Deliverable 2

Performance evaluation, material and specification development for basalt fiber reinforced polymer (BFRP) reinforcing bars embedded in concrete

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Chapter 1

Introduction

It is the goal of this report to summarize the performance evaluation of basalt fiber reinforced polymer (BFRP) rebars. BFRP rebars are comparatively new material in the industry. Before using any new material in the infrastructure projects, the physical and mechanical properties of the material must be evaluated and compared to acceptance criteria (if applicable). In this report, physical properties such as cross-sectional dimensions, fiber content, and moisture absorption properties are described. In addition, physical properties, including the apparent horizontal shear strength, the transverse shear strength and the tensile properties were characterized. All tests were conducted according to the methods described by the American Society for Testing and Materials (ASTM) in line with the relevant test protocols. Data acquisition software, such as LabView and MTS TestWorks was used to collect the raw data with high data rates. The collected raw data were analyzed using R-statistics[1] and R-Studio[2] software packages.

For the purpose of this research, BFRP rebar from three different manufacturers were evaluated. Two different sizes were tested, which included # 3, and # 5 rebars. All tested materials were provided by the BFRP rebar manufacturers Galen Panamerica, No Rust Rebar, and Pultrall. One Manufacturer provide two sub-types of rebars, which were made from different resin types while all other production parameters were held constant (according to the manufacturer) All specimen types analyzed in this research are shown In the following figures 1.1 and 1.2. The surface enhancement properties of rebars are described in the table 1.1 It can be seen that all products featured

Table 1.1: Physical characteristics of tested BFRP rebars

Name	Cross-Section	Surface Enhancement	Resin Type
A	Round (solid)	Sand coat	HP
B	Round (solid)	Surface lugs	Epoxy
C	Round (solid)	Helical Wraps	Epoxy

sand coating as a surface enhancement to improve the bond-to-concrete properties. In addition to the surface sand, one product (No Rust Rebar) also had helical fibers made from polyethylene terephthalate, produced by Dacron®

[1]R.app GUI 1.70 (7434 El Capitan build), S. Urbanek & H.-J. Bibiko, R Foundation for Statistical Computing, 2016

[2]Version 1.1.383 2009-2017 RStudio, Inc.

(a) Galen Panamerica (b) No Rust Rebar (c) Pultrall

Figure 1.1: Sample pictures of tested BFRP # 3 Rebars

(a) Galen Panamerica (b) No Rust (c) Pultrall

Figure 1.2: Sample pictures of tested BFRP # 5 Rebars

Chapter 2

Test Procedures

2.1 Introduction

In this chapter, the test procedures of all the evaluated properties of rebar are described and detailed in individual sections.

2.2 Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by displacement.

The test procedure to determine the density and specific gravity (relative density) of plastics by displacement methods is described in this paragraph to explain how the rebar diameter (or cross section) was specified for each product. The cross-sectional properties were measured according to ASTM D 792(ASTM-International, 2015), while the density of each specimen was calculated via the buoyancy principle. A clean specimen was conditioned for 40 h prior to testing in a temperature range from 21 °C to 25 °C (70 °F to 74 °F) at a relative humidity between 40 % and 60 %. The specimen was then cut to the desired length of 25 mm (1 in.) using an electric precision saw. The length of each curtailed specimen was measured 3 times, at 120° intervals perpendicular to the longitudinal axis of the FRP rebar, and the average value was noted for density calculations. Afterwards, the weight of dry and conditioned specimen was measured using an electronic balance, and recorded to the nearest 0.05 g (0.0017 oz.). The recorded weight of the curtailed specimen was measured to be no less than 10 g (0.352 oz.). and the value was used as the initial specimen weight, (W_i), needed for density calculations. A glass beaker of known volume was used as immersion vessel to hold the water in which the sample was submerged . However, the immersion vessel was tared from the weighing mechanism to obtain only the weight of the sample under buoyancy. The temperature of the water bath was monitored for each test and constant water temperatures of 21 °C to 25 °C (70 °F to 74 °F) were maintained throughout all experiments. A corrosion resistant copper wire was used as a sample holder and attached to the fixture that was independent of the water bath/vessel but introduced the forces into the scale and the specimen was carefully attached to one end of copper wire. The weight of the specimen along with the copper wire was measured and recorded as weight (Specimmen + wire) (W_{s+w}). The immersion vessel was placed on the support (independent of the weighing mechanism), and the specimen was completely submerged in the water with the help of the copper wire. To remove any entrapped air or air bubbles at the surface of the FRP rebar, the specimen was carefully rubbed with the wire across the surface and submerged in a rotating motion. Any water that was displaced onto the scale was wiped without disturbing the immersion vessel. The weight of the submerged specimen was measured and recorded as final weight (W_f). The density of the test specimen was determined via the buoyancy principle and the cross-sectional dimensions were calculated by dividing the determined volume by the measured specimen length. For reliability of test results and to obtain representative values for the BFRP rebar product as a whole, the test was repeated five times for specimens taken from different sections of the production lot and the average value was assigned. For the calculation of FRP rebar strength properties, the measured cross-sectional area is an important characteristic because the tensile strength of rebar is partially dependent on it's diameter. The cross-sectional area of the specimen must be determined in the laboratory because the cross-sectional properties may vary within an individual product due to imperfections in the manufacturing process. Stresses in the rebar depends on the cross sectional area, as stress is force divided by area. The stresses in the rebar changes with the change in the cross-sectional area. However, only bar strength based on nominal area is used in construction acceptance and structural calculations (actual measured area maybe used for volume fraction calculations).

2.3 Standard Test Method for Ignition Loss of Cured Reinforced Resins

The procedure for Ignition loss test for cured reinforced resins is explained in this paragraph to describe how the fiber content for the tested FRP rebars was determined. ASTM D 2584 -11(ASTM-International, 2011) outlines this procedure and details the required conditions. Similar to the specimen preparation for the cross-sectional dimension experiments, the specimens for this procedure were also conditioned in a temperature range from 21 °C to 25 °C (70 °F to 74 °F) at a relative humidity between 40 % and 60 %, for at least 40 hours prior to testing. The conditioned sample was then cut to the desired length of 25 mm (1 in.) with a precision of 0.05 mm (0.0019 in.). The weight of the conditioned sample (W_s), was then recorded to the nearest 0.05 g (0.0017 oz.) using an electronic balance. This weight was used as the 100 % reference value for calculating the fiber and resin contents (relative to the initial weight). Likewise, a clean and oven dried crucible was weighed (W_c),to the nearest 0.05 g (0.0017 oz.) to obtain the initial weight of the sample holder. The FRP rebar specimen was transferred to the crucible and the total weight of the specimen and the crucible (W_i), was recorded to the nearest 0.05 g (0.0017 oz.). To burn off all resin, the crucible (of known mass) along with the specimen were exposed to a temperature of 542 °C to 593 °C (1000 °F to 1100 °F) in a muffle furnace until the specimens reached a constant weight. The crucible was then carefully removed from the muffle furnace and allowed to cool down to room temperature, before the cooled crucible including the fibers (and sand for rebars that used surface enhancement made from sand) was weight using a precision electronic balance. This weight was recorded as final weight (W_f). For the rebar products made with sand at the surface for bond enhancement, the weight of the sand (W_s), was recorded and subtracted from the initial weight of the crucible and the specimen to obtain comparable and absolute fiber content percentages. Because fibers (and sand) are not susceptible to loss on ignition, the reduction in weight due to the burning process is equivalent to the weight of resin, and hence, the percentage of fibers was determined through the difference in weight before and after the burning process. For reliability of test results and to obtain representative values for the BFRP rebar product as a whole, the test was repeated five times for specimens taken from different sections of the production lot and the average value was assigned.

The fiber content percentage plays a key role in transferring the stresses through the cross section. The tensile stresses are transferred from one fiber to another during stressing. To increase the tensile strength of the rebar, to improve the ductility of the rebar, and to improve the overall quality of rebar production, it is important to understand the resin matrix and determine the fiber to resin ratio.

2.4 Moisture Absorption of Basalt FRP

The test procedure described in ASTM D 5229(ASTM, 2014) defines the standard method for determining the moisture absorption characteristics of FRP and is an indicator of porosity. This paragraph explains how the porosity of the tested rebars was calculated. ASTM D 5229 offers seven different test procedures (A through E,Y, and Z) to assign moisture absorption properties for FRP in different environments. Procedure A is most commonly used, and was used for this research project. Each specimen was first oven dried for 48 h to eliminate moisture entrapped in the pores or at the surface. The dried and conditioned specimens were placed in storage bags to ensure that no moisture contaminated the specimens. Three diameter measurements were taken at 120° intervals, perpendicular to the longitudinal axis of the FRP rebar, and those measurements were recorded to the nearest 0.001 mm ($\frac{4}{10\,000}$ in.). Then, each specimen was weighted with a precision of 0.05 g (0.0017 oz.) in its dry state and recorded as W_i. The specimens were then submerged in distilled water. The water along with the submerged specimens were stored in a air circulated oven to maintain the temperature of 50 °C (122 °F) throughout the entire duration of the conditioning. First weight measurements to record W_1 after water conditioning were taken after two weeks. To obtain additional measurements, the specimens were removed from the water bath in two week intervals (continuous conditioning) and surface dried with a fresh paper towel until no free water remained on the surface of the FRP rebar. The final weight of each specimen (W_f) was measured and recorded to the nearest 0.05 g (0.0017 oz.). This procedure was repeated and weight gains were monitored until three consecutive two-week measurement did not differ by more than 0.02 % from one another. For reliability of test results and to obtain representative values for the BFRP rebar product as a whole, the test was repeated five times for specimens taken from different sections of the production lot and the average value was assigned.

2.5 Horizontal Shear Test

The FRP rebar product was tested for horizontal shear properties. The horizontal shear test was conducted according to ASTM D 4475 (ASTM-International, 2012a) standards. This test alone does not relate to design properties, but the horizontal shear failure is an indicator for the strength of the resin to fiber bonding, and therefore, is a well suited quality control criteria and used for comparison among multiple specimens from the same manufacturer. First, the diameter at the center of the specimen was recorded and the specimens were conditioned at a temperature range from 21 °C to 25 °C and a moisture content between 40 % and 60 % before they were cut to a length of approximately 5 times the diameter. A minimum of 5 specimen were tested per sample. The horizontal shear strength was assessed through a three-point load test over a span length that is short enough to avoid bending failure. The load was applied at the center of specimen with a displacement rate of 1.3 $\frac{\text{mm}}{\text{min}}$ until the shear failure was reached via horizontal delamination (failure of the resin or resin-fiber interface). The ultimate load and the break type (number of fracture surfaces) were recorded and analyzed.

2.6 Transverse Shear Test

The transverse shear strength is an important characteristic if the bars are used as dowels in concrete pavement, stirrups in concrete beams, or as general shear reinforcement elements. ASTM D 7617 (ASTM-International, 2012b) was used in the process of testing and analyzing the data. Before testing, the specimens were conditioned according to the ASTM D 5229 (ASTM, 2014). The conditioned specimen were then cut to a minimum length of 225 mm so that they fit in the shearing apparatus which is a device that produces double shear on the FRP rebar specimen. This device has two bar seats, two lower plates, and two guides machined from steel which are connected with two threaded rods using bolts, and nuts. The conditioned and curtailed bars were placed inside the shear test device and loaded with a displacement rate such that the test is continuous for at least 1 minute, but not more than 10 minutes until the force reaches 70 % of the ultimate load. The transverse shear strength was determined using the ultimate load and the cross sectional area of the specimen measured as per nominal diameter of the rebar.

2.7 Tensile Strength Tests

The rebars were tested according to the ASTM D 7205, which describes a specific test method for specimen preparation and testing. It details how to protect the rebar ends via steel pipe anchors at both ends. Because of the low shear and crushing strength of FRP rebars this method is necessary to prevent the rebar from failing in shear before reaching the ultimate tensile strength. The grips of the testing machine would lead to a premature failure of the specimen. The anchors are potted with expansive grout which transfers the force from the testing machine into the rebar through compression and friction of the rebar surface and the grout. The dimensions of the anchors relate to the rebar diameter and the free specimen length between the anchors is described with 40 times the rebar diameter.

