



# Article Developing a Sprayed-Glass Fiber-Reinforced Polymer Retrofitting System for Decommissioned Wooden Utility Poles

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Abstract: Wooden utility poles are vulnerable to degradation and decay, which requires maintenance or replacement. The strengthening and retrofitting techniques for wooden poles are either prone to corrosion or encountering installation difficulties. However, the use of sprayed fiber-reinforced polymer (FRP) composites seems to be a viable solution as it has proven its efficiency and applicability for reinforced concrete members and connections. This study includes a comprehensive experimental program where the mechanical properties of the sprayed-glass FRP (GFRP) composite was evaluated in terms of tensile, compressive and shear strength, in addition to its bond strength to wood and confinement efficiency. Afterwards, the results of the material testing phase were implemented on full-scale old utility poles to evaluate their structural performance with varying composite thicknesses and sprayed zone lengths. The behavior of the retrofitted poles reflected remarkable effectiveness for the sprayed-GFRP composite and highlighted the need for a design model for the optimum length for the sprayed zone. Two simplified analytical models were introduced which predicted the failure loads and locations for the tested poles and estimated the required length for the retrofitted zone, which all agreed well with the experimental results of the tested poles.

**Keywords:** wooden utility poles; fiber-reinforced polymers (FRP); sprayed FRP; rehabilitation; pull-of tests; confinement; load-carrying capacity; analytical models

# 1. Introduction

As the support of the overhead distribution and transmission lines, utility poles play an imperative role in electric supply. Despite the presence of precast concrete poles and steel towers, wooden poles stand out the most due to their sustainability, accessibility, excellent non-conductivity, and construction versatility [1], with an estimated 150 million wooden utility poles in North America [2]. Wooden utility poles are usually selected to carry wind loads on the pole and the loads transmitted by the cables, in addition to the self-weight of the cables, crossarms and any other attachments. Wooden poles are typically recognized by their perimeter and horizontal load-carrying capacity, which is mostly species-dependent [3].

Replacement of an entire pole is required when it is severely damaged, upgrades in the design guidelines are introduced, or adjustments are made to the electricity transmission lines. On average, wooden poles often need to be replaced after 40 years of service [4]. However, many factors can limit the lifespan of wooden utility poles, such as the inherent characteristics of the wood, treatment quality, exposure conditions, maintenance frequency and quality, environmental degradation, decay, damage caused by humans and/or wood-peckers, and traffic accidents [5,6]. Environmental deterioration and decay stand out as inevitable problems for wooden poles, which can be only slowed down by the use of preservatives [7]. It should be noted, however, that the replacement process is excessively expensive. For instance, over 5000 wooden utility poles are replaced annually in Manitoba,



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**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). Canada, with an average replacement cost of \$3500 per pole [8]. This will result in an approximately \$350 million investment deficit by the year 2032. For example, in the United States, approximately 1.5 million wooden poles are replaced every year. This urges for more cost-effective alternatives to lower the replacement rate of wooden poles.

Rehabilitation of wooden poles can help restoring their load-carrying capacity and, thereby, extending their service lives. Furthermore, the associated costs with pole replacement such as new poles, transportation, and labor, in addition to the complexity of the disposal process for preservative-treated decommissioned poles are avoided by retrofitting the old or damaged poles instead of replacing them. Many retrofitting techniques have been introduced to restore, or even improve, the load-carrying capacity of wooden poles [9–13], which are mostly using steel trusses or units attached to the wooden poles [14]. Although such steel trusses or units can be galvanized to reduce the possibility of corrosion, this may only delay or slow down the corrosion process, which reduces the efficiency of the retrofitting system.

To overcome the detrimental effects of corrosion, the non-corroding fiber-reinforced polymers (FRPs) were proposed to rehabilitate deficient wooden poles. The use of externally bonded (EB) FRP laminates to retrofit wooden utility poles started in the 1970s [15], and, since then, it became more popular due to its prominent performance. Several studies investigated the advantages of using prestressed or non-prestressed FRP laminates to strengthen or repair timber members and the associated durability challenges [16–21]. Previous research found that retrofitting using EB-FRP wraps, shells or splines can successfully restore the load-carrying capacity of the old or damaged wooden poles and/or piles [22–24]. Nevertheless, the complexity associated with installation of such composites and the required skilled labor might be amongst the reasons for their limited application.

More recently, sprayed-FRP composites have been used in structural retrofitting and strengthening of reinforced concrete (RC) structures in the inaccessible regions for EB-FRP systems (e.g., beam-column joints). In this method, a special spray gun is used to chop and spray fibers along with resin and catalyst on the retrofitted member at a high speed. resulting in a layer of randomly oriented fibers within the polymer matrix. The resin, which is typically thermosetting, is responsible for the workability and performance of the sprayed composite, while the fibers, which are typically carbon or glass, influence the strength of the composite. While sprayed FRP composites may exhibit slightly lower strength and stiffness than unidirectional FRP laminates, they exhibit larger ultimate strain and somewhat some ductility. The main engineering application of sprayed FRP composites is retrofitting, especially irregular-shaped elements and connections [25–29]. Previous research demonstrated the ease of application and lower susceptibility to debonding of sprayed-FRP members [25,26]. In addition, enhanced ultimate load capacity and energy absorption were obtained for bridge girders sprayed with glass FRP (GFRP) composites compared to those retrofitted using EB-FRP [27]. Furthermore, the use of sprayed-FRP to retrofit RC and masonry structures increased the strength, stiffness, and energy absorption capacities under different loading configurations including seismic [28,29]. Such promising results of sprayed-FRP technique for RC and masonry structures make it worthy to investigate for wooden utility poles.

