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Peel-and-Stick FRP System for Concrete Confinement

by

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Abstract

Unidirectional glass fibers were used to make an innovative peel-and-stick FRP system for concrete confinement. The proposed FRP laminate is a three-layer system where the fibers are sandwiched between two layers of thermoplastic polymer that does not fully penetrate through the fiber. The system is not installed by manual lay-up, which makes the application easy and rapid. A pilot research was conducted on thirty-four concrete cylinders, 150 mm x 300 mm (6 x 12 in) in size, wrapped with the peel-and-stick FRP system to be tested under pure axial compression. The objective of the study was to test the performance in strengthening and installation of the confinement with the new system. Two wrapping configurations with the peel-and-stick FRP were tested. In the first configuration, the peel-and-stick FRP was applied directly onto the concrete surface; in the second, an adhesive primer was used onto the concrete surface prior to the application of the peel-and-stick FRP system. The purpose of the primer was to evaluate the possibility of protecting the FRP laminate from the penetration of concrete fragments after cracking. The investigated variables were: fiber volume, number of plies and material used as the primer. Observations made during and after testing indicated that the primer prevents damage resulting from concrete fragments displacing radially outward. The results also showed ease of installation and an increase in toughness, but no increase in compression capacity due to the slippage of the fibers within the resin layers which translates in a ductile failure of the system.

Introduction

The need to upgrade and rehabilitate existing reinforced concrete (RC) columns has been a key concern for civil engineers. Corrosion resistance, rapid processing, and low cost are the primary advantages that facilitated the migration from steel jackets to fiber reinforced polymers (FRP) in the early 1990's [1-4]. After years of research, this technology has been applied in many projects all over the world, and guidelines for applying this technique in practice are currently available [5-6]. The most common FRP technology in use for in-situ confinement of RC columns is manual lay-up where plies with fibers in the hoop direction are impregnated with a polymeric resin and wrapped around the column. Because these systems proved to be strong, non-corrosive, of-rapid-installation, and durable, FRP using carbon or E-glass (CFRP and GFRP) has gained widespread acceptance for civil applications [7-9].

FRP offers engineers a viable solution for confinement; nonetheless, a considerable margin exists to improve the FRP confinement technique. Currently, the limitations include susceptibility to damage of the fibers during installation, poor quality control, and the need for skilled labor to prepare and install the FRP. The factors contributing to these limitations are resin preparation, impregnation, and curing. Since the resin consists of a delicate balance between base and catalyst (hardener), any aberration in proportion can severely reduce performance and durability of the cured composite. In terms of impregnation, a poor wetting can manifest as voids in the cured composite. Lastly, resin curing in the field is difficult to control since temperature and humidity variations are inevitable. These variations can affect curing rate and the quality of the cured composite [10-11].

In cases where conditions are not conducive to manual lay-up for confinement, a viable option could be the peel-and-stick installation. By removing field impregnation, a peel-and-stick GFRP system can be used to wrap and confine columns with greater ease. These unique systems utilize an adhesive-backed film of polymer reinforced by unidirectional glass FRP.

The novel system is presented here in two configurations, named one-part PSFRP system and two-part PSFRP system respectively. In the first system, the structural material, glass fiber reinforced thermoplastic resin, is applied directly onto the concrete and no primer is used. In the second configuration, a peel-and-stick primer is applied to the concrete surface, and the structural part of the two-part system is installed on top of it. The primer is intended to prevent penetration/laceration of concrete fragments when concrete expands radially outwards. The structural part of the system can be defined as new generation composite material where the thermoset resin is replaced with a thermoplastic polymer, fibers are not completely impregnated anymore, and the system is not as rigid as a pre-cured commercial FRP laminate and allows to be easily applied around the concrete.

This paper discusses the application of a peel-and-stick FRP (PSFRP) concrete confinement system. Plain concrete cylinders were wrapped with different configurations of this novel composite system and tested in uniaxial compression to evaluate the effects on compressive strength and toughness.

Experimental Program

Test matrix

Thirty-four plain concrete cylinders were tested in this experimental program. Twenty-two of those were confined with the novel system, in particular: sixteen were continuously wrapped with the one-part PSFRP, and six with the two-part system. The remaining cylinders were collected from each concrete batch and used as a benchmark for each batch. All cylinders were allowed to cure for at least 28 days before confinement and testing. The nominal dimensions of the cylinders were 153 x 305 mm (6 x 12 in). In the case of one-part PSFRP system, for each material tested, four different ply configurations were used: one, two, four, and eight plies. In the case of two-part PSFRP system, two plies of peel-and-stick primer were applied directly on the concrete and then covered with four plies of the structural composite. Different primers and structural materials were used. The PSFRP was applied continuously, and an overlap of 102 mm (4 in) was used at the end of primer or structural part.