2.8 Acceptance Criteria

While acceptance criteria for basalt FRP rebars are not fully established yet, criteria for other fiber based rebars have been adopted. One of the most established composite rebar materials is the glass fiber reinforced polymer (GFRP) rebar. For reference, the data in the Tables 2.1 and 2.2 shows common acceptance criteria for (GFRP) rebars. The results obtained by testing BFRP rebars

Table 2.1: Acceptance criteria for GFRP rebar # 3

			FDOT 932-3/2017	AC454	ASTM D 7957
Test Method	Test Description	Unit	Criteria	Criteria	Criteria
ASTM D 792	Measured Cross Sectional Area	$in.^2$	0.104 – 0.161	0.104 – 0.161	0.104 – 0.161
ASTM D 2584	Fiber Content	% wt.	$\geqslant 70$	$\geqslant 70$	$\geqslant 70$
ASTM D 570	Moist. Absorption short term @50 °C	%	$\leqslant 0.25$	$\leqslant 0.25$	$\leqslant 0.25$
ASTM D 570	Moist. Absorption long term @50 °C	%	$\leqslant 1.0$	n/a	$\leqslant 1.0$
ASTM D 7205	Min. Guaranteed Tensile Load	kip	$\geqslant 13.2$	$\geqslant 13.2$	$\geqslant 13.2$
ASTM D 7205	Min. Guaranteed Tensile Strength	ksi	n/a	n/a	n/a
ASTM D 7205	Tensile Modulus	ksi	$\geqslant 6,500$	$\geqslant 6,500$	$\geqslant 6,500$
ASTM D 7205	Max. Strain	%	n/a	n/a	n/a
ASTM D 7617	Min. Guaranteed Transverse Shear	ksi	$\geqslant 22$	$\geqslant 22$	$\geqslant 19$
ASTM D 4475	Horizontal Shear Stress	ksi	n/a	$\geqslant 5.5$	n/a
ACI440. 3 R,B.3	Bond-to-concrete strength	ksi	$\geqslant 1.1$	$\geqslant 1.1$	$\geqslant 1.1$

Table 2.2: Acceptance criteria for GFRP rebar # 5

			FDOT 932-3/2017	AC454	ASTM D 7957
Test Method	Test Description	Unit	Criteria	Criteria	Criteria
ASTM D 792	Measured Cross Sectional Area	in.^2	0.288 – 0.388	0.288 – 0.388	0.288 – 0.388
ASTM D 2584	Fiber Content	% wt.	$\geqslant 70$	$\geqslant 70$	$\geqslant 70$
ASTM D 570	Moist. Absorption short term @50 °C	%	$\leqslant 0.25$	$\leqslant 0.25$	$\leqslant 0.25$
ASTM D 570	Moist. Absorption long term @50 °C	%	$\leqslant 1.0$	n/a	$\leqslant 1.0$
ASTM D 7205	Min. Guaranteed Tensile Load	kip	$\geqslant 29.1$	$\geqslant 32.2$	$\geqslant 29.1$
ASTM D 7205	Min. Guaranteed Tensile Strength	ksi	n/a	n/a	n/a
ASTM D 7205	Tensile Modulus	ksi	$\geqslant 6,500$	$\geqslant 6,500$	$\geqslant 6,500$
ASTM D 7205	Max. Strain	%	n/a	n/a	n/a
ASTM D 7617	Min. Guaranteed Transverse Shear	ksi	$\geqslant 22$	$\geqslant 22$	$\geqslant 19$
ASTM D 4475	Horizontal Shear Stress	ksi	n/a	$\geqslant 5.5$	n/a
ACI440. 3 R,B.3	Bond-to-concrete strength	ksi	$\geqslant 1.1$	$\geqslant 1.1$	$\geqslant 1.1$

are compared to GFRP rebar acceptance criteria because BFRP acceptance criteria in the US are yet to be established. Accordingly, the listed criteria (while established for glass) serve as reference points and are used for comparison and initial benchmark data.

Chapter 3

Results

3.1 Introduction

The following results were obtained at the FAMU-FSU College of Engineering in the High Performance Materials Institute (HPMI). All tests were conducted in accordance with the relevant American Society for Testing and Materials (ASTM) test protocol. The collected raw data were analyzed with the engineering software R-statistics[1] and R-Studio[2]. The results are presented throughout this chapter in tables and graphs for visual representation. For clarity, each property was individually studied and presented seperately. At the end of the chapter, a summary of the test results is provided to comprehensively present each specific product, document its performance, and to compare it to the acceptance criteria in FDOT 932, AC 454, and ASTM D 7957 (for glass based FRP rebars).

3.2 Cross Sectional Properties

The effective rebar diameter was measured according to the ASTM D 792-13. Due to the variety of FRP rebars on the market and depending on the proprietary production methods, rebars from different manufacturers with different surface enhancement vary from to the stated nominal diameter. Table 3.1 below lists the results of water displacement method according to the ASTM D 792-13 of the Galen Panamerica products.

[1] R.app GUI 1.70 (7434 El Capitan build), S. Urbanek & H.-J. Bibiko, © R Foundation for Statistical Computing, 2016

[2] Version 1.1.383 © 2009-2017 RStudio, Inc.

Table 3.1: Results from diameter measurements for rebar size # 3 and # 5

Specimen		Specimen Length				Weight				
		$L1$	$L2$	$L3$	$Average$	a	$a+s$	b	s	ΔM
		cm	cm	cm	cm	g	g	g	g	g
Galen HP No. 3	HP1	2.550	2.527	2.512	2.530	3.976	11.774	9.768	7.798	1.970
	HP2	2.514	2.519	2.527	2.520	3.979	11.775	9.760	7.796	1.964
	HP3	2.558	2.533	2.521	2.537	3.977	11.783	9.769	7.806	1.963
	HP4	2.513	2.512	2.527	2.517	3.942	11.739	9.742	7.797	1.945
	HP5	2.570	2.536	2.523	2.543	3.932	11.730	9.756	7.798	1.958
Galen HE No. 3	HE1	2.511	2.529	2.506	2.515	4.056	11.868	9.723	7.812	1.911
	HE2	2.509	2.521	2.511	2.514	4.161	11.958	9.743	7.797	1.946
	HE3	2.564	2.559	2.560	2.561	4.226	12.023	9.791	7.797	1.994
	HE4	2.539	2.539	2.569	2.549	4.200	11.995	9.768	7.795	1.973
	HE5	2.504	2.503	2.527	2.511	4.144	11.972	9.752	7.828	1.924
Galen HP No. 5	HP1	2.557	2.535	2.538	2.543	11.410	19.019	13.636	7.609	6.027
	HP2	2.530	2.547	2.569	2.549	11.145	18.940	13.589	7.795	5.794
	HP3	2.539	2.558	2.549	2.549	11.147	18.965	13.601	7.791	5.810
	HP4	2.535	2.536	2.541	2.537	11.253	19.050	13.652	7.797	5.855
	HP5	2.534	2.548	2.534	2.539	11.154	18.951	13.600	7.797	5.803
Galen HE No. 5	HE1	2.505	2.502	2.524	2.510	11.097	18.890	13.450	7.793	5.657
	HE2	2.511	2.525	2.510	2.515	11.154	18.954	13.476	7.800	5.676
	HE3	2.515	2.521	2.532	2.523	11.174	18.975	13.501	7.801	5.700
	HE4	2.520	2.577	2.546	2.548	11.266	19.062	13.544	7.796	5.748
	HE5	2.581	2.545	2.550	2.559	11.181	18.978	13.482	7.797	5.685

3.3 Fiber Content

The measured fiber content results are plotted in the Figure 3.1. The bar chart compares rebars

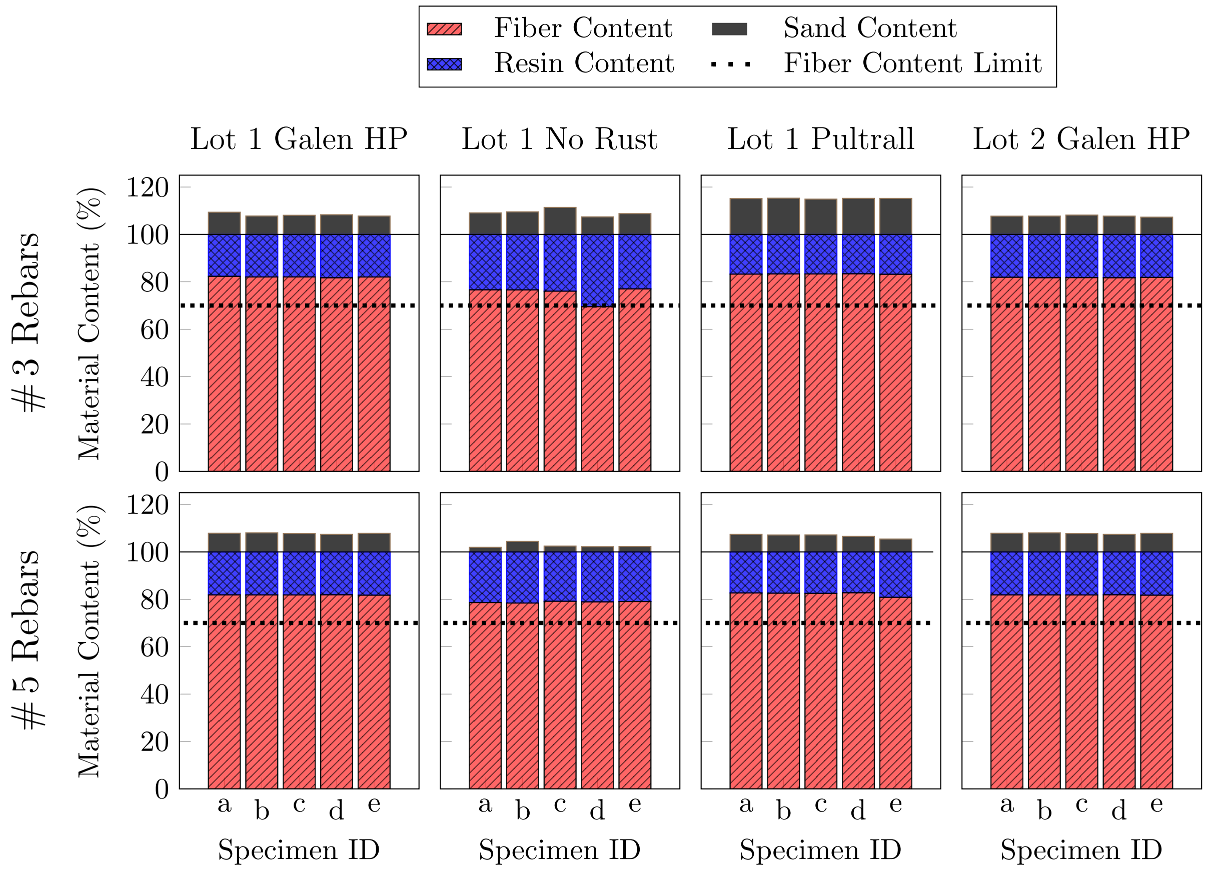


Figure 3.1: Fiber content percentage of rebars from Galen, No Rust, and Pultrall manufacturers

from different manufacturers, both the bar sizes and both the lots. All the rows in the plot indicate rebar sizes and all the columns indicate different manufacturers. Each individual column represents one specimen. The red hatched part of each column indicates fiber content percentage of the rebar specimen, the blue part represents the resin content percentage and the black part represents sand content percentage. The surface of the rebar specimens were sand coated to increase the bond to concrete. The 100% value of rebars are based on total specimen weight minus the sand content. All the rebar specimen easily met the minimum requirement of 70% fiber content. The only marginal exception was specimen d of # 3 rebar from No Rust Rebar. Overall, the measured fiber content results show the production consistency for all rebar manufacturers, lots, and sizes.

