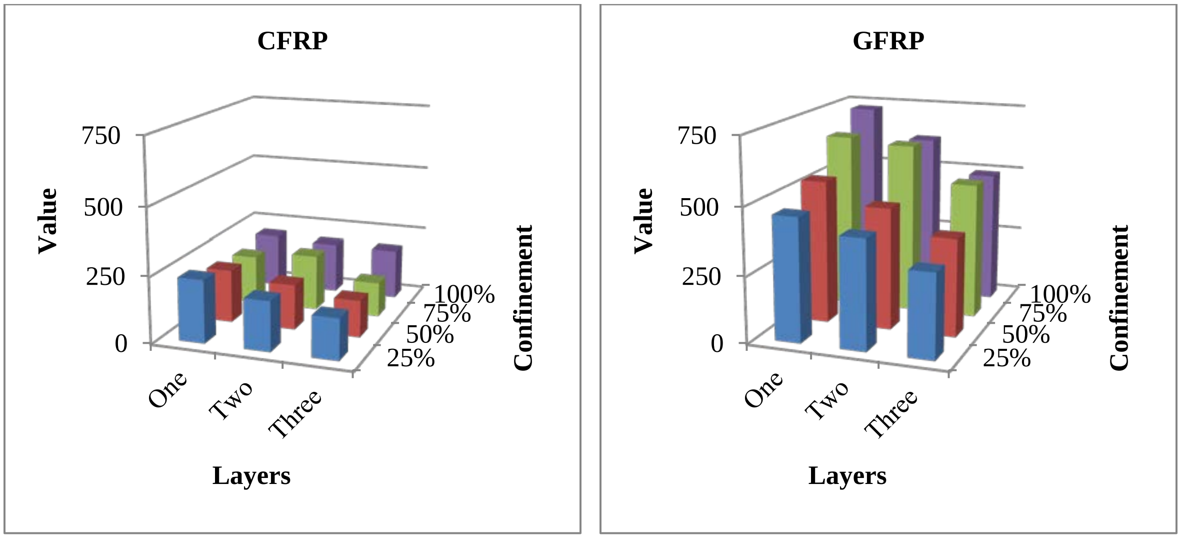


Figure 4. Effect of Fiber, Confinement and Layers on Value.

CONCLUSIONS

The following conclusions can be made regarding the results of the value engineering and performance analysis of partially confined concrete:

1. The results of the study regarding the performance of 100% confined specimens with circumferential splice overlaps of 1/8, 1/4 and 1/2 provide evidence indicating that a 1/4 overlap is adequate for preventing premature failure.
2. Fiber location has a slight effect on the mechanical behavior of partially confined concrete. This may be due to the tendency of specimens that are not confined on each end to fail at lower stress levels.
3. Specimens confined with GFRP outperformed CFRP specimens at confinement levels of 50% and greater; however, the opposite was observed for 25% confinement ($p < 0.01$).
4. The compressive strength of the specimens consistently increased with higher levels of confinement ($p < 0.01$). When compared to the unconfined control specimens, substantial increases in strength were even realized for lower confinement levels.
5. An increase in the number of layers of FRP also corresponded with increased compressive strength ($p < 0.01$).
6. Not only did the specimens confined with GFRP outperform their CFRP counterparts more often, the GFRP provides a considerable cost advantage. Specimens confined with one layer of FRP also have an economic advantage over specimens with multiple layers.

In many scenarios, partial confinement of concrete with FRP can provide considerable structural strengthening while maintaining economic feasibility.

Based on these conclusions, there is a need for further research in the following areas:

1. Additional research is required to determine the cause of CFRP's performance over GFRP at lower confinement levels.
2. Additional materials, design patterns and mechanical properties should be investigated to determine if partial confinement is adequate for structural strengthening applications.
3. An analytical model should be proposed for predicting the ultimate compressive strength of partially confined concrete.

REFERENCES

1. Hart, S. D. (2008). *Performance of confined concrete columns under simulated life cycles.* Manhattan, Kansas: Kansas State University.
2. Sheikh, S. A., & Uzumeri, S. M. (1982). Analytical model for concrete confinement in tied columns. *ASCE Journal of the Structural Division*, *108* (12), 2703-2722.
3. Mander, J. B., Priestley, M. J., & Park, R. (1988). Theoretical stress-strain model for confined concrete. *ASCE Journal of Structural Engineering*, *114* (8), 1804-1826.
4. Cusson, D., & Paultre, P. (1995). Stress-strain model for confined high-strength concrete. *ASCE Journal of Structural Engineering*, *121* (3), 468-477.
5. Samaan, M., Mirmiran, A., & Shahawy, M. (1998). Model of concrete confined by fiber composites. *ASCE Journal of Structural Engineering*, *124* (9), 1025-1031.
6. Teng, J. G., & Lam, L. (2004). Behavior and modeling of fiber reinforced polymer-confined concrete. *ASCE Journal of Structural Engineering*, *130* (11), 1713-1723.
7. Harajli, M. H., Hantouche, E., & Soudki, K. (2006). Stress-strain model for fiber-reinforced polymer jacketed concrete columns. *ACI Structural Journal*, *103* (5), 672-682.
8. Teng, J. G., Huang, Y. L., Lam, L., & Ye, L. P. (2007). Theoretical model for fiber-reinforced polymer-confined concrete. *ASCE Journal of Composites for Construction*, *11* (2), 201-210.
9. US Composites. (2011, August 22). *Product Overview*. Retrieved from US Composites: http://www.uscomposites.com/products.html
10. Leung, H. Y., & Burgoyne, C. J. (2001). Compressive behaviour of concrete confined by aramid fibre spirals. *The International Conference on Structural Engineering Mechanics and Computation*, (pp. 1357-1346). Cape Town, South Africa.
11. Wei, H., Wu, Z., Guo, X., & Yi, F. (2009). Experimental study on partially deteriorated strength concrete columns confined with CFRP. *Engineering Structures*, *31*, 2495-2505.
12. Park, R. J. (1999). *Value engineering: A plan for invention.* Boca Raton, Florida: CRC Press.
13. ASTM Standard C192. (2007). *Standard practice for making and curing concrete test specimens in the laboratory*. West Conshohocken, Pennsylvania: ASTM International.
14. ASTM Standard C39. (2012). *Standard test method for compressive strength of cylindrical concrete specimens.* West Conshohocken, Pennsylvania: ASTM International.