This study starts with a series of material tests to explore the mechanical properties of the sprayed-GFRP composite including tensile, compressive and shear strength in addition to their confinement efficiency and bond strength to the wood material. The results of the material testing phase are then used to provide predictions for the load-carrying capacity of retrofitted decommissioned poles, which will then be verified through a series of experimental laboratory testing on full-scale pole specimens in accordance with ASTM D1036–99 [30].

#### 2. Experimental Program—Phase I

#### 2.1. Materials

Glass fibers and unsaturated polyester resin, with percentages of 65 and 35%, respectively, comprised the GFRP composite utilized in this study. The mixing proportions of the sprayed composite were controlled through the settings of the spray gun, shown in Figure 1a, which has a fiber chopper that chopped the glass fibers to an approximate length of 15 mm. A mechanical arm is used to direct the spray gun, to which a pump is used to convey the resin from the resin tank shown in Figure 1b.



Figure 1. The spraying system: (a) spray gun, and (b) spray machine.

Two bonding adhesives, as recommended by Manitoba Hydro, were evaluated in this study: the Phenol Resorcinol Formaldehyde resin (PRF) with a resin-to-catalyst ratio of 100:20 [31], and the Novolak Hydroxy Methylated Resorcinol (n-HMR), with a 5-% HMR solid content [32]. In addition, small 200 mm long samples of Class-3 Red Pine (RP) wooden poles, classified as per CSA O15-15 [3], were prepared for the pull-off tests by cutting two parallel flat surfaces. For the confinement tests, two concrete mixtures were used: a normal-strength concrete (NSC) mix and a high-strength concrete (HSC) one with a target compressive strength of 35 and 70 MPa, respectively.

#### 2.2. Specimens

Six sets of coupon specimens, with at least five coupons each, were prepared for the tensile [33], compressive [34] and shear strength [35] tests. Figure 2 shows the dimensions of the coupon specimen. The GFRP composite was sprayed on a relatively large surface inside a pre-set formwork to ensure the required thickness of the coupons is achieved. Then, the composite was left to cure. After curing, the coupons were cut out of the obtained composite sheet to the required sizes as shown in Figure 3.

Three coupon sets were tested to assess the tensile properties of sprayed-GFRP composites, with varied coupon thicknesses of 2.5, 6.0, and 10.0 mm. In addition, all compression coupons had a thickness of 2.5 mm due to a limitation with the test setup. For the shear coupons, 2.5- and 6 mm thicknesses were evaluated.

For the pull-off test specimens, the composite was sprayed on several wood samples in their original air-dried condition. On the other hand, the rest of the samples were subjected to a conditioning procedure one day before spraying to simulate the exposure of the poles to humidity before spraying (e.g., rain). This included immersing the wood samples in a water tank for seven consecutive hours, followed by air drying overnight for about 17 h before spraying the composite. Twelve wood samples had the Phenol Resorcinol Formaldehyde (PRF) resin [31] applied before spraying the GFRP composite. Alternatively, the Novolak Hydroxy Methylated Resorcinol (n-HMR) adhesive [32] was applied on another six specimens. The two remaining specimens, a dry one and a wet one, were sprayed with the GFRP composite directly without any adhesive to assess the direct bond performance between the sprayed GFRP and wood.



**Figure 2.** Details of the coupon specimens: (**a**) tension coupons, (**b**) compression coupons, and (**c**) shear coupons. (reproduced from ASTM D3039-17, ASTM D3410-16, and ASTM D5379-19 [33–35]– all dimension in mm).



Figure 3. Coupon specimens: (a) tension coupons, (b) compression coupons, and (c) shear coupons.

The GFRP coating was sprayed on all the sides of the wood samples. Prior to that, a thin layer of resin was sprayed to enhance the bonding performance between the sprayed-composite and wood. Throughout the process, small hand rollers were used to maintain a uniform thickness for the sprayed composite and force the entrapped air out. In addition, rolling helped fill the small holes and cracks on the outer surface of the timber with the composite. Spraying and rolling were successively repeated until the required thickness was reached, which was checked against marked pins. Figure 4 shows the spraying process for the wood samples.

As listed in Table 1, each set of specimens was designated by a four-character alphanumeric code. The first letter represents the adhesive type; P, H, or O for PRF, n-HMR or no adhesive (original), respectively. The second character represents the sample conditioning; W or D for wet or dry, respectively. The third digit represents the thickness of the sprayed-GFRP composite (i.e., 6, 8 and 10 mm), whereas the last digit denoted the curing time of the adhesive prior to spraying the composite (i.e., 0, 10, 30 and 50 min). For the specimens sprayed without prior priming, the last character was X.



**Figure 4.** Spraying process for pull-off samples: (**a**) spraying the composites, (**b**) rolling the sprayed composites, and (**c**) sprayed composites curing.

Table 1. Pull-off test matrix and test results.

Specimen Set ID	Adhesive Type	Pole Condition	Sprayed- GFRP Thickness (mm)	Adhesive Curing Time (min)	Bond Strength (MPa)
P-D-6-10 P-D-6-30 P-D-6-50		Dry	6	10 30 50	$\begin{array}{c} 0.74 \pm 0.3 \\ 0.96 \pm 0.6 \\ 1.12 \pm 0.6 \end{array}$
P-W-6-10 P-W-6-30 P-W-6-50	PRF	Wet	Ŭ	10 30 50	$\begin{array}{c} 1.24 \pm 0.3 \\ 1.70 \pm 1.0 \\ 0.99 \pm 0.4 \end{array}$
P-D-8-10 P-D-8-30 P-D-8-50		Dry	8	10 30 50	$\begin{array}{c} 0.81 \pm 0.3 \\ 1.57 \pm 0.5 \\ 1.29 \pm 0.2 \end{array}$
P-D-10-30			10	30	$0.94\pm0.3$
H-D-6-0 H-W-6-0		Dry Wet	6	0 0	$\begin{array}{c} 1.25\pm0.2\\ 1.28\pm0.2\end{array}$
H-D-8-0 H-W-8-0	n-HMR	Dry Wet	8	0 0	$0.72 \pm 0.2 \\ 0.95 \pm 0.2$
H-D-10-0 H-W-10-0		Dry Wet	10	0 0	$\begin{array}{c} 0.9\pm0.2\\ 1.23\pm0.1 \end{array}$
O-D-6-X O-W-6-X	N/A	Dry Wet	6	N/A	$\begin{array}{c} 1.17 \pm 0.4 \\ 1.23 \pm 0.2 \end{array}$