The following Figure 3.2 exemplifies the rebar appearance after the loss on ignition test procedure. While the specimens shown in the figure were material samples from Galen Panamerica, the

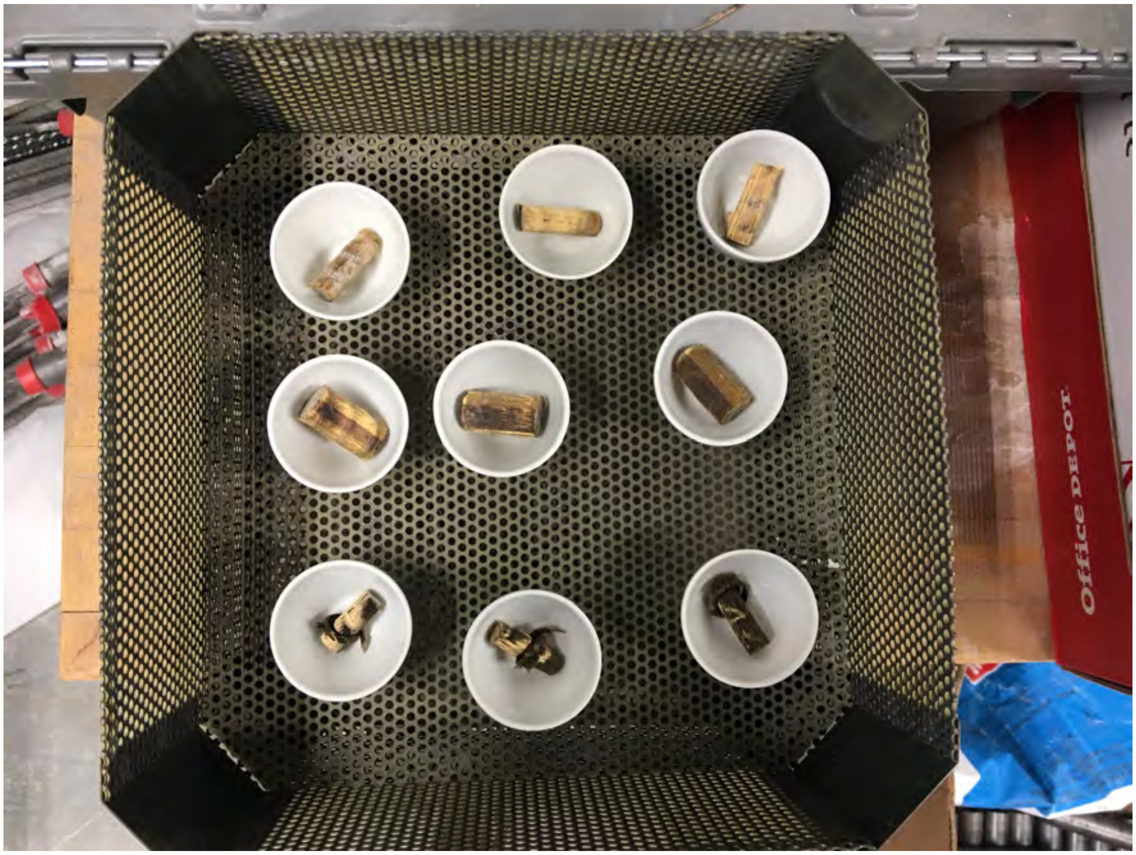


Figure 3.2: Fiber content specimen of GP HP # 3, 5 after test

appearance of the rebars after the test were similar for all rebar types.

3.4 Moisture Absorption

The graph plotted in Figure 3.3 represents weight change of the rebar specimen stored in distilled water over the entire test period. All the rebar yielded a comparable results except # 3 rebar from Galen with HP resin. All the rebar types did not satisfy the AC454 limitations for the absorption limit of 0 25% in first 24 hours of exposure.

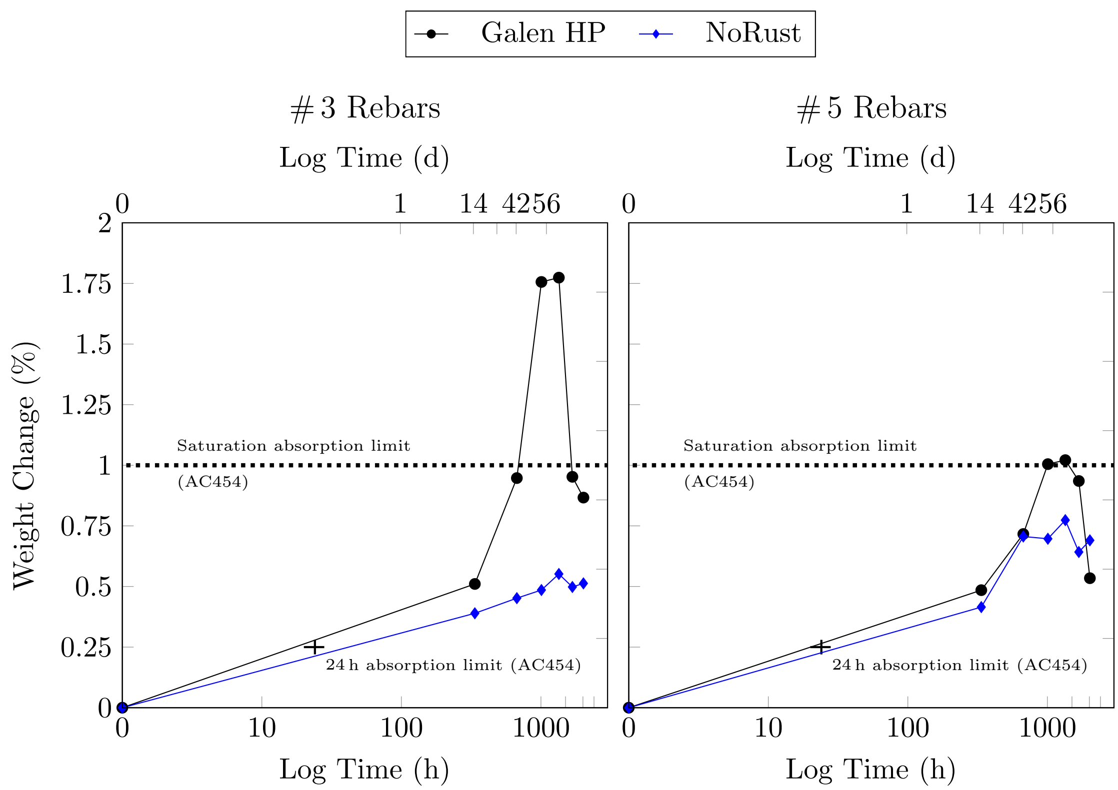


Figure 3.3: Moisture Absorption results of rebars from Galen and No Rust rebar manufacturers

3.5 Horizontal Shear

3.5.1 Load vs. Displacement

The graphs in Figure 3.4, 3.5, and 3.6 compares the load vs. displacement behavior of short span 3 point bending for # 3 and # 5 rebars from all manufacturer. The x-axis of the graph represents the cross-head extension and the y-axis represents the applied load.

The graph in Figure 3.4 show a nearly linear behavior until it reached the ultimate failure load.

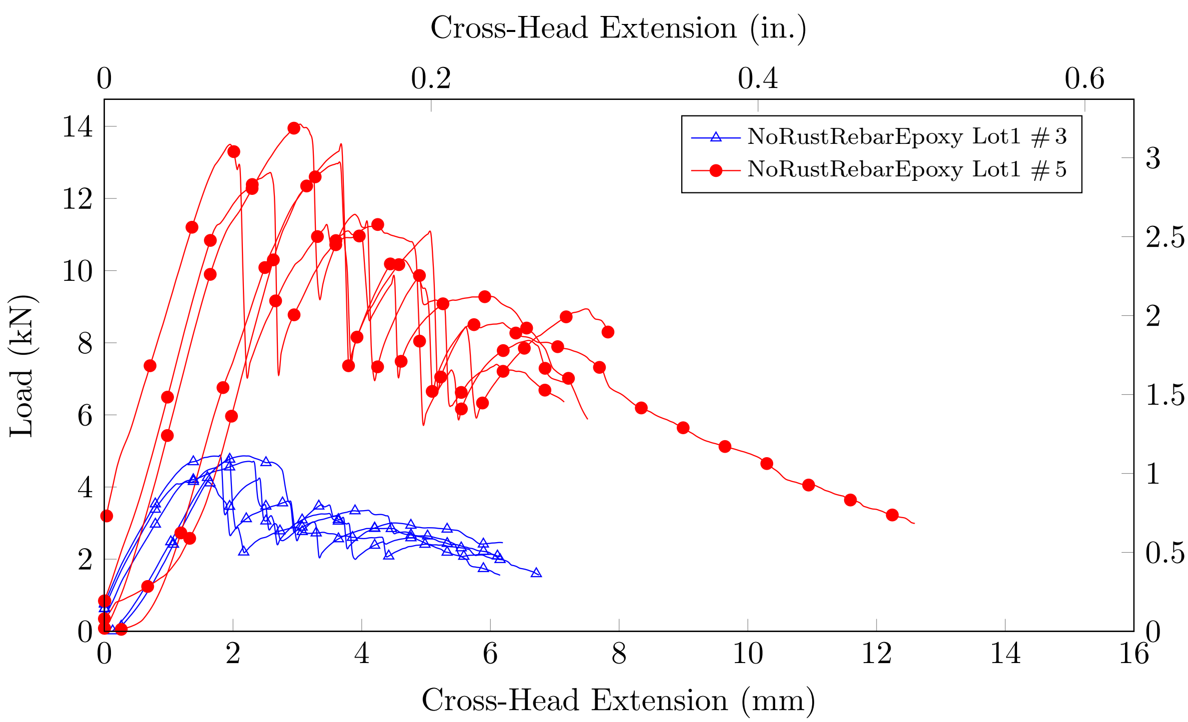


Figure 3.4: Extension vs. Horizontal Shear Load behavior of No Rust rebar Lot 1 size 3 and 5

The graphs shown in Figures 3.5 compares the load vs. displacement behavior of short span 3 point bending of # 3 and # 5 rebars from lot 1 from Galen Panamerica. The graphs show a linear behavior until it reached 90 % of the ultimate failure load.

The graph in Figure 3.5 compares the load vs. displacement behavior of short span 3 point bending of # 3 and # 5 rebars from lot 2 from Galen Panamerica. The graphs show a linear behavior until it reached 90% of the ultimate failure load.

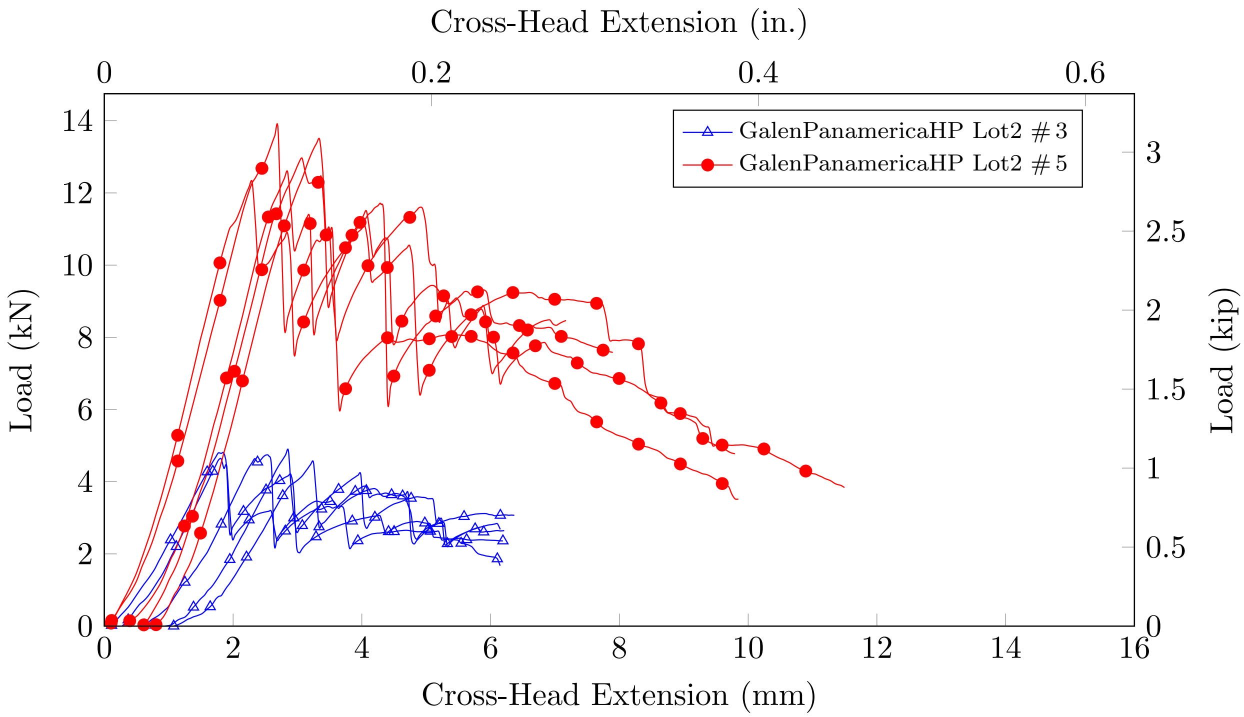


Figure 3.5: Extension vs. Horizontal Shear Load behavior of Galen Panamerica Lot 1 HP rebar size 3 and 5