Table 1 summaries the configurations tested. A two-part code was used to identify the specimens. The first part of the code identifies the parent system. Thus, the first two characters identify the type of confinement system used, ''PSI'' for one-part Peel-and-Stick and ''PSII'' for two-parts Peel-and-Stick. The second part of the code identifies the type and amount of reinforcement. In particular, the character is the type of reinforcement used, described in more details later on in this paper. The digit represents the number of plies used. If two characters are given after the identification of the system, this means that the system applied is two-part PSFRP. In this case, the first character and digit represent the primer (material and number of plies), and the second character represents the structural material. Thus PSII/E2-B4 refers to a cylinder concrete confined with a two-part PSFRP, with two plies of primer E, and four plies of structural material type B.

Material properties

The specimens were built from two different batches of concrete, and each batch was used for a specific system configuration: I. one-part PSFRP, II. two-part PSFRP. Once the specimens were cast, they were allowed to cure for 28 days in a curing room with 100% relative humidity. Table 2 summarizes the average compressive strength for each batch of concrete.

The confinement of the concrete cylinders with the novel system was made continuously. The composite was laid flat on a table top, and the cylinder was set horizontally on it. A weight was put at the end of the composite strip to provide a constant and a uniform load on it during the wrapping. No concrete surface preparation was required before applying the system. It is recognized that this installation technique of rolling a specimen on the ply is only applicable to laboratory testing. It was selected to provide a consistency and eliminate installation variability from the parameters under investigation.

Table 3 summaries the materials used to make the PSFRP system. The properties of the embedded fibers are summarized in Table 4. The laminate strength per unit width is 615 kN/m (126 kip/yd) for the one with 450 g/m2 (1.5 oz/ft2) of fibers and 1230 kN/m (253 kip/yd) for the one with 900 g/m2 (3.0 oz/ft2).

Test setup

The compression tests were conducted under uniaxial load in accordance with ASTM C 39/C 39 M-05 [12]. The compression tests were performed using an 889 kN (200 kip) capacity screw-driven Baldwin Testing Machine under cross-head displacement control at a constant rate of 0.5 mm/min (0.02 in/min) until failure. Load and displacement measurements were recorded until failure.

Two circular steel cups with rubber mat inside were used as the capping of the specimen (ASTM C-617) [14]. The steel cups on top and bottom of the concrete cylinder ensure a uniform compressive load distribution from the test machine onto the specimen. The rubber mats inside the cups attenuate the influence of any local defects on the surface of the cylinder, which may cause adverse stress concentrations during loading.

Test Results and Discussions

The benchmark compression tests showed that the concrete had an unconfined concrete compressive strength f'_{co} of 26.67 MPa (3,868 psi) for the batch I and 36.75 MPa (5,330 psi) for the batch II. All PSFRP-confined cylinders did not show a complete failure of the jacket system, and each test was stopped after a plateau was reached.

Normalized stress-strain curves of PSFRP confined concrete under uniaxial compression load are shown from Figure 1 to Figure 5. The normalized stress was calculated dividing the stress of each specimen by the pick value of the benchmark. Analogously the normalized strain is the ratio of the strain of each specimen and the strain of the benchmark at the pick value. The results are compared based on the number of structural plies applied (1, 2, 4 and 8). In each figure, normalized stress-strain curves of the unconfined concrete specimen from the same series are shown for comparison.

Mode of failure

Concrete fracture is a brittle failure characterized by very little plastic deformation. When a concrete structure is confined by FRP, the failure behavior changes and the ultimate strength may increase drastically [15]. Test ran with the PSFRP system showed that the failure mode of the novel material is accompanied by significant plastic deformation and can be defined as ductile failure (Figure 6).

The difference in failure modes between the cylinders confined with traditional FRP and the novel system may be attributed to the slippage between PSFRP's layers due to the adhesive used. The resin used for commercial FRP is a thermo-set polymer and after curing, the composite becomes a rigid entity. However, the resin used in the PSFRP allows the interface between plies to act as a shear plane for layers to slip. It is possible to hypothesize that PSFRP can contain the concrete for very large displacements avoiding any brittle fracture.

Observations made during and after testing of the one-part PSFRP indicate that the fibers fractured from penetration / laceration of concrete fragments that expand radially outward and not due to tensile stress. Once the cause of this failure was indentified, the two-part system was introduced. In this configuration, the primer on the concrete surface protects the fibers of the structural part of the system. The tests proved that the protective material used prevents laceration of the fibers due to concrete fragmentation.