A series of axial compressive tests were planned to evaluate the confinement efficiency of the sprayed-GFRP composites for the wooden poles. However, to avoid the complexity and potential anomalies associated with testing retrofitted timber specimens, ten sets of  $150 \times 300$  mm concrete cylinders were used: five with NSC and five with HSC. A set of each concrete type (i.e., NSC and HSC) was tested without any composite as a benchmark. Based on the results of the pull-off tests, as discussed later, the GFRP composite was sprayed without prior priming with any adhesive for the concrete cylinders.

Table 2 summarizes the test matrix, where each specimen set was defined by a letter, N or H, denoting the concrete type as NSC or HSC, respectively, and a number, X, 4, 6, 8 or 10, indicating the thickness of the sprayed composite in mm, where X represented the control specimens. It is worth noting that the confinement effect may vary for wooden poles than the case for the tested concrete cylinders including the variation from one pole to another considering the natural non-homogenous wood material. However, the results of the sprayed cylinders were deemed to be informative regarding the confinement efficiency of the sprayed GFRP composites.

Specimen Set ID	Remarks
N-X	Control normal-strength concrete (NSC) cylinders
N-4	NSC cylinders with 4 mm thick sprayed-GFRP composites
N-6	NSC cylinders with 6 mm thick sprayed-GFRP composites
N-8	NSC cylinders with 8 mm thick sprayed-GFRP composites
N-10	NSC cylinders with 10 mm thick sprayed-GFRP composites
H-X	Control high-strength concrete (HSC) cylinders
H-4	HSC cylinders with 4 mm thick sprayed-GFRP composites
H-6	HSC cylinders with 6 mm thick sprayed-GFRP composites
H-8	HSC cylinders with 8 mm thick sprayed-GFRP composites
H-10	HSC cylinders with 10 mm thick sprayed-GFRP composites

Table 2. Confinement test matrix.

#### 2.3. Test Setups and Procedures

The tests on the sprayed-GFRP tension, compressive and shear coupons were conducted as per ASTM D3039-17, ASTM D3410-16 2016, and ASTM D5379-19 2019 [33–35], respectively. A 100-kN capacity testing machine was used to conduct the tests, where a different fixture was used for each test, as appropriate (Figure 5). Since no standard is available to evaluate the bond strength for wood rehabilitation systems, pull-off tests in accordance with ASTM D7522-21 [36] for FRP laminates bonded to concrete or masonry were conducted (Figure 6). Therefore, it is recommended to evaluate this test method as an approved means to evaluate the bond strength of sprayed FRP composites on wooden members. On the other hand, the bond strength of the composites should be reassessed in case a new standard test method is introduced in the future.



Figure 5. Test setups for coupon specimens: (a) tension, (b) compression, and (c) shear coupons.



Figure 6. Pull-off tests: (a) preparation of test spots, and (b) test setup.

For the confinement tests, each concrete cylinder was placed on top of a rigid steel base. A 5000-kN capacity hydraulic testing machine was utilized to apply the axial compressive loading on the concrete cylinders (Figure 7) as per ASTM C39-20 [37]. Multiple electrical

strain gauges were installed transversally on the surface of the composite to record the real-time hoop strains of the GFRP composite as the test proceeded. It should be noted that the conducted confinement tests involved uniform axial compression resulting in more uniform confinement, while utility poles are commonly subjected to flexure, resulting in compressive stress on a portion of the cross-section.



Figure 7. Confinement test setup.

## 3. Test Results and Discussion—Phase I

## 3.1. Coupon Tests

As evident from Table 3, the ultimate tensile strength of the sprayed-GFRP coupons increased by only 8% when the coupon thickness increased by 180% (i.e., from 2.5 to 6 mm). Further increase of the coupon thickness from 6 mm to 10 mm (i.e., 40% increase) resulted in an increase of 15% for the tensile strength, which indicates a non-linear increase of the ultimate tensile strength of the sprayed-GFRP composite as its thickness increases. For the tensile chord elastic modulus, an increase was observed only when the composite thickness increased beyond 6 mm. The failure modes for the tensile coupons were mostly sudden and violent. Some examples of failed tensile coupons are shown in Figure 8a.

Table 3. Test results of tension coupons.

Coupon Thickness (mm)	oupon Thickness Ultimate Tensile (mm) Strength (MPa)		Ultimate Strain (%)		
2.5	$112.7\pm3.3$	$10,\!661\pm 246$	$1.4\pm0.2$		
6.0	$122.0\pm4.2$	$10,\!142\pm295$	$1.9\pm0.1$		
10.0	$139.8\pm3.1$	$11,\!348\pm117$	$1.8\pm0.1$		



Figure 8. Examples of failure modes for: (a) tension, (b) compression, and (c) shear coupons.

By comparing Tables 3 and 4, the ultimate compressive strength (i.e., 105.7 MPa) and elastic modulus (i.e., 9051 MPa) of the GFRP composite were slightly lower than their tensile counterparts. Considering the reported data on the compressive strength of GFRP bars,

which was experimentally found to be about 50% the tensile strength [38,39], the results observed herein are highly promising for the sprayed GFRP composite. As shown in Figure 8b, all compressive coupons failed through the thickness near the instrumented region.