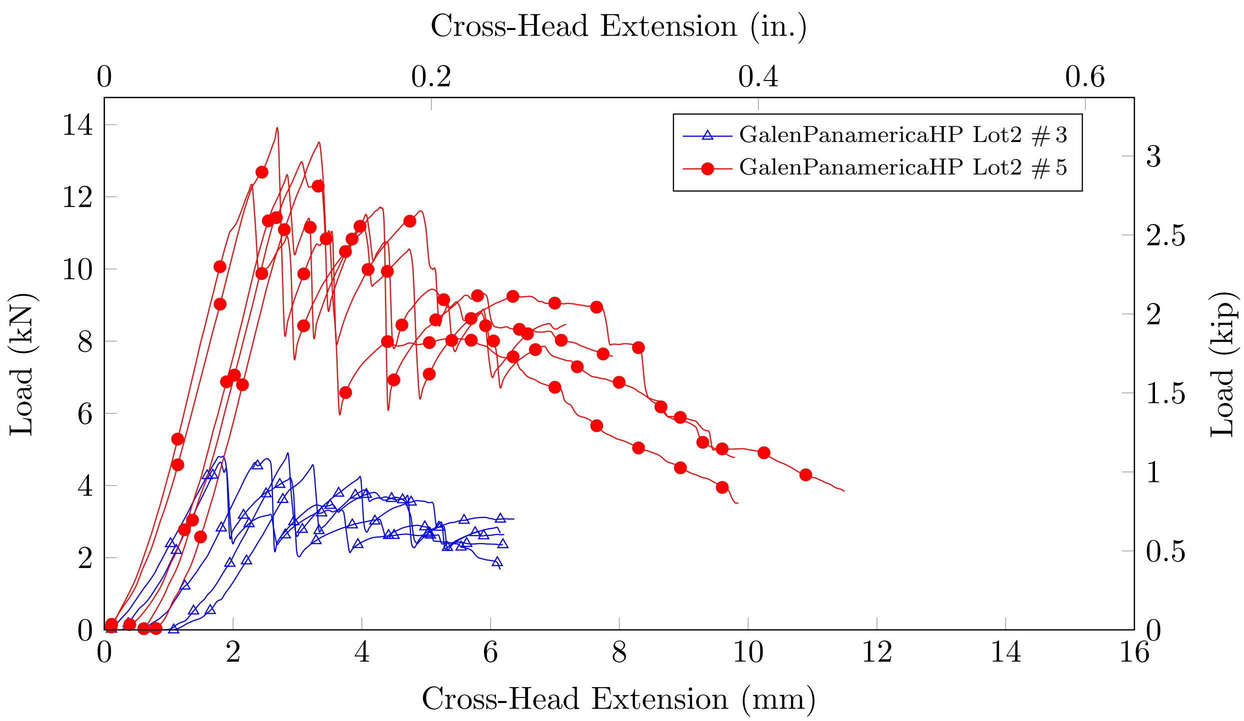


Figure 3.6: Extension vs. Horizontal Shear Load behavior of Galen Panamerica Lot 2 HP rebar size 3 and 5

3.5.2 Stress vs. Displacement

The following graphs in Figures 3.7, 3.8, and 3.9 show the comparison of the stress vs. displacement behavior of short span 3 point bending of # 3 and # 5 rebars from all manufacturer. The x-axis of graph represents the cross-head extension and the y-axis represents the shear stress.

The graph in figure 3.7 show a linear behavior until it reached the ultimate failure load. The

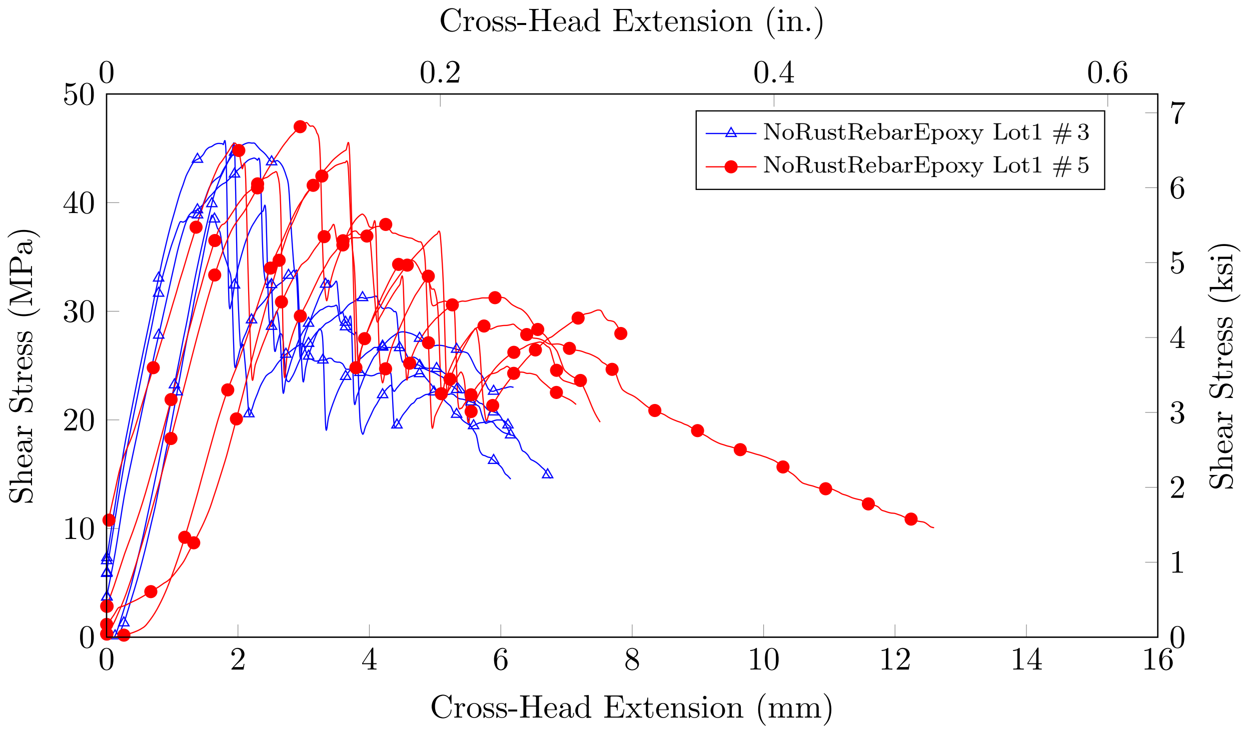


Figure 3.7: Horizontal shear stress vs. Extension behavior of No Rust rebar Lot 1 size 3 and 5

graph in Figure 3.8 compares the stress vs. displacement behavior of short span 3 point bending of # 3 and # 5 rebars from lot 1 from Galen Panamerica. The graph in Figure 3.9 compares the stress vs. displacement behavior of short span 3 point bending of # 3 and # 5 rebars from lot 1 from Galen Panamerica.

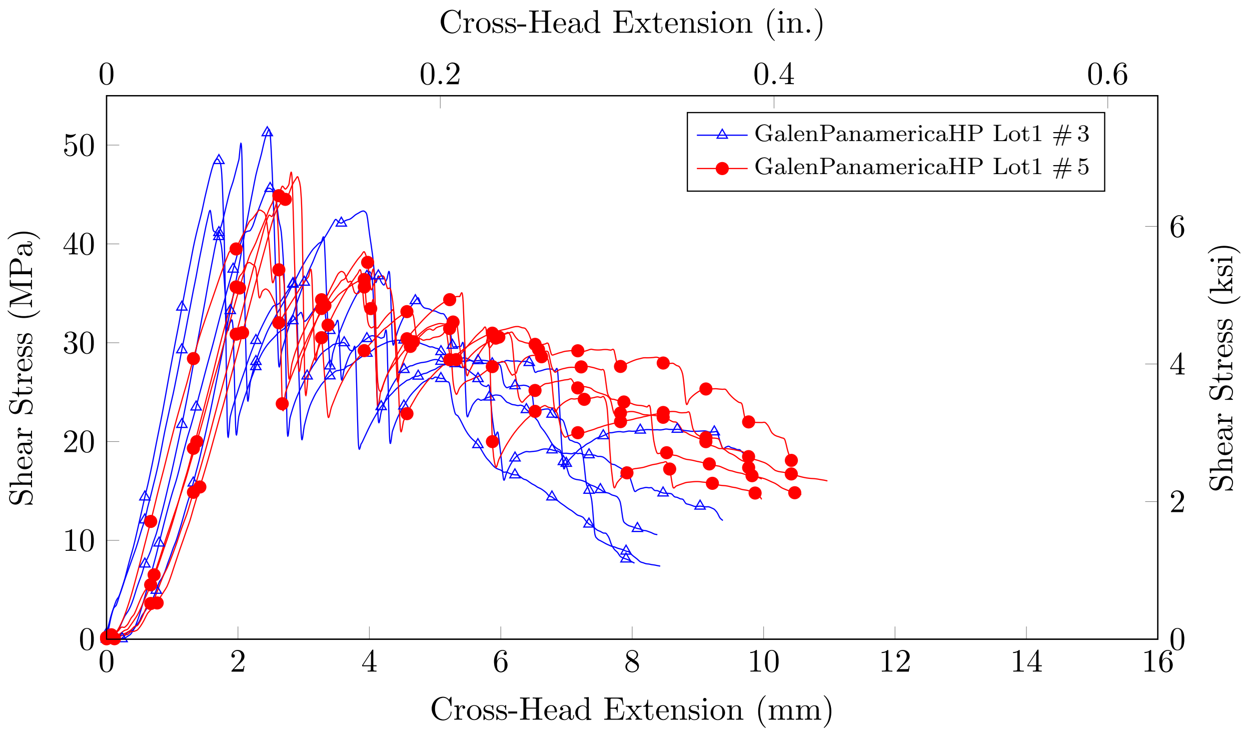


Figure 3.8: Horizontal shear stress vs. Extension behavior of Galen Panamerica Lot 1 HP rebar size 3 and 5

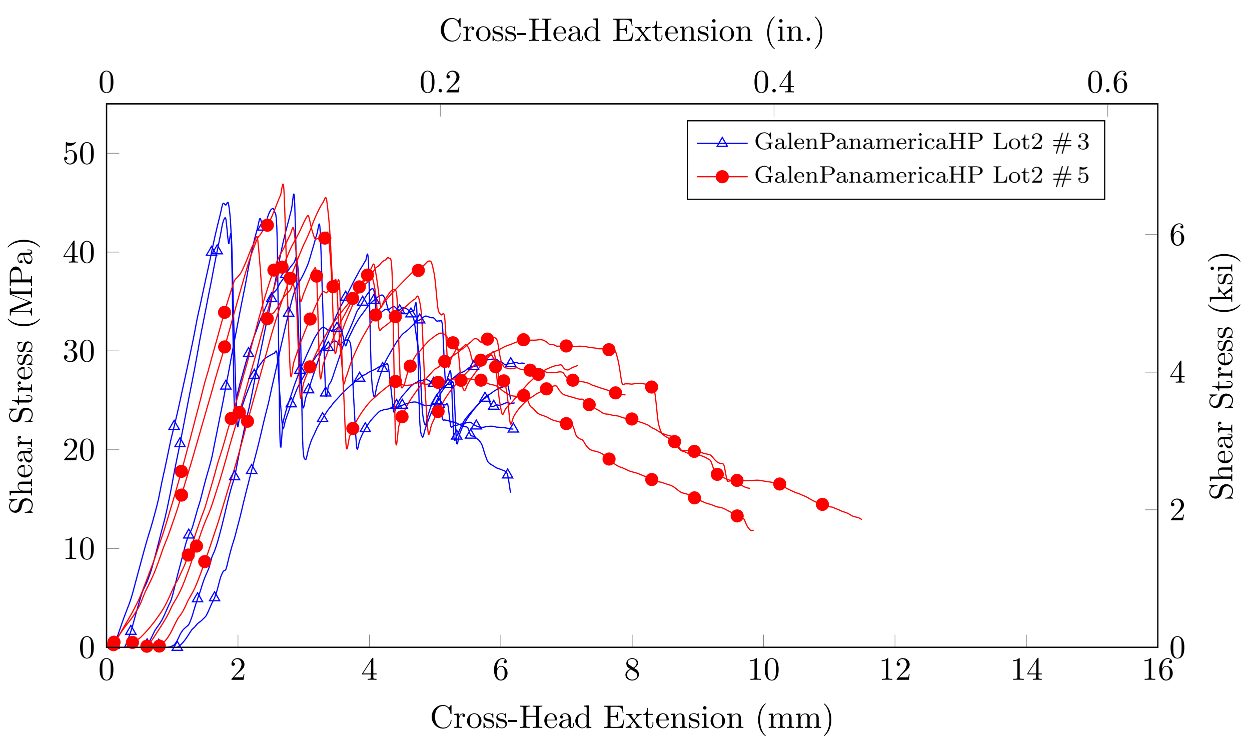


Figure 3.9: Horizontal shear stress vs. Extension behavior of Galen Panamerica Lot 2 HP rebar size 3 and 5

3.6 Modes of Failure

Figure 3.10 shows the failed BFRP specimen after completion of the horizontal shear test.