Post-mortem inspection of the cylinders revealed that the bond of the adhesive used appears to be stronger at the interface between concrete and composite than between adjacent layers of PSFRP. The inspection was based on manually, unwrapping the composite applied to the concrete cylinder.

Compressive Strength

Figure 1 through Figure 5 show the normalize stress vs. strain curves of the tested cylinders with the same amount of structural plies. The behavior of both configurations of PSFRP is almost the same of the control specimen until the peak load, while the post-peak behavior is quite different. The control unconfined cylinders exhibit a brittle behavior, characterized by a sudden and complete decrease in capacity after the peak, while most of the PSFRP confined specimens exhibit some ductile behavior and plastic deformation. All cylinders confined with the two-part PSFRP system, except for PS/I2/A4, show a second peak, but the load capacity remains less than the initial peak.

It is likely that the ductile behavior is related to slipping at the interface between adjacent plies of PSFRP as well as the ply in contact with concrete.

Energy dissipation (Toughness)

Using a modified ACI 544 Toughness Index [16], a dimensionless study of the PSFRP energy dissipation performance was conducted. The ACI 544 Toughness Index is defined as the ratio of the area under the stress-strain curve up to an arbitrary strain to the area under the same curve up to first-crack strain. The selected strain of reference is based on the specific application. However since in this study the specimens are tested under pure compression the evaluation of the cracking-point is impractical and the index is defined using the displacement corresponding to Last Proportional Strain (δ_{LP}) instead to the first-crack strain (Figure 7). The normalized strain correlated to 3.0 was selected strain limit. The values of Toughness Index, I_{LP}, are included in the normalized stress-strain graph of Figure 1 to Figure 5.

An improvement in the toughness due to the application of PSFRP as quantified by the Toughness Index may be noticed. Most of the specimens showed a doubling of the energy adsorbed as indicated by a higher value of the Index. The interlaminar slippage has an important function in increasing the toughness.

Conclusion

The following conclusion can be drawn from this experimental program:

1. The test results identified that the failure of all wrapped cylinders was accompanied by significant plastic deformation, resulting in a ductile behavior. This behavior may be attributed to the slippage between the PSFRP layers due to the thermoplastic adhesive used.
2. Compression strengthening with PSFRP system has been proven to not remarkably increase the compression capacity of concrete cylinders at this level of fiber volume.
3. Observations made during and after testing of the one-part PSFRP system indicate that, the fibers fracture, not due to tensile stress, but due to penetration / laceration of concrete fragments that expands radially outwards. However, the use of a protective primer prevents this behavior, but does not help the fibers to become engaged after the concrete brakes.
4. The Toughness Index calculated from the normalized stress–strain curves highlights an increase in toughness. The index of PSI/B1 and PSI/B4 is 5 when for the control specimen is only 2. This phenomenon is related to the relative slippage of the adhesive layers.

The findings reported in this paper apply only to the materials and configurations tested and more work needs to be continued before general conclusions on PSFRP can be provided.

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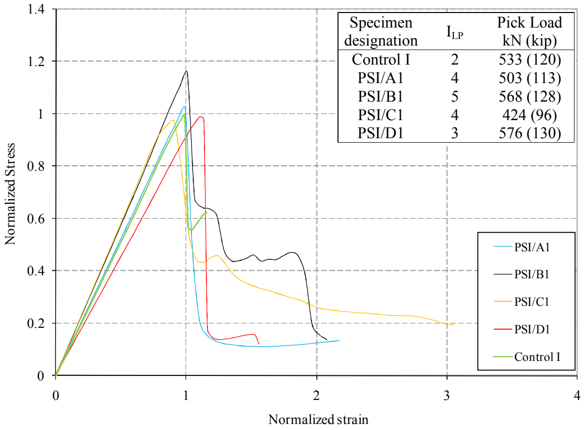
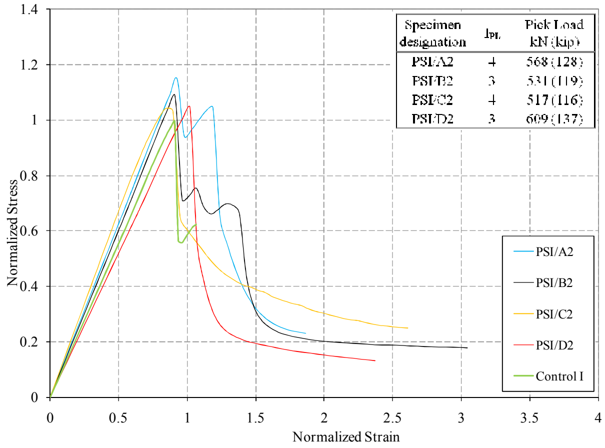
Figures:



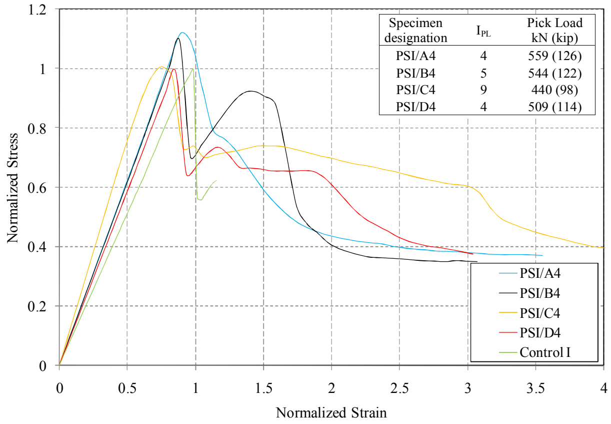
Specimen designation	I_{LP}	Pick Load kN (kip)
Control I	2	533 (120)
PSI/A1	4	503 (113)
PSI/B1	5	568 (128)
PSI/C1	4	424 (96)
PSI/D1	3	576 (130)

Figure 1 – Normalized stress-strain diagram for concrete cylinders confined with 1 ply of PSFRP or FRP



Specimen designation	I_{PL}	Pick Load kN (kip)
PSI/A2	4	568 (128)
PSI/B2	3	531 (119)
PSI/C2	4	517 (116)
PSI/D2	3	609 (137)

Figure 2 – Normalized stress-strain diagram for concrete cylinders confined with 2 plies of PSFRP or FRP



Specimen designation	I_{PL}	Pick Load kN (kip)
PSI/A4	4	559 (126)
PSI/B4	5	544 (122)
PSI/C4	9	440 (98)
PSI/D4	4	509 (114)

Figure 3 – Normalized stress-strain diagram for concrete cylinders confined with 4 plies of PSFRP or FRP

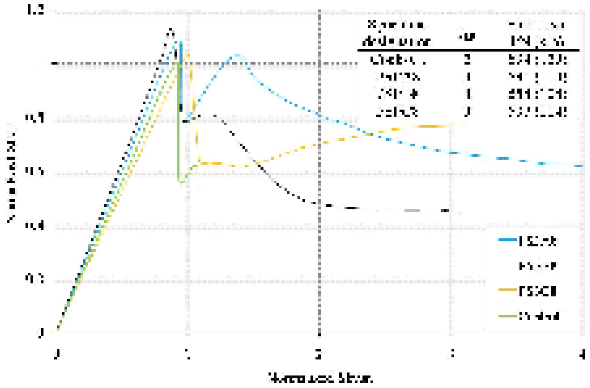
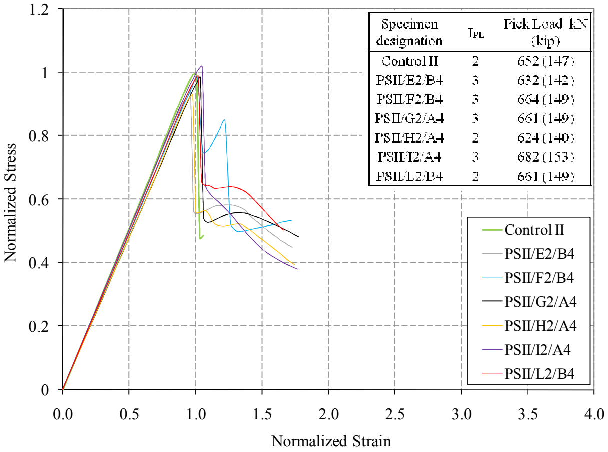


Figure 4 – Normalized stress-strain diagram for concrete cylinders confined with 8 plies of PSFRP or FRP



Specimen designation	I_{PL}	Pick Load kN (kip)
Control II	2	652 (147)
PSII/E2/B4	3	632 (142)
PSII/F2/B4	3	664 (149)
PSII/G2/A4	3	661 (149)
PSII/H2/A4	2	624 (140)
PSII/I2/A4	3	682 (153)
PSII/L2/B4	2	661 (149)

Figure 5 - Normalized stress-strain diagram for concrete cylinders confined with two-part PSFRP