 Table 4. Test results of compression coupons.

Coupon Thickness (mm)	Ultimate Compressive Strength (MPa)	Compressive Chord Modulus of Elasticity (MPa)	Ultimate Strain (%)
2.5	$105.7\pm2.8$	$9051\pm586$	$1.3\pm0.1$

A significant increase (i.e., 58%) was observed for the ultimate shear strength as the coupon thickness increased from 2.5 mm to 6 mm (Table 5). As shown in Figure 8c, rupture of most coupons with the 2.5 mm thickness occurred away from the notched zone, which reflects an undesirable mode of failure. Poor fiber distribution of such small thickness as 2.5 mm could be the reason for this mode of failure. Such observations provide experimental evidence, from the material perspective, on the minimum sprayed composite thickness of 3–4 mm used by previous researchers [25,28,40,41]. Based on that, it was decided to use a minimum composite thickness of 4 mm, for the remainder of Phase I in addition to Phase II of this project to guarantee satisfactory fiber distribution within the sprayed-GFRP layer.

Table 5. Test results of shear coupons.

Coupon Thickness	Coupon Thickness Ultimate Shear		Ultimate Shear		
(mm)	(mm) Strength (MPa)		Strain (%)		
2.5 6.0	$\begin{array}{c} 46.9\pm3.5\\ 98.4\pm8.4\end{array}$	$\begin{array}{c} 1981\pm226\\ 3142\pm240 \end{array}$	$\begin{array}{c} 3.9\pm0.2\\ 3.9\pm0.5\end{array}$		

## 3.2. Pull-Off Tests

Table 4 lists the pull-off test results. Some inconsistencies exist for the bond strength for different parameters, particularly composite thickness, which can be justified by the variation in the properties of wood at the different test spots along with the difficulty controlling the thickness of the sprayed-GFRP composite over the limited length of the wood samples (i.e., 200 mm).

For the PRF-primed specimens, the bond strength was marginally affected by the thickness of the sprayed composite for all curing times except for 30 min. For the half-hour curing time of the PRF coat, almost double the bond strength was achieved by increasing the thickness of sprayed-GFRP from 6 to 8 mm (i.e., 33% increase). In addition, the specimens with a PRF curing time of 30 min exhibited a consistently larger bond strength than their PRF-primed counterparts. Furthermore, the wet conditioned samples exhibited a higher bond strength than that of the dry samples, except for those with a 50 min curing time of the PRF. Some failure remarks for the PRF-primed samples are shown in Figure 9a. An important observation was that all the PRF-primed specimens failed at the interface between the adhesive and the sprayed composite, which implies inferior bond between the PRF and the composite. Therefore, PRF was not recommended for use in the rehabilitation process in Phase II of this study.

For the sprayed samples pre-primed with n-HMR, a higher bond strength was also observed for the wetted wood specimens compared to that of the dry samples when sprayed with an 8- and 10 mm thick composite. While similar bond strengths can be noticed for PRF and n-HMR-primed specimens, the failure of the latter occurred through wood (Figure 9b), which proved the feasibility of using n-HMR as an adhesive for wooden poles prior to retrofitting with the sprayed-GFRP composite.



**Figure 9.** Examples of failure modes for: (a) PRF-primed, (b) n-HMR-primed, and (c) directly sprayed specimens.

Due to the insignificant influence of composite thickness on the bond strength of the sprayed wood samples when PRF and n-HMR adhesives were used, only one composite thickness (i.e., 6 mm) was used for the samples without adhesive. For those specimens, the effect of conditioning on the bond strength was marginal. In a similar manner to the n-HMR-primed specimens, the dominant mode of failure for the samples without adhesive was within wood, as shown in Figure 9c. Consequently, it was decided, for Phase II of this research, to spray the GFRP composite directly on the pole without adhesives.

## 3.3. Confinement Tests

The test results of NSC and HSC cylinders are listed in Tables 6 and 7, respectively, where it can be observed that the improvements resulting from the utilized retrofitting technique were more pronounced for NSC cylinders. For instance, using a 4 mm thick layer of sprayed-GFRP resulted in increased compressive strength by approximately 37 and 13% for the NSC and HSC retrofitted cylinders, respectively, compared to the control set. In addition, further increase of the thickness of sprayed composite (i.e., 6, 8, 10 mm) resulted in higher compressive strength with the ranges of about 263–318% and 87–90% for NSC and HSC sprayed cylinders, respectively, over that of the control set. These results proved the efficiency of the confinement provided by the sprayed composite, which needs to be further verified through testing full-scale wooden poles sprayed with the proposed retrofitting system. The failure mode of the sprayed concrete cylinders incorporated rupture of the sprayed-GFRP layer in the hoop direction accompanied by concrete crushing. Examples of failed retrofitted cylinders are shown in Figure 10.

Compressive Strength (MPa)	Confinement Ratio		
31.71	_		
43.33	1.37		
127.96	4.04		
115.23	3.63		
132.45	$\geq 4.18$		
	Compressive Strength (MPa) 31.71 43.33 127.96 115.23 132.45		

Table 6. Test results of the normal-strength concrete cylinders.

\* The compressive strength is determined excluding the results of the cylinders that did not fail during the tests.

The confinement ratio was calculated as the ratio of the compressive strength between the sprayed cylinders and the control cylinders. Comparing the confinement ratio of NSC or HSC cylinders with different thicknesses of the sprayed-GFRP layer, it can be noted that the confinement effect increases significantly as the sprayed layer thickness increases from 4 to 6 mm. However, insignificant increases in the confinement ratio can be observed as the thickness of the sprayed coating exceeds 6 mm.

Specimen Set ID	Compressive Strength (MPa)	Confinement Ratio		
H-X	72.94	_		
H-4	82.46	1.13		
H-6 *	137.75	$\geq 1.89$		
H-8 *	138.84	$\geq 1.90$		
H-10	136.57	1.87		

Table 7. Test results of the high-strength concrete cylinders.