(a) Galen Panamerica HP # 3,

(b) Galen Panamerica HP # 5

(c) No Rust # 3

(d) No Rust # 5

Figure 3.10: Failure pattern for tested rebar after horizontal shear test

3.7 Summary of Horizontal Shear Strength Properties

The statistical values for the horizontal shear strength properties of the tested products are listed in the following Table 3.2. A total 30 specimen, five per each manufacture and each size were tested in total. An average of five specimen was calculated and shown in the table. All the BFRP rebar samples are satisfying the minimum GFRP criteria for horizontal shear strength which is shown in Tables 2.1, and 2.2.

Table 3.2: Horizontal Shear test statistical values for each sample group (US Customary Units)

Exposure		Sample Group				Statistical Values				
						Shear Stress				
Age d	T °C	Manuf. Type	Resin Type	Size #	Lot No.	$\wedge$ ksi	$\vee$ ksi	μ ksi	σ ksi	CV %
0	23	GalenPanamerica	HP	3	1	6.4	7.5	7.0	0.5	6.57
0	23	GalenPanamerica	HP	3	2	6.2	6.7	6.5	0.2	2.79
0	23	GalenPanamerica	HP	5	1	5.6	6.8	6.4	0.5	7.98
0	23	GalenPanamerica	HP	5	2	6.0	6.8	6.4	0.3	4.99
0	23	NoRustRebar	Epoxy	3	1	5.8	6.7	6.4	0.4	5.90
0	23	NoRustRebar	Epoxy	5	1	6.2	6.9	6.5	0.3	3.89

3.8 Transverse Shear

3.8.1 Load vs. Displacement

The graphs plotted in Figures 3.11, 3.12, and 3.13 compares the load vs. displacement behavior of short span 3 point bending of # 3 and # 5 rebars from all manufacturer. The x-axis of graph represents the cross-head extension and the y-axis represents the applied load.

The graph in figure 3.11 shows a linear behavior until it reached the ultimate failure load.

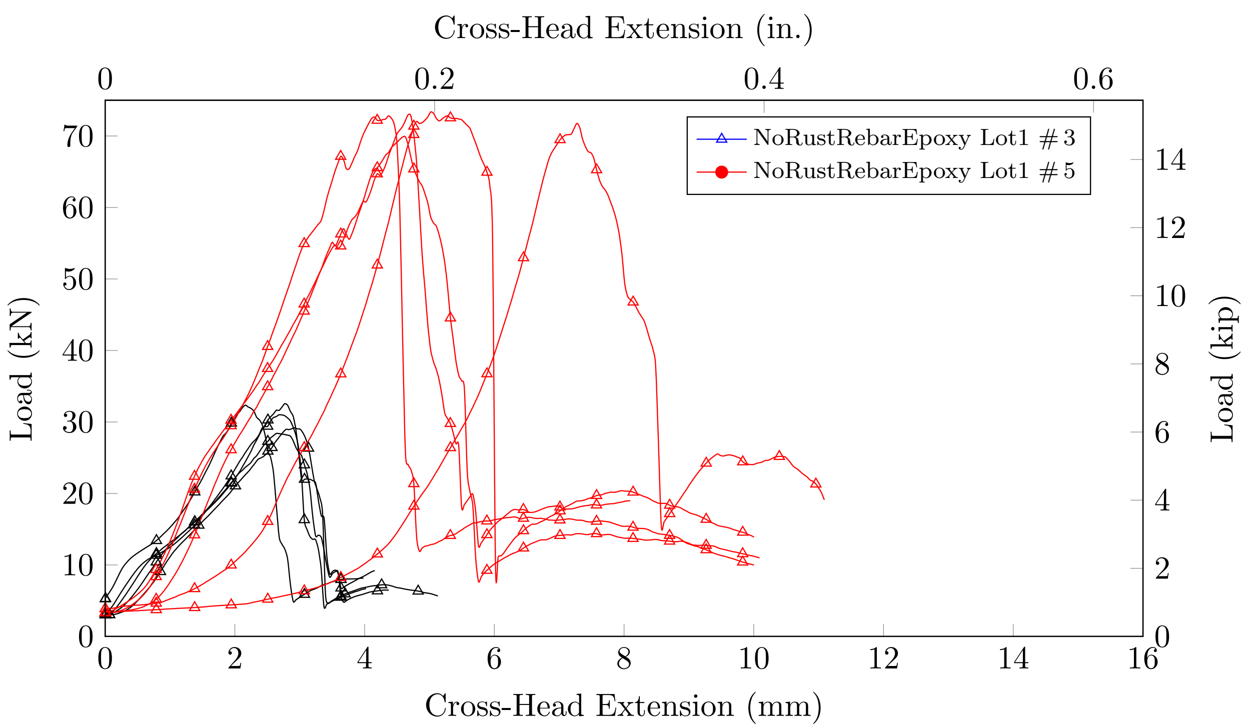


Figure 3.11: Extension vs. Transverse Shear Load behavior of No Rust rebar Lot 1 size 3 and 5

The graph in Figure 3.12 compares the load vs. displacement behavior of short span 3 point bending of # 3 and # 5 rebars from lot 1 from Galen Panamerica. The graphs show a linear behavior until it reached 90% of the ultimate failure load.

The graph in Figure 3.13 compares the load vs. displacement behavior of short span 3 point bending of # 3 and # 5 rebars from lot 2 from Galen Panamerica. The graphs show a linear behavior until it reached 90% of the ultimate failure load.

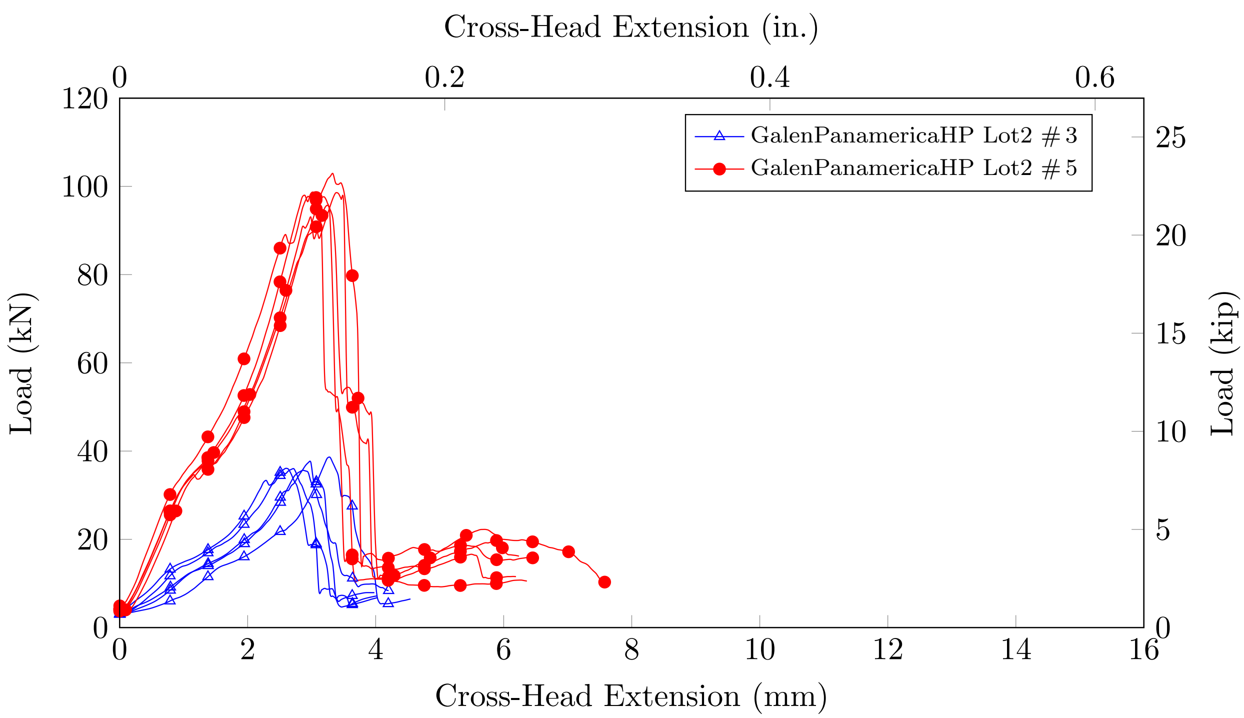


Figure 3.12: Extension vs. Transverse Shear Load behavior of Galen Panamerica Lot 1 HP rebar size 3 and 5

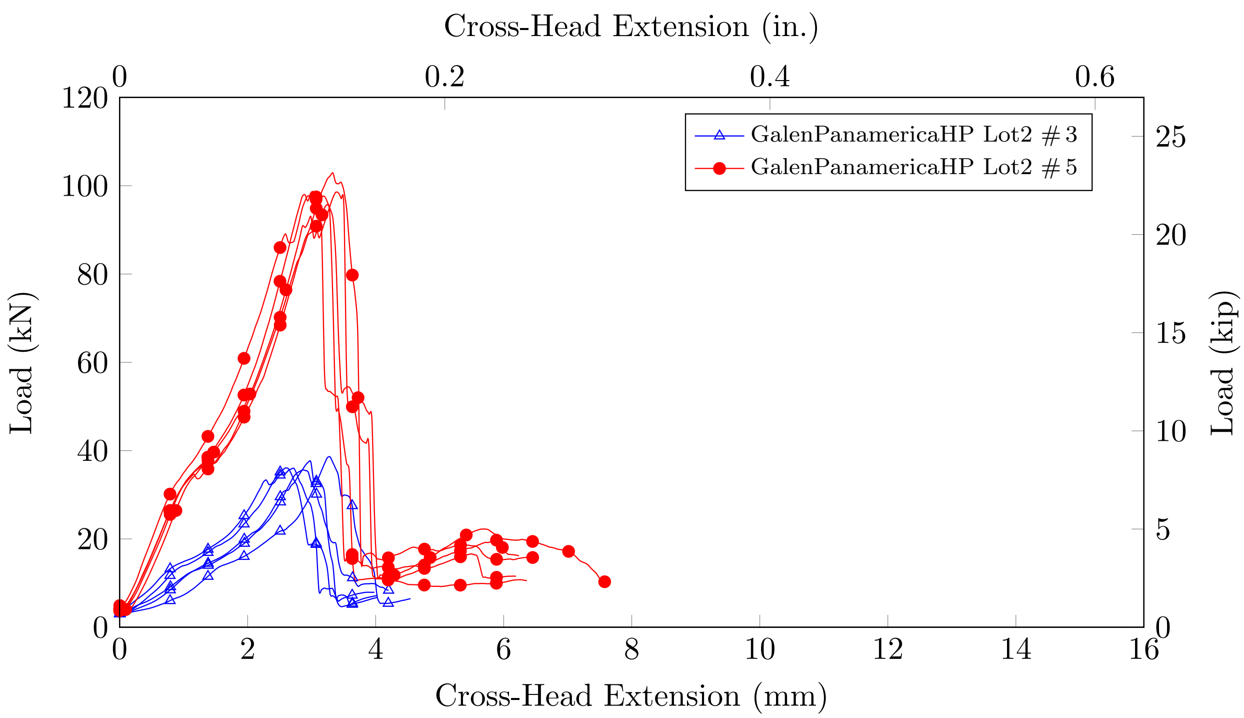


Figure 3.13: Extension vs. Transverse Shear Load behavior of Galen Panamerica Lot 2 HP rebar size 3 and 5

3.8.2 Stress vs. Displacement

The graphs in Figures 3.14, 3.15, and 3.16 compares the stress vs. displacement behavior of short span 3 point bending of # 3 and # 5 rebars from all rebar manufacturer. The x-axis of graph represents the cross-head extension and the y-axis represents the shear stress.