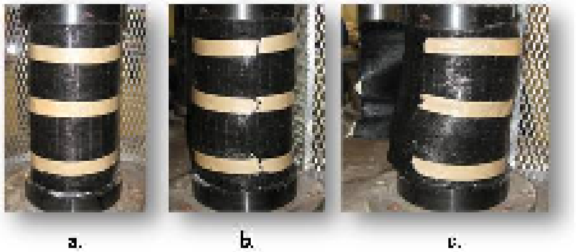


Figure 6 – Cylinders wrapped by PSII/F2-B4 tested under uni-axial load – (a) zero displacement; (b) 10 mm (0.4 in) displacement; (c) 15 mm (0.6 in) displacement

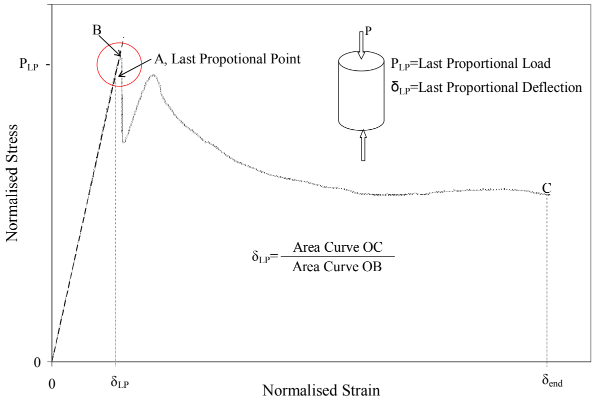


Figure 7 – Toughness Index definition

Table 1: Test Matrix

Specimen Designation	Number of plies		Embedment Structural Material	Batch Number
	Primer	Structural		
PSI/A1	-	1	Polyethylene	1
PSI/A2	-	2		
PSI/A4	-	4		
PSI/A8	-	8		
PSI/B1	-	1	Polyethylene	1
PSI/B2	-	2		
PSI/B4	-	4		
PSI/B8	-	8		
PSI/C1	-	1	Polyethylene	1
PSI/C2	-	2		
PSI/C4	-	4		
PSI/C8	-	8		
PSI/D1	-	1	Polyurethane	1
PSI/D2	-	2		
PSI/D4	-	4		
PSI/D8	-	8		
PSII/E2-B4	2	4	Polyethylene	2
PSII/F2-B4				
PSII/L2-B4			Polyurethane	
PSII/G2-B4				
PSII/H2-A4	2	4	Polyethylene	2
PSII/I2-A4				

Table 2: Compression Strength of Concrete betches

Batch	Average compressive Strength, MPa (psi)	Standard Deviation MPa (psi)	C.O.V.
I. (One-part PSFRP)	26.67 (3868)	1.94 (0.28)	7%
II. (Two-part PSFRP)	36.75 (5330)	1.08 (0.16)	2.9%

Table 3: Peel-and-Stick Material Systems

Material ID	Reinforcement	Resin	Fibers Weight, g/m^2 (oz/ft^2)	Thickness mm (in)	Configuration
A (structural)	E-Glass fibers	Polyethylene film	450 (1.5)	0.89 (0.035)	Adhesive/E-Elass/Polyethylene film
B (structural)	E-Glass fibers	Polyethylene film	450 (1.5)	0.85 (0.033)	Adhesive/Polyethylene film/E-glass/Polyethylene film
C (structural)	E-Glass fibers	Polyethylene film	900 (3.0)	1.38 (0.054)	Adhesive/E-Glass/Polyethylene film
D (structural)	E-Glass fibers	Polyurethane film	900 (3.0)	1.42 (0.056)	Adhesive/E-Glass in Polyurethane matrix
E (primer)	1 mm stainless steel film	Polyethylene film	-	1.75 (0.069)	Adhesive/1mm steel film/Polyethylene film
F (primer)	2 mm stainless steel film	Polyethylene film	-	2.71 (0.107)	Adhesive/1mm steel film/Polyethylene film
G (primer)	E-Glass fibers	Polyurethane film	900 (3.0)	1.01 (0.04)	Adhesive/PU film/Glass fabric/PU film/Adhesive
H (primer)	None	Polyurethane film Lenxinton	-	0.84 (0.033)	Adhesive/PU film Lexington/Adhesive
I (primer)	None	Polyurethane film Bristol	-	0.87 (0.034)	Adhesive/PU film Bristol/Adhesive
L (primer)	Kevlar fibers	Polyurethane film	350 (115)	1.02 (0.04)	Adhesive/Kevlar in PU matrix/Adhesive

Table 4: Fibers Properties

Fiber	Tensile Strength MPa (ksi)	Modulus of Elasticity, MPa (ksi)	Elongation %	Diameter µm
E-Glass	3,447 (500)	72,395 (1.05x10^4)	4.8	16.6