\* The compressive strength is determined, excluding the results of the cylinders that did not fail during the tests.



**Figure 10.** Examples of failure modes for retrofitted concrete cylinders: (**a**) N-4, (**b**) H-4, (**c**) N-6, and (**d**) H-10.

The relationships of the axial stress versus the hoop strain of the sprayed composite for the retrofitted NSC and HSC cylinders are depicted by Figures 11a and 11b, respectively. It can be observed that the slope of the axial stress-hoop strain relationship exhibited a significant decrease following an axial stress value equal to the axial strength of the unconfined (i.e., control) cylinders, which can be attributed to triggering the confining effect of the sprayed-GFRP layer. The remainder of the axial stress-hoop strain relationships were mostly linear up to failure, which can be attributed to the elastic behavior of the GFRP composite. In addition, a substantial increase can be observed for the final ascending branches as the thickness of the sprayed composite increased from 4 to 6 mm, whereas insignificant changes were observed as the composite thickness increased beyond 6 mm. The inconsistencies that can be noticed in Figure 11a,b between the maximum hoop strain and the composite thickness can be justified by the fact that sometimes the rupture of the GFRP layer occurred away from the locations of the strain gauges, which might have made it more difficult to catch the actual strains experienced by the composite at such locations. It should be noted that these results indicate the efficiency of the confinement provided by the sprayed-GFRP composite, yet the actual confinement efficiency, within the context of retrofitting wooden utility poles, should be determined through a comprehensive experimental program, where an appropriate standard specimen is determined to represent the wooden poles.

It was concluded from the results of Phase I of this study that the optimum system is to use a 6 mm thick layer of sprayed-GFRP composite directly applied on the retrofitted wooden poles without using any adhesive. The previous test results indicated satisfactory tensile strength in the longitudinal and transverse directions in addition to sufficient compressive, shear, and bond strengths. While the material tests indicated negligible benefit (or adverse effects) by increasing the composite thickness, it was deemed imperative to verify such effect on full-scale pole specimens. Section 6.1 summarizes the analytical procedure used to estimate the ultimate load capacity of the poles and the anticipated failure manifestations and their locations.



Figure 11. Stress-strain relationships for retrofitted concrete cylinders: (a) NSC, and (b) HSC.

## 4. Experimental Program—Phase II

# 4.1. Test Matrix

This phase included the loading tests on full-scale old wooden poles to assess the effectiveness of the proposed retrofitting technique, with different composite thicknesses and lengths, restoring the original load-carrying capacity of the poles. The details of the used wooden poles are summarized below.

The testing program had a total of five full-scale wooden utility poles that were decommissioned after full-service life in a distribution line (referred to herein as old), including a Class-3 Douglas Fir (DF) pole, and Class-3 and -4 Lodgepole Pine (LP) pole, defined as per Clause 6.5.3 of CSA O15-15 [3]. It is worth mentioning that CSA O15-15 [3] sets the same limits for same-class Douglas Fir and Lodgepole Pine poles. Therefore, the two classes were expected to behave in a similar manner. It should also be noted that despite the anticipated differences between each pole, this phase aimed at evaluating the performance of the retrofitted decommissioned poles against code requirements rather than against each other. The total length of all poles in practice was 12.20 m (40 ft), including, approximately, 1.83 m (6-ft) embedded length underneath the ground line. However, the poles were modified to conform to the height limitations of the testing facility and loading equipment. These modifications included cutting off the upper 4.88 m (16 ft) and the lower 610 mm (2 ft) of each pole. It was assumed that the tested modified poles in this study were representative of the actual poles in practice, following tests in the literature [22,23]. Consequently, it is recommended to perform field tests on complete utility poles, including several different species, to verify the efficiency of the developed systems for a wider variety of wooden poles. The spraying process followed a similar procedure to that described for

the preparation of the pull-off test samples. A four-character alphanumeric code was used to describe each test pole, as summarized in Table 8. The first two letters denote the wood species that the pole is made of [3]. The second digit (i.e., 3 or 4) identifies the class of the pole in accordance with the requirements of CSA O15-15 [3]. The third number (i.e., 4, 6, 8) represents the thickness of the sprayed-GFRP composite in mm, while X implies the control pole, whereas the last number indicates the length of the sprayed-GFRP layer in the longitudinal direction of the pole, which was either 1000 or 2000 mm (an X is used instead for the control pole).

Specimen ID	P <sub>exp</sub> (kN)	P <sub>exp,adj</sub> (kN) <sup>a</sup>	P <sub>CSA</sub> (kN) <sup>b</sup>	$P_{exp,adj}/P_{CSA}$	P <sub>exp,adj</sub> /P <sub>o</sub> <sup>c</sup>
DF3-X-X	23.9	11.9	13.3	0.89	_
LP3-4-2000	45.9	22.9	13.3	1.72	1.92
LP3-6-2000	34.1	17.0	13.3	1.28	1.43
LP4-6-1000	26.5	13.2	10.7	1.23	1.38 <sup>d</sup>
LP4-8-1000	24.5	12.2	10.7	1.14	1.27 <sup>d</sup>

Table 8. Experimental failure loads for test poles versus code requirements.

<sup>a</sup> Calculated as per Equation (1). <sup>b</sup> Determined as per Table B.1 of CSA O15-15 [3]. <sup>c</sup> Calculated considering  $P_o$  to be the adjusted experimental load of the control pole. <sup>d</sup> Calculated considering  $P_o$  to be the product of adjusted experimental load of the control pole and the ratio of  $P_{CSA}$  for Class 4 poles to Class 3 ones (i.e., a  $P_o$  value of 9.6 kN).