The graph in Figure 3.14 show a linear behavior until it reached the ultimate failure load.

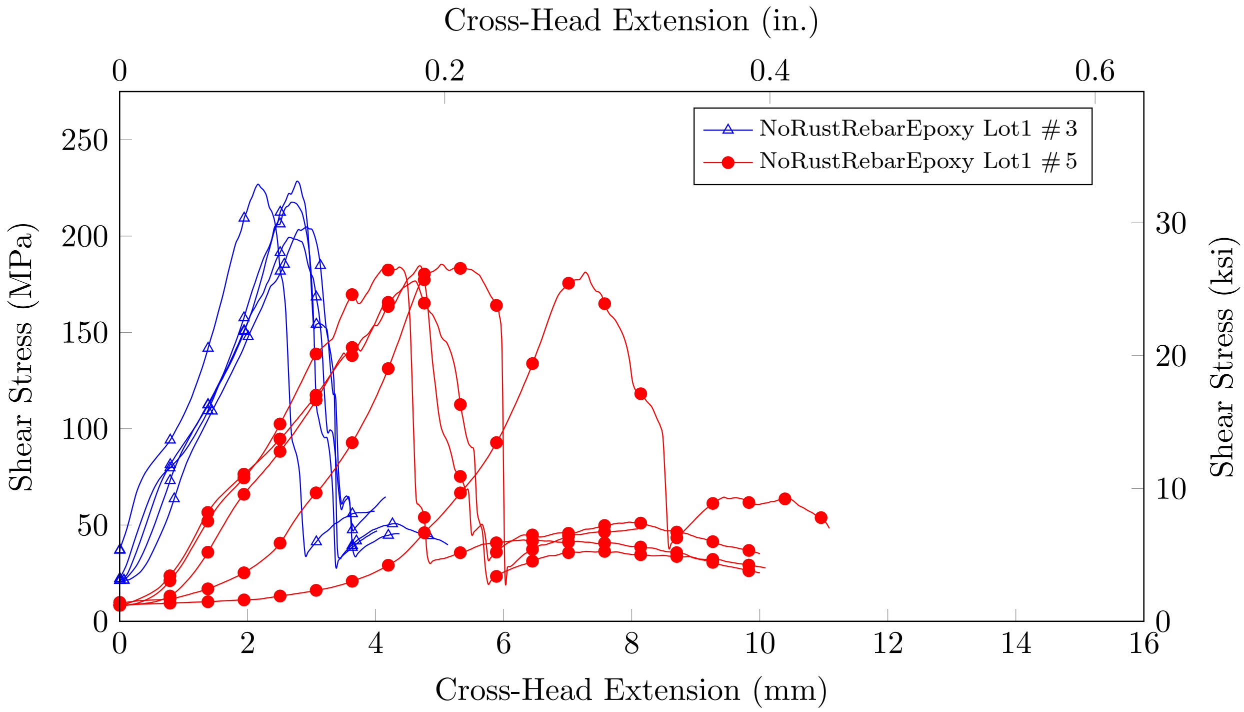


Figure 3.14: Transverse shear stress vs. Extension behavior of No Rust rebar Lot 1 size 3 and 5

The graph in Figure 3.15 compares the stress vs. displacement behavior of short span 3 point bending of # 3 and # 5 rebars from lot 1 from Galen Panamerica. The graphs show a linear behavior until it reached the ultimate failure load.

The graph in Figure 3.16 compares the stress vs. displacement behavior of short span 3 point bending of # 3 and # 5 rebars from lot 2 from Galen Panamerica. The graphs show a linear behavior until it reached the ultimate failure load.

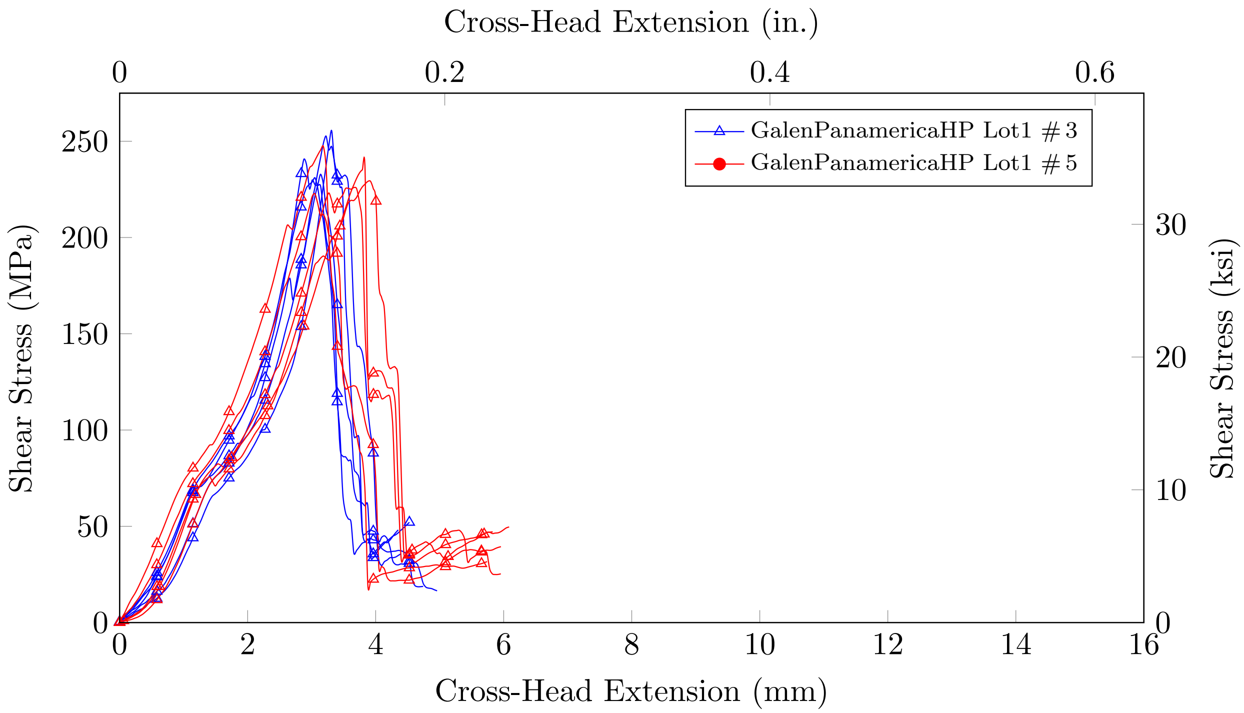


Figure 3.15: Transverse shear stress vs. Extension behavior of Galen Panamerica Lot 1 HP rebar size 3 and 5

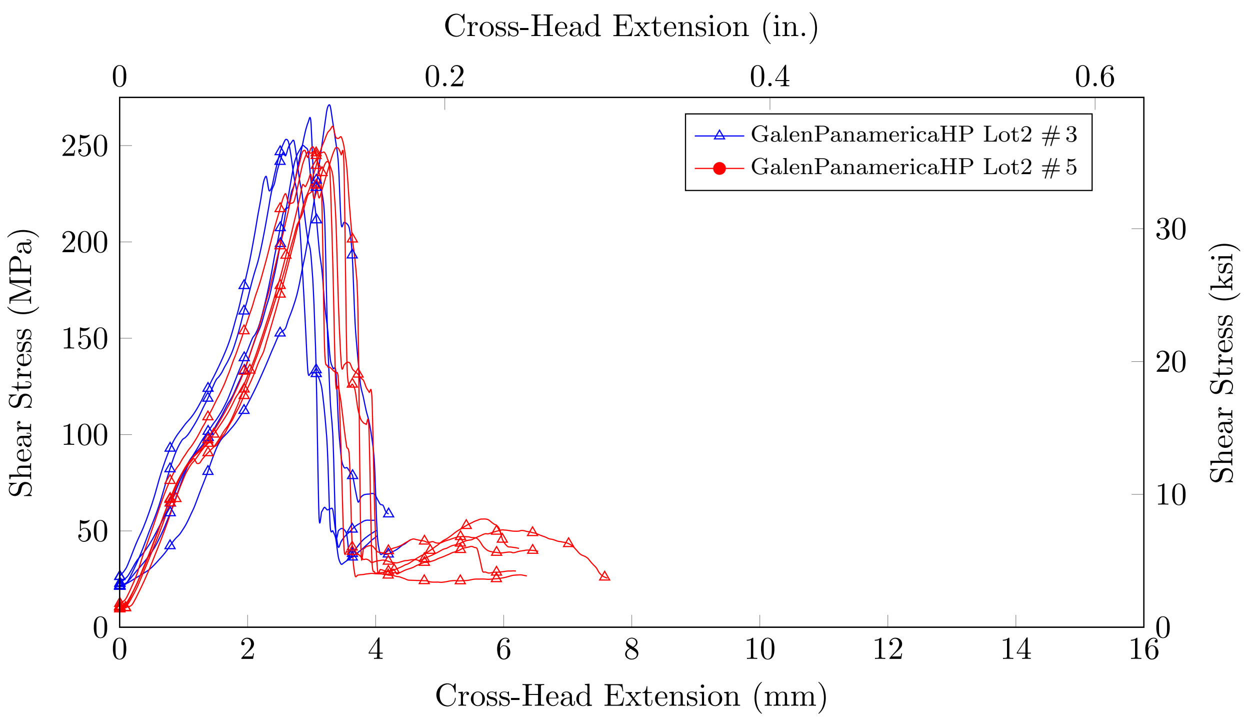
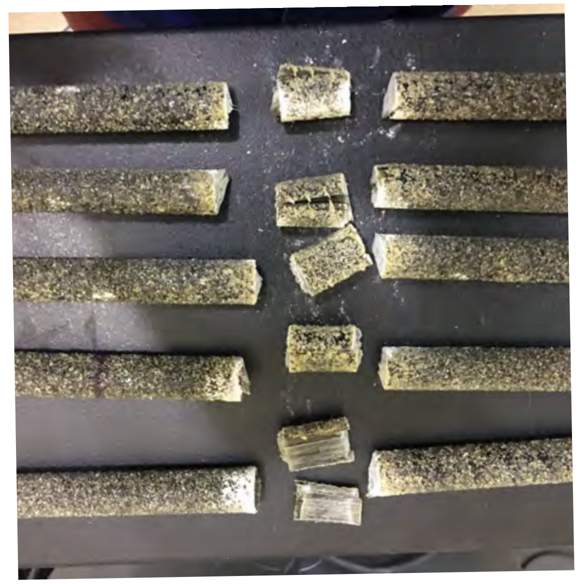


Figure 3.16: Transverse shear stress vs. Extension behavior of Galen Panamerica Lot 2 HP rebar size 3 and 5

3.9 Modes of Failure

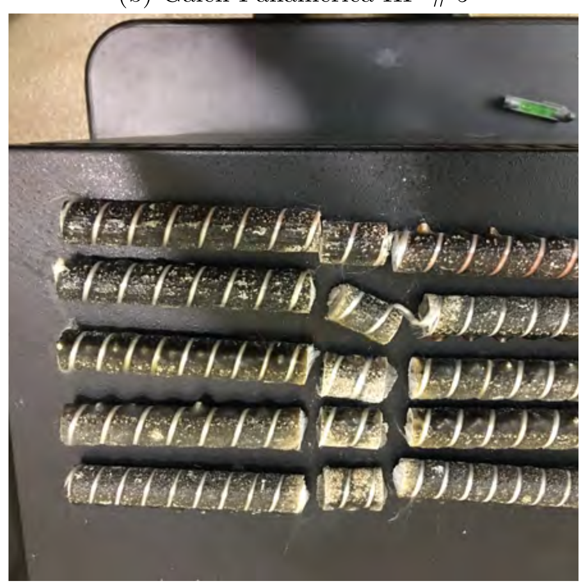
The Figure 3.17 in this section shows the pictures of failed BFRP specimen due to transverse shear load.

(a) Galen Panamerica HP #3



(b) Galen Panamerica HP #5

(c) No Rust #3



(d) No Rust #5

Figure 3.17: Failure pattern for tested rebar after horizontal shear test

3.10 Summary of Transverse Shear Properties

The statistical values for the transverse shear strength properties of the tested products are listed in the following Table 3.3. A total 30 specimen, five per each manufacture and each size were tested in total. An average of five specimen was calculated and shown in the table. It can be seen in Tables 2.1, and 2.2 that all the BFRP rebar samples are satisfying the minimum required criteria for GFRP transverse shear stress.

Table 3.3: Transverse Shear test statistical values for each sample group (US Customary Units)

Exposure		Sample Group				Statistical Values				
						Shear Stress				
Age d	T °C	Manuf. Type	Resin Type	Size #	Lot No.	$\wedge$ ksi	$\vee$ ksi	μ ksi	σ ksi	CV %
0	23	GalenPanamerica	HE	3	1	28.4	30.6	29.4	1.0	3.39
0	23	GalenPanamerica	HP	3	1	33.6	37.5	35.2	1.6	4.64
0	23	GalenPanamerica	HP	3	2	36.5	39.8	37.7	1.4	3.71
0	23	GalenPanamerica	HP	5	1	32.4	35.9	33.7	1.4	4.14
0	23	GalenPanamerica	HP	5	2	35.3	38.0	36.5	1.0	2.71
0	23	NoRustRebar	Epoxy	3	1	29.1	33.2	31.4	1.9	6.00
0	23	NoRustRebar	Epoxy	5	1	25.7	26.9	26.5	0.5	1.94

3.11 Tensile Test

The obtained and processed data during the tensile strength test are explained in this section. The following graphs in Figures 3.18, and 3.19 show the load vs. displacement and stress vs. strain behavior of Galen HP rebar.

3.11.1 Load vs. Displacement Behavior

The graphs in the Figure 3.19 compare the load vs .displacement behavior of rebar. The x-axis of graph represents the cross-head extension and the y-axis represents the applied load.

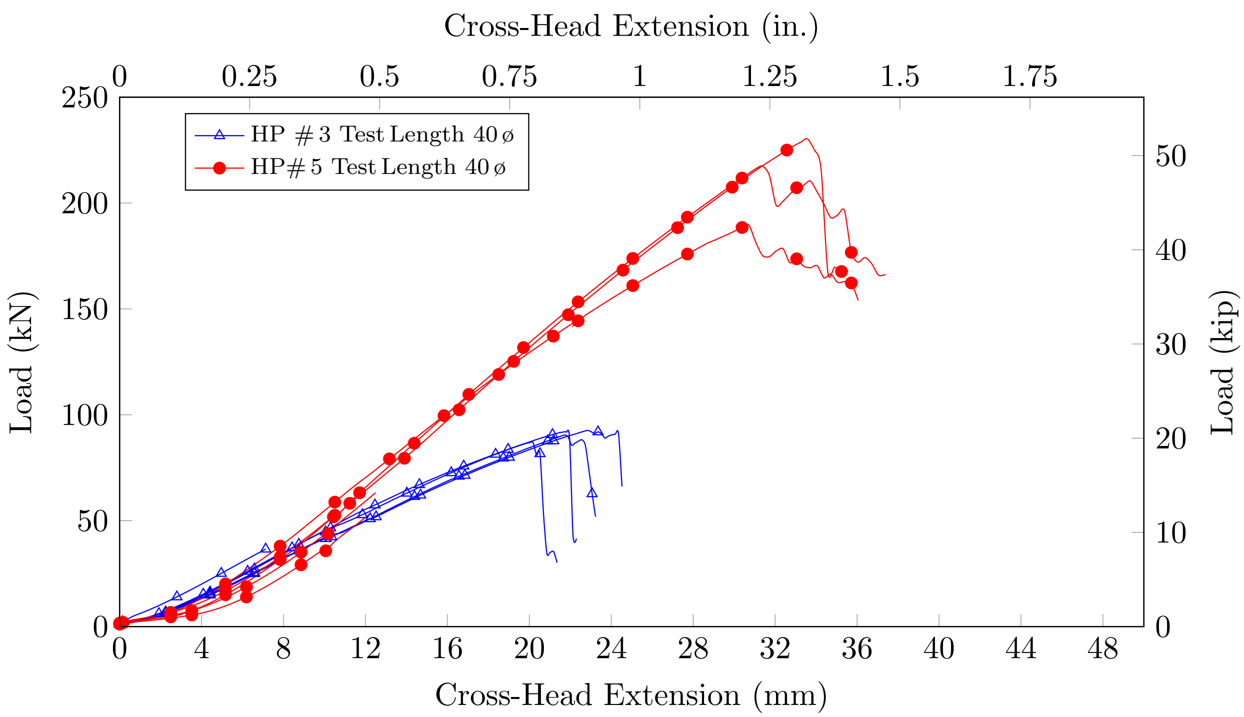


Figure 3.18: Tensile strengt vs. Displacement behavior of Galen Panamerica Lot 1 HP rebar size 3 and 5

3.11.2 Stress vs. Strain Behavior

The graphs in the Figure 3.19 compare the stress vs .strain behavior of rebar. The x-axis of graph represents the applied stress and the y-axis represents the strain in rebar.

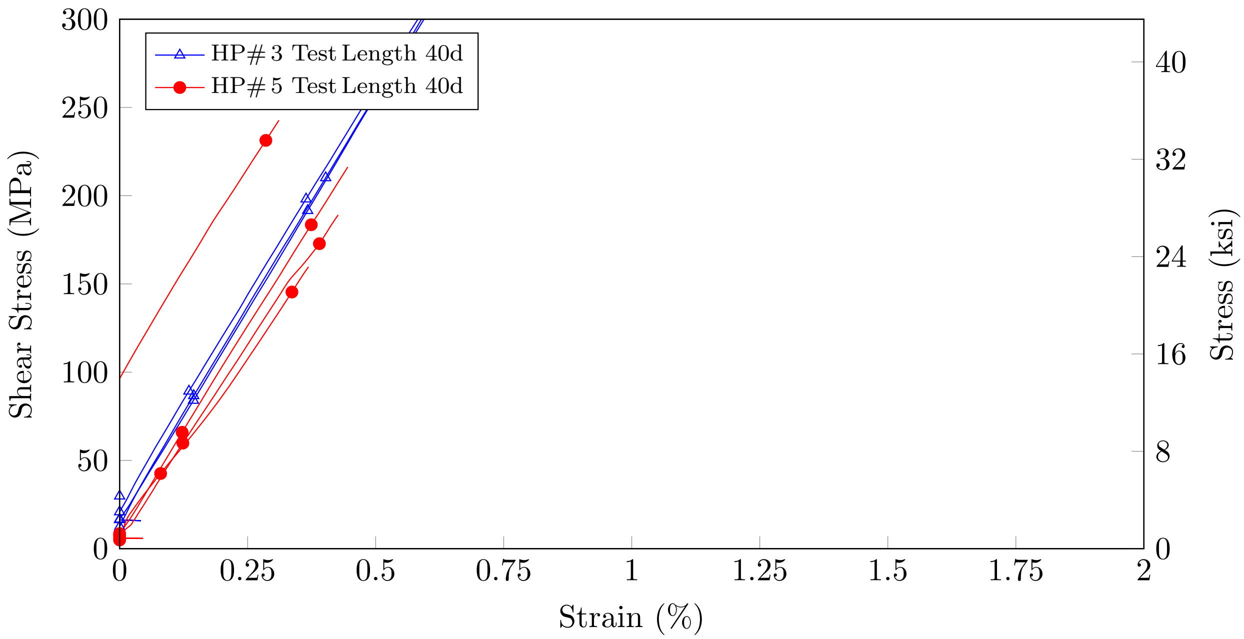


Figure 3.19: Tensile Stress vs. Strain behavior of Galen Panamerica Lot 1 HP rebar size 3 and 5

3.12 Modes of Failure

According to ASTM D 7205, three different failure modes may occur during a tensile strength test. The first and expected one is the tensile rupture outside of the anchor pipes. Due to insufficient sample preparation or test procedure issues, two more failure modes may occur. The rebar could slip within the grouted anchor (rebar slippage) or the anchor could slip out of the fixture/grips (anchor slippage). Nevertheless, the last two described failure modes lead to unusable results when defining the material characteristics. However, for this research project, no specimen failed due to rebar or anchor slippage. Hence, tensile rupture of the BFRP rebar was the recorded failure mode for each bar that was tested.

Figure 3.20 show the # 3 rebar specimens from Galen Panamerica for resin type HP. Similarly, Figure 3.21 show the failed specimens for the # 5 rebars, for the same manufacturer and the resin type.

Figure 3.20: GP HP # 3, final failure pattern after tensile test

Figure 3.21: GP HP # 5, final failure pattern after tensile test

All Galen Panamerica specimens, regardless of the resin type, failed in a similar manner. After the peak load was reached a bundle of outer fibers failed and brushed out over the entire free specimen length. After the first load-drop, this behavior continued at each additional sudden load drop until delamination reached the center of the rebar, and the specimen eventually separated into two parts along the rebar axis.

3.13 Summary of Tensile Properties

The statistical values for the tensile properties of all products are listed in the following Table 3.4. A total of 10 specimen, 5 per rebar size were tested and the results were analyzed. An average of statistical values of all 5 specimen is shown in Table 3.4

Table 3.4: Tensile strength test statistical values for each sample group (US Customary Units)

Exposure		Sample Group					Statistical Values									
							Tensile Strength					Elastic Modulus				
Age d	T °C	Manuf. Type	Resin Type	Size #	Lot No.	FreeSpecimenLength Times Dia	$\wedge$ ksi	$\vee$ ksi	μ ksi	σ ksi	CV %	$\wedge$ ksi	$\vee$ ksi	μ ksi	σ ksi	CV %
0	23	Galen Panamerica	HP	3	1	40	178.2	189.3	183.8	4.8	0.03	8	8	8	0	0.0
0	23	Galen Panamerica	HP	5	1	40	139.5	171.7	161.2	12.9	0.08	7	8	8	1	0.1

3.14 BFRP Rebar Performance

This section summarizes the material performance of the evaluated BFRP rebar samples based on the acceptance criteria for glass FRP rebars as shown in Tables 2.1, and 2.2 based on three different standards. Table 3.5 details the obtained results and the acceptance criteria for # 3 of Galen Panamerica rebar. It can be seen that the cross section properties, and fiber content properties of

Table 3.5: Acceptance criteria for Galen Panamerica rebar # 3

			Per diameter		FDOT 932-3/2017		AC454		ASTM D 7957	
Test Method	Test Description	Unit	Nom.	Exp.	Criteria	✓/✗	Criteria	✓/✗	Criteria	✓/✗
ASTM D 792	Measured Cross Sectional Area	in.^{2}	0.110	0.109	0.104 – 0.161	✓	0.104 – 0.161	✓	0.104 – 0.161	✓
ASTM D 2584	Fiber Content	% wt.	82.035	82.035	$\geqslant 70$	✓	$\geqslant 70$	✓	$\geqslant 70$	✓
ASTM D 570	Moist. Absorption short term @50 °C	%	0.26	0.26	$\leqslant 0.25$	✗	$\leqslant 0.25$	✗	$\leqslant 0.25$	✗
ASTM D 570	Moist. Absorption long term @50 °C	%	1.77	1.77	$\leqslant 1.0$	✗	n/a	n/a	$\leqslant 1.0$	✗
ASTM D 7205	Min. Guaranteed Tensile Load	kip	19.68	19.68	$\geqslant 13.2$	✓	$\geqslant 13.2$	✓	$\geqslant 13.2$	✓
ASTM D 7205	Min. Guaranteed Tensile Strength	ksi	163.38	163.38	n/a	n/a	n/a	n/a	n/a	n/a
ASTM D 7205	Tensile Modulus	ksi	6,933	6,933	$\geqslant 6,500$	✓	$\geqslant 6,500$	✓	$\geqslant 6,500$	✓
ASTM D 7205	Max. Strain	%	2.34	2.34	n/a	n/a	n/a	n/a	n/a	n/a
ASTM D 7617	Min. Guaranteed Transverse Shear	ksi	33.59	33.59	$\geqslant 22$	✓	$\geqslant 22$	✓	$\geqslant 19$	✓
ASTM D 4475	Horizontal Shear Stress	ksi	6.38	6.38	n/a	n/a	$\geqslant 5.5$	✓	n/a	n/a
ACI440. 3 R,B.3	Bond-to-concrete strength	ksi	TBD	TBD	$\geqslant 1.1$	n/a	$\geqslant 1.1$	n/a	$\geqslant 1.1$	n/a

the rebar were in the acceptance range, where as the moisture absorption properties of the rebar exceeded. The rebar surpassed all acceptance ranges for all evaluated strength parameters. The following Table 3.6 shows that # 5 rebar of Galen Panamerica were within the acceptance range for cross section, fiber content, and shear properties, where as the modulus of elasticity was lower than the required minimum. Tables 3.7 and 3.8 demonstrate that both No Rust rebar sizes met or exceeded the acceptance criteria. The Tensile strength and bond-to-concrete characteristics for the rebar samples are still to be evaluated. The acceptance criteria for fiber content properties of # 3 and # 5 rebar samples from Pultrall manufacturer is shown in Table 3.9 and Table 3.10 respectively. Both rebar sizes measured fiber content values above the minimum 70 % criteria. A complete performance evaluation of these rebar samples are still underway.