It should be noted that the lower end of the sprayed region was about 500 mm below the ground line for all tested poles to avoid failure at the groundline section [24]. In practice, this can be accomplished by removing the soil around the pole to allow access to the spraying device. Consequently, the sprayed-GFRP composite is extended approximately 500 and 1500 mm above the groundline section for the poles, retrofitted using 1000- (i.e., LP4-6-1000 and LP4-8-1000) and 2000 mm (i.e., LP3-4-2000 and LP3-6-2000) sprayed layers, respectively, as depicted in Figure 12.



Figure 12. Details of retrofitted poles: (a) specimens LP4-6-1000 and LP4-8-1000, and (b) specimens LP3-4-2000 and LP3-6-2000.

#### 4.2. Test Setup and Procedure

The cantilever test method, as per ASTM D1036–99 [30], was utilized to test all pole specimens in an upright position. The lateral load application device and a compression load cell were attached to the pole about 610 mm (2.0 ft) below the tip of the pole. A steel

cable was connected to the loading assembly from one end and passed through a set of pulleys to a 10-tonne capacity overhead crane on its other end, as shown in Figure 13, to transfer the lateral loading from the crane to the loading assembly attached to the pole. A 1.22 m (4.0-ft) high RC base, anchored to the laboratory floor, was used to simulate the confining effect of the soil in practice, where the top surface of the base represented the ground line. The RC base had a cylindrical void to house the wooden pole, where the gap between the pole and the inner face of the cylindrical void was filled with non-shrink grout for the bottom half of the height of the RC base, while the rest of that gap was filled with fine sand. The grout was used to compensate for the shorter embedment depth of the pole within the RC block (i.e., 1.22 m) compared to the actual depth in practice (i.e., 1.83 m) while avoiding significant rotation or uplift of the pole while testing. On the other hand, the fine sand was utilized to avoid excessive fixity of the pole and to simulate the effect of the soil around the pole in real life. Furthermore, a horizontally aligned linear variable displacement transducer (LVDT) was installed at the lateral loading point to plot the deflection of the wood pole against lateral loading. Despite the utilized approximations made to simulate the actual case of utility poles in practice while conforming to the lab constraints, the visual and experimental data of the tests indicated a proper response to the applied loading condition.



Figure 13. Test setup: (a) elevation view, and (b) plan view.

# 5. Test Results and Discussion—Phase II

# 5.1. Horizontal Load Capacity and Mode of Failure

Table 8 shows the ultimate loads exhibited by the control and retrofitted poles. Since the tested poles were cut short to comply with the laboratory constraints, as mentioned earlier in Section 5.1, an adjusted load value was calculated for each pole, as demonstrated by Equation (1) below. Such adjusted load values can be compared against the horizontal load limits set by CSA-O15-15 [3].

$$P_{exp,adj} = P_{exp} \left( \frac{L_{lab} - 1220 - 610}{L_{actual} - 1829 - 610} \right)$$
(1)

where  $P_{exp}$  is the experimental failure load of the pole,  $P_{exp,adj}$  is the adjusted load value,  $L_{lab}$  is the length of the isolated pole specimen used in the lab (i.e., 6706 mm),  $L_{actual}$  is the original length of the decommissioned wooden pole (i.e., 12,192 mm in this study), the length 1829 mm denotes the actual embedment length of the pole below the ground line in practice, the height 1220 mm is the height of the concrete base used in the laboratory to simulate the pole embedment, and the length of 610 mm is the distance below the tip of the pole where the horizontal loading is applied or expected for the laboratory and in-practice cases, respectively. The adjusted load, calculated using Equation (1), assumed consistency of the pole properties across its full height in practice (i.e., 40 ft). Therefore, care should be given towards assessing the old wooden poles over their length as per the code provisions [3] to provide the appropriate thickness and length of the sprayed composites.

The effectiveness of the sprayed-GFRP retrofitting system is evident as the load capacity of the retrofitted old poles exceeded quite significantly the requirements of CSA-O15-15 [3] for new poles. This exceeds the efficiency of the FRP wrap system proposed by Saafi and Asa [24], which was able to restore only 85% of the load-carrying capacity of the intact poles. The poles sprayed with a 1.0 m long GFRP composite exceed their at-installation load-carrying capacity [3] by 23 and 14% for a composite thickness of 6 and 8 mm, respectively. Such observation suggests not to increase the thickness of the sprayed layer beyond 6 mm, which also agrees well with the findings of Phase I of this study. That was also the reason why the Class 3 LP poles were retrofitted using 4- and 6 mm thick sprayed-GFRP layers. Nonetheless, it is prudent to verify this conclusion based on tests of a wider spectrum of retrofitted wooden poles from different species with different thicknesses of sprayed GFRP composite. The increased length of the sprayed composite layer (i.e., 2.0 m) enabled the poles to achieve about 43 to 92% higher load capacity than the control pole. Furthermore, the load carrying capacity of LP3-4-2000 and LP3-6-2000 exceeded the horizontal load required for new Class 3 LP poles [3] by 72 and 28%, respectively.

The failure of the control pole DF3-X-X was progressive where section by section was failing in tension, until the pole finally failed as shown in Figure 14a. In addition, all retrofitted poles, except for LP3-4-2000, exhibited a sudden tension failure of the wooden pole, which was located above the sprayed region for specimens LP4-6-1000, LP4-8-1000, and LP3-6-2000, as shown in Figure 14c–e, whereas no delamination or rupture was observed for the sprayed-GFRP layer. Similar observations were reported by Saafi and Asa [24] for some of their FRP-wrapped wooden poles. On the other hand, the retrofitted pole, LP3-4-2000, was the only pole to fail by rupture of the GFRP layer in the longitudinal direction at the ground line (Figure 14b). The failure manifestations exhibited by the other retrofitted poles, when compared to that of LP3-4-2000, indicate an excessively rigid sprayed region, accompanied by stress concentrations at the top of the sprayed zone, resulting in the poles failing right above the sprayed regions.



Figure 14. Failure modes of tested poles: (a) DF3-X-X, (b) LP3-4-2000, (c) LP3-6-2000, (d) LP4-6-1000, and (e) LP4-8-1000.

# 5.2. Normalized Load-Deflection Response

The load-deflection response was normalized to provide informative comparison between the tested poles with different properties and dimensional characteristics. Following what was suggested by Lopez-Anido et al. [22], the deflection was normalized by the cantilever length of the pole above the ground line, while the load was normalized by the bending stiffness and cantilever length of the poles as expressed by Equations (2) and (3), respectively.

$$\delta = \frac{\Delta}{L_{lab} - 1220 - 610} \tag{2}$$

$$p = \frac{P_{exp}(L_{lab} - 1220 - 610)^2}{E_w I_w}$$
(3)

where  $\delta$  is the normalized deflection, p is the normalized load of the pole,  $\Delta$  is the deflection measured at the loading point of the pole during the test,  $E_w$  is the elastic modulus of the pole obtained from Table E.3 of CSA-O15-15 [3],  $I_w$  is the moment of inertia at the groundline section of the pole assuming uniform moment of inertia along the pole, while  $P_{exp}$ ,  $L_{lab}$ , 1220, and 610 are defined in the same manner as in Equation (1). Figure 15 depicts the normalized load-deflection responses of the tested poles in Phase II.



Figure 15. Normalized load-deflection response for the tested poles.

The normalized load-deflection response proceeded mostly in a linear manner for all tested poles, apart from a few drops near 50 and 90% the ultimate load value, before the pole restored its load resistance. It can be observed that retrofitting with sprayed-GFRP composite enhanced the load carrying capacity and stiffness of the poles. The lower stiffness exhibited by LP4-8-1000 compared to LP4-6-1000 could be attributed to the significant stress concentrations at the top of the sprayed composite layer, as explained earlier, or due to individual differences between the dismissed poles used for those specimens [23]. In addition, the similar normalized load capacity and stiffness noticed for LP4-6-1000 and LP3-6-2000 may align well with the fact that the sprayed composite in both conditions provided sufficient rigidity to the sprayed zone, which caused the failure to occur prematurely above the retrofitted region. On the other hand, the increased stiffness of LP3-4-2000 can be attributed to the rigid composite section formed at the ground line.

#### 6. Analytical Study

## 6.1. Load Capacity Prediction

Using load prediction equations from the literature in addition to the material properties identified in Phase I, the horizontal load capacity, causing failure of the composite section (i.e., wood + FRP) at the ground line, was estimated for the retrofitted specimens. Table 9 summarizes the calculations made in this analytical study. The ultimate load capacity of the wooden pole was calculated using the minimum horizontal load as per CSA-O15-15 [3] and the reciprocal of Equation (1) to comply with the length of the pole tested in the laboratory. Based on the ratio between the experimental load capacity of pole DF3-X-X to the minimum value set by CSA-O15-15 [3], the portion of horizontal load capacity provided by the old pole for the retrofitted specimens was estimated as 90% of the values set by the code [3]. On the other hand, three different design models were used to quantify the additional load capacity provided by the sprayed-GFRP layer. The material properties of the sprayed composite in Tables 1–3 were used, where linear interpolation was used to find the properties for each composite thickness used in Phase II.

Specimon ID	P <sub>exp</sub> P <sub>w,GL</sub>		P <sub>FRP</sub> (kN) <sup>b</sup>		P <sub>t.GL</sub>	P <sub>w.a</sub>	P <sub>cr</sub>		L <sub>FRP</sub>	
Specimen ID	(kŇ)	(kN) <sup>a</sup>	Equation (4)	Equation (5)	Equation (6)	(kN) c	(kN) <sup>d</sup>	(kN) <sup>e</sup>	O.F	(mm) <sup>g</sup>
DF3-X-X LP3-4-2000 LP3-6-2000 LP4-6-1000 LP4-8-1000	23.9 45.9 34.1 26.5 24.5	24 24 24 19.4 19.4	7.0 11.5 10.1 15.7	7.9 12.9 11.3 15.7	7.8 12.5 11.0 14.9	31.9 36.9 30.7 35.1	34.7 34.7 21.6 21.6	24 31.9 34.7 21.6 21.6	~1.0 1.44 0.98 1.23 1.14	1708 2203 2302 2687

Table 9. Load predictions and optimum sprayed zone length.

<sup>a</sup> Load capacity contributed by the wooden pole at the ground line, calculated as 90% the minimum horizontal load as per Table B.1 of CSA O15-15 [3], adjusted to conform to the constraints of the laboratory (reciprocal of Equation (1)). <sup>b</sup> Load capacity contributed by the sprayed FRP layer at the groundline section, determined using Equation (4), (5), or (6). <sup>c</sup> Total load capacity at groundline section (wood + FRP), considering  $P_{FRP}$  to be calculated in accordance with Equation (5). <sup>d</sup> Load capacity of the wooden pole above the sprayed zone, assuming constant moment resistance along the pole. <sup>e</sup> The minimum of  $P_{t,GL}$  and  $P_{wa}$ , indicating the failure to occur at the location that gives lower load capacity. <sup>f</sup> The ratio of  $P_{exp}$  to  $P_{cr}$ , indicating the overstrength the pole has over the estimated capacity. <sup>g</sup> The optimum length of the sprayed-GFRP layer, causing a simultaneous failure at the ground line and above the sprayed zone.