Table 3.6: Acceptance criteria for Galen Panamerica rebar # 5

			Per diameter		FDOT 932-7/2017		AC454		ASTM D 7957	
Test Method	Test Description	Unit	Nom.	Exp.	Criteria	✓/✗	Criteria	✓/✗	Criteria	✓/✗
ASTM D 792	Measured Cross Sectional Area	$in.^2$	0.307	0.353	0.288 – 0.388	✓	0.288 – 0.388	✓	0.288 – 0.388	✓
ASTM D 2584	Fiber Content	% wt.	81.8	81.8	⩾ 70	✓	⩾ 70	✓	⩾ 70	✓
ASTM D 570	Moist. Absorption short term @50 °C	%	0.25	0.25	⩽ 0.25	✓	⩽ 0.25	✓	⩽ 0.25	✓
ASTM D 570	Moist. Absorption long term @50 °C	%	1.17	1.17	⩽ 1.0	✗	n/a	n/a	⩽ 1.0	✗
ASTM D 7205	Min. Guaranteed Tensile Load	kip	42.82	42.82	⩾ 29.1	✓	⩾ 32.2	✓	⩾ 29.1	✓
ASTM D 7205	Min. Guaranteed Tensile Strength	ksi	119.6	121.16	n/a	n/a	n/a	n/a	n/a	n/a
ASTM D 7205	Modulus	ksi	5710	5836	⩾ 6, 500	✗	⩾ 6, 500	✗	⩾ 6, 500	✗
ASTM D 7205	Max. Strain	%	2.12	2.07	n/a	n/a	n/a	n/a	n/a	n/a
ASTM D 7617	Min. Guaranteed Transverse Shear	ksi	32.38	28.115	⩾ 22	✓	⩾ 22	✓	⩾ 19	✓
ASTM D 4475	Horizontal Shear Stress	ksi	5.56	4.826	n/a	n/a	⩾ 5.5	✗	n/a	n/a
ACI440. 3 R,B.3	Bond-to-concrete strength	ksi	TBD	TBD	⩾ 1.1	n/a	⩾ 1.1	n/a	⩾ 1.1	n/a

Table 3.7: Acceptance criteria for No Rust rebar # 3

			Per diameter		FDOT 932-3/2017		AC454		ASTM D 7957	
Test Method	Test Description	Unit	Nom.	Exp.	Criteria	✓/✗	Criteria	✓/✗	Criteria	✓/✗
ASTM D 792	Measured Cross Sectional Area	$in.^2$	TBD	TBD	0.104 – 0.161	n/a	0.104 – 0.161	n/a	0.104 – 0.161	n/a
ASTM D 2584	Fiber Content	% wt.	75.17	75.17	⩾ 70	✓	⩾ 70	✓	⩾ 70	✓
ASTM D 570	Moist. Absorption short term @50 °C	%	0.2	0.2	⩽ 0.25	✓	⩽ 0.25	✓	⩽ 0.25	✓
ASTM D 570	Moist. Absorption long term @50 °C	%	0.55	0.55	⩽ 1.0	✓	n/a	n/a	⩽ 1.0	✓
ASTM D 7205	Min. Guaranteed Tensile Load	kip	TBD	TBD	⩾ 13.2	n/a	⩾ 13.2	n/a	⩾ 13.2	n/a
ASTM D 7205	Min. Guaranteed Tensile Strength	ksi	TBD	TBD	n/a	n/a	n/a	n/a	n/a	n/a
ASTM D 7205	Tensie Modulus	ksi	TBD	TBD	⩾ 6, 500	n/a	⩾ 6, 500	n/a	⩾ 6, 500	n/a
ASTM D 7205	Max. Strain	%	TBD	TBD	n/a	n/a	n/a	n/a	n/a	n/a
ASTM D 7617	Min. Guaranteed Transverse Shear	ksi	29.07	n/a	⩾ 22	✓	⩾ 22	✓	⩾ 19	✓
ASTM D 4475	Horizontal Shear Stress	ksi	5.75	n/a	n/a	n/a	⩾ 5.5	✓	n/a	n/a
ACI440. 3 R,B.3	Bond-to-concrete strength	ksi	TBD	TBD	⩾ 1.1	n/a	⩾ 1.1	n/a	⩾ 1.1	n/a

Table 3.8: Acceptance criteria for No Rust rebar # 5

			Per diameter		FDOT 932-3/2017		AC454		ASTM D 7957	
Test Method	Test Description	Unit	Nom.	Exp.	Criteria	✓/✗	Criteria	✓/✗	Criteria	✓/✗
ASTM D 792	Measured Cross Sectional Area	$in.^2$	TBD	TBD	0.288 – 0.388	n/a	0.288 – 0.388	n/a	0.288 – 0.388	n/a
ASTM D 2584	Fiber Content	% wt.	78.4	78.4	$\geqslant 70$	✓	$\geqslant 70$	✓	$\geqslant 70$	✓
ASTM D 570	Moist. Absorption short term @50 °C	%	0.18	0.18	$\leqslant 0.25$	✓	$\leqslant 0.25$	✓	$\leqslant 0.25$	✓
ASTM D 570	Moist. Absorption long term @50 °C	%	0.77	0.77	$\leqslant 1.0$	✓	n/a	n/a	$\leqslant 1.0$	✓
ASTM D 7205	Min. Guaranteed Tensile Load	kip	TBD	TBD	$\geqslant 29.1$	n/a	$\geqslant 32.2$	n/a	$\geqslant 29.1$	n/a
ASTM D 7205	Min. Guaranteed Tensile Strength	ksi	TBD	TBD	n/a	n/a	n/a	n/a	n/a	n/a
ASTM D 7205	Tensile Modulus	ksi	TBD	TBD	$\geqslant 6,500$	n/a	$\geqslant 6,500$	n/a	$\geqslant 6,500$	n/a
ASTM D 7205	Max. Strain	%	TBD	TBD	n/a	n/a	n/a	n/a	n/a	n/a
ASTM D 7617	Min. Guaranteed Transverse Shear	ksi	25.67	TBD	$\geqslant 22$	✓	$\geqslant 22$	✓	$\geqslant 19$	✓
ASTM D 4475	Horizontal Shear Stress	ksi	6.22	TBD	n/a	n/a	$\geqslant 5.5$	✓	n/a	n/a
ACI440. 3 R,B.3	Bond-to-concrete strength	ksi	TBD	TBD	$\geqslant 1.1$	n/a	$\geqslant 1.1$	n/a	$\geqslant 1.1$	n/a

Table 3.9: Acceptance criteria for Pultrall rebar # 3

			Per diameter		FDOT 932-3/2017		AC454		ASTM D 7957	
Test Method	Test Description	Unit	Nom.	Exp.	Criteria	✓/✗	Criteria	✓/✗	Criteria	✓/✗
ASTM D 792	Measured Cross Sectional Area	$in.^2$	TBD	TBD	0.104 – 0.161	n/a	0.104 – 0.161	n/a	0.104 – 0.161	n/a
ASTM D 2584	Fiber Content	% wt.	83.3	83.3	$\geqslant 70$	✓	$\geqslant 70$	✓	$\geqslant 70$	✓
ASTM D 570	Moist. Absorption short term @50 °C	%	TBD	TBD	$\leqslant 0.25$	n/a	$\leqslant 0.25$	n/a	$\leqslant 0.25$	n/a
ASTM D 570	Moist. Absorption long term @50 °C	%	TBD	TBD	$\leqslant 1.0$	n/a	n/a	n/a	$\leqslant 1.0$	n/a
ASTM D 7205	Min. Guaranteed Tensile Load	kip	TBD	TBD	$\geqslant 13.2$	n/a	$\geqslant 13.2$	n/a	$\geqslant 13.2$	n/a
ASTM D 7205	Min. Guaranteed Tensile Strength	ksi	TBD	TBD	n/a	n/a	n/a	n/a	n/a	n/a
ASTM D 7205	Tensile Modulus	ksi	TBD	TBD	$\geqslant 6,500$	n/a	$\geqslant 6,500$	n/a	$\geqslant 6,500$	n/a
ASTM D 7205	Max. Strain	%	TBD	TBD	n/a	n/a	n/a	n/a	n/a	n/a
ASTM D 7617	Min. Guaranteed Transverse Shear	ksi	TBD	TBD	$\geqslant 22$	n/a	$\geqslant 22$	n/a	$\geqslant 19$	n/a
ASTM D 4475	Horizontal Shear Stress	ksi	TBD	TBD	n/a	n/a	$\geqslant 5.5$	n/a	n/a	n/a
ACI440. 3 R,B.3	Bond-to-concrete strength	ksi	TBD	TBD	$\geqslant 1.1$	n/a	$\geqslant 1.1$	n/a	$\geqslant 1.1$	n/a

Table 3.10: Acceptance criteria for Pultrall rebar # 5

			Per diameter		FDOT 932-3/2017		AC454		ASTM D 7957	
Test Method	Test Description	Unit	Nom.	Exp.	Criteria	✓/✗	Criteria	✓/✗	Criteria	✓/✗
ASTM D 792	Measured Cross Sectional Area	in.^{2}	TBD	TBD	0.288 – 0.388	n/a	0.288 – 0.388	n/a	0.288 – 0.388	n/a
ASTM D 2584	Fiber Content	% wt.	82.28	82.28	$\geqslant$ 70	✓	$\geqslant$ 70	✓	$\geqslant$ 70	✓
ASTM D 570	Moist. Absorption short term @50 °C	%	TBD	TBD	$\leqslant$ 0.25	n/a	$\leqslant$ 0.25	n/a	$\leqslant$ 0.25	n/a
ASTM D 570	Moist. Absorption long term @50 °C	%	TBD	TBD	$\leqslant$ 1.0	n/a	n/a	n/a	$\leqslant$ 1.0	n/a
ASTM D 7205	Min. Guaranteed Tensile Load	kip	TBD	TBD	$\geqslant$ 29.1	n/a	$\geqslant$ 32.2	n/a	$\geqslant$ 29.1	n/a
ASTM D 7205	Min. Guaranteed Tensile Strength	ksi	TBD	TBD	n/a	n/a	n/a	n/a	n/a	n/a
ASTM D 7205	Tensile Modulus	ksi	TBD	TBD	$\geqslant$ 6, 500	n/a	$\geqslant$ 6, 500	n/a	$\geqslant$ 6, 500	n/a
ASTM D 7205	Max. Strain	%	TBD	TBD	n/a	n/a	n/a	n/a	n/a	n/a
ASTM D 7617	Min. Guaranteed Transverse Shear	ksi	TBD	TBD	$\geqslant$ 22	n/a	$\geqslant$ 22	n/a	$\geqslant$ 19	n/a
ASTM D 4475	Horizontal Shear Stress	ksi	TBD	TBD	n/a	n/a	$\geqslant$ 5.5	n/a	n/a	n/a
ACI440. 3 R,B.3	Bond-to-concrete strength	ksi	TBD	TBD	$\geqslant$ 1.1	n/a	$\geqslant$ 1.1	n/a	$\geqslant$ 1.1	n/a

Bibliography

ASTM (2014). *Standard Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials*, (D5229). ASTM International, West Conshohocken, PA.

ASTM-International (2011). *Standard Test Method for Ignition Loss of Cured Reinforced Resins*, (D2584-11). West Conshohocken, PA.

ASTM-International (2012a). *Standard Test Method for Apparent Horizontal Shear Strength of Pultruded Reinforced Plastic Rods By the Short-Beam Method*, (D4475 - 02 (REAPPROVED 2008)). West Conshohocken, PA.

ASTM-International (2012b). *Standard Test Method for Transverse Shear Strength of Fiber-reinforced Polymer Matrix Composite Bars*, (D7617/D7617M - 11). West Conshohocken, PA.

ASTM-International (2015). *Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement*, (D792-13). West Conshohocken, PA.