The first design model was proposed by Saafi and Asa [24] to compute the required thickness of FRP plies,  $t_{FRP}$ , based on the tensile and shear strength of the FRP material, as expressed in Equation (4). A trial-and-error procedure was used herein, where the lateral load was iterated until a thickness equal to that used in the specimen was obtained.

$$t_{FRP} = \frac{D}{2} - 0.5 \left[ D^4 - \frac{32DP(L - E - 610)}{\pi f_{FRP}} \right]^{0.25} + \frac{2P}{\pi D\tau_{FRP}}$$
(4)

where *D* is the diameter of the pole at ground line, *P* is the horizontal load applied at 610 mm from the tip of the pole, *L* is the length of the wooden pole (taken as  $L_{lab}$  in this study, as described in Equation (1)), *E* is the embedment length of the pole below the ground line (defined herein as 1220 mm), 610 is defined in the same manner as in Equation (1), and  $f_{FRP}$  and  $\tau_{FRP}$  are the tensile and shear strengths of the sprayed composite, respectively.

The second analytical model was that developed by Fam and Son [42] to estimate the moment resistance of thin walled FRP tubes used in FRP tubes partially filled with concrete for use in utility poles. The moment capacity of a hollow FRP tube based on strength-type failure,  $M_{Hollow-S}$ , is given by Equation (5).

$$M_{Hollow-S} = 0.79t D^2 f_u \tag{5}$$

where *t* is the thickness of the composite, *D* is as described in Equation (4), and  $f_u$  is defined herein as the tensile strength of the sprayed-FRP composite.

Similarly, the design model introduced by Jawdhari et al. [43] to estimate the moment capacity of partially damaged concrete filled FRP tubes (Equation (6)),  $M_r$ , was used, considering the damage level,  $\alpha$ , to be zero and disregarding the contribution of the concrete filling thereof.

$$M_r = 0.0043 \left( 1 - 1.22 \alpha^{0.385} \right) f_u^{0.64} D^2 t + M_{cr}$$
(6)

where  $f_u$ , D, and t are as described in Equation (5), and  $M_{cr}$  is the cracking moment of the concrete filling section, which was neglected in this study. The load capacity contribution in the previous two methods was estimated by dividing the moment capacity of the FRP by the lever arm of the tested poles (i.e., 4876 mm).

The failure load of LP3-4-2000 exhibited much overstrength over the predicted value. Therefore, it was decided to use the load predictions provided by Equation (5) to determine the total load capacity assuming the failure occurs at the groundline section, as listed in Table 9. The estimated total load,  $P_{est}$ , was then identified as the lesser of the predicted load causing failure of the composite section at the ground line, or that causing failure of the section right above the sprayed zone. The expected failure

modes matched those observed experimentally, with an overstrength factor (i.e., ratio of experimental-to-predicted load value) ranging between 0.98 and 1.23, apart from LP3-4-2000 which exhibited an overstrength factor of 1.44.

## 6.2. Sprayed Zone Length

To avoid the premature failure of the wooden pole above the sprayed-GFRP layer before reaching the moment capacity of the composite section at the ground line, the overall length of the sprayed composite,  $L_{FRP}$ , should be calculated as per Equation (7).

$$L_{FRP} = (L - E - 610) \left[ 1 - \frac{P_{w,GL}}{P_{t,GL}} \right] + 500$$
(7)

where *L*, *E*, and 610 are defined in the same manner as in Equation (4),  $P_{w,GL}$  and  $P_{t,GL}$  are the horizontal load capacity at the groundline section provided by the wooden pole and the composite section, respectively (as calculated in the previous subsection), the length 500 mm is the length of the sprayed composite below the ground line.

The values of  $L_{FRP}$  for the tested specimens are listed in Table 9. It can be noticed that all tested retrofitted poles, except for LP3-4-2000, had their sprayed-GFRP layers shorter than the optimum length values, which corroborated the experimental observations. However, more experimental testing, with wider ranges of parameters and wood species, is required to further validate the proposed simplified model and to extend the applicability of the proposed technique to damaged wooden poles, for which the proposed method may have high potential.

## 7. Conclusions

Based upon the results of the experimental and analytical components of this study, the following conclusions can be drawn:

- On the contrary to FRP bars, the compressive strength and modulus of elasticity of the sprayed-GFRP coupons were lower than the respective tensile properties by only 6 and 15%, respectively.
- Undesirable failure modes occurred in the case of 2.5 mm thickness, which indicated the unsuitability of using such small thickness (i.e., 2.5 mm) for retrofitting purposes.
- Spraying the GFRP composites on the wooden samples directly without using any
  adhesive resulted in satisfactory bond strengths and modes of failure. Therefore, it
  was decided to use this method for the second phase of this study.
- The confinement tests indicated significant increase in the compressive strength by up to 318 and 90% for NSC and HSC specimens, respectively, especially when a 6 mm composite thickness was used.
- All retrofitted poles failed above the sprayed zone, except for the pole retrofitted with a 2.0 m long, 4 mm thick sprayed-GFRP layer, which exhibited failure through the sprayed FRP layer at the groundline section. This indicates that the composite thicknesses of 6 and 8 mm resulted in excessive confinement for the pole that caused the premature failure through the wood rather than the composite section.
- The failure loads of all retrofitted old poles exceeded the horizontal load requirements of CSA O15-15 [3] and the load capacity of the control old pole by up to 72 and 92%, respectively.
- Two simplified analytical models were developed: one to estimate the load-carrying capacity of the retrofitted old poles based on the thickness of sprayed-GFRP composites, while the other model estimated the optimum length for the sprayed-GFRP layer to retrofit old poles to guarantee full utilization of the composite section at the ground line. The results of both models agreed well with the experimental load capacities and locations of failure.

The outcomes of this study highlight the efficiency of the sprayed-GFRP retrofitting technique as a cost-effective solution for old wooden utility poles. More experimental

research is encouraged to increase the confidence in such rehabilitation technique by exploring its potential on wider ranges of the different parameters.

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