Deliverable 4 (Revised)

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

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BFRP Design Specifications

In an effort to reduce or eliminate the deteriorating effects due to corrosion of steel reinforcement in internally reinforced concrete infrastructure, the Florida Department of Transportation (FDOT) is currently spending significant resources on research projects that target non-corrosive materials, such as fiber reinforced polymer (FRP) reinforcement bars (rebars). Basalt based FRP (BFRP) rebars are considerably new in the United States, but they have been used successfully in other parts of the world y de Caso et al. (2012) as a non-corrosive alternative. ASTM standards to test the material properties of these rebars and AASHTO-LRFD specifications for the design of concrete bridges reinforced with BFRP rebars are yet to be developed such as: Only ICC-ES Acceptance Criteria AC454 provides referenced design recommendations and a method of acceptance for BFRP reinforcing under US building codes for alternative materials. The current FDOT Standard Specifications for Road and Bridge Construction Section 932, which details FRP internal reinforcement for concrete structures, does not include nor addresses requirements or minimum criteria for basalt fiber rebars.

To support the development of basalt specific acceptance criteria for FDOT specifications section 932, this research was conducted with a focus on the physiomechanical properties of commonly available BFRP rebar products. A test matrix — to address the cross-sectional properties, fiber content, moisture absorption, transverse shear strength, horizontal shear strength, tensile properties, and bond-to-concrete characteristics for three dissimilar rebar products and two sizes (# 3 and # 5) — was developed to test and evaluate the most essential engineering material properties for BFRP rebars. Based on established test protocols and acceptance criteria for glass FRP (GFRP) rebars, BFRP rebars were evaluated and all test samples (specimen groups) from all three manufacturers satisfied the minimum requirements for GFRP rebars. However, it can be seen in Tables 1 and 2 that BFRP rebars have substantially higher material properties and higher performance in comparison to GFRP rebars. These results form the basis to propose additional material specifications and acceptance criteria for FDOT Specifications Section 932 (Standard specifications for road and bridge construction) and AASHTO- LRFD Bride Design Guide Specifications (BDGS).

Rebars made of glass and basalt FRP composites are mostly elastic until rupture, but fail in a brittle manner (Rossini et al., 2018). The transverse and horizontal shear strength of rebars is relatively low compared to tensile strength. Dependent on the surface enhancement properties of a particular FRP rebar product, the bond-to-concrete strength may vary significantly. Accordingly, acceptance criteria based on empirical methods have to be established, before these rebars can be use as internal reinforcement for concrete structures. The guaranteed shear strength and bond-to-concrete strength of the rebars is an average of experimental result of a sample. In other words, the mean sample shear strength of the rebars is considered as guaranteed shear strength of the rebars and mean bond-to-concrete strength is considered as the guaranteed bond-to-concrete strength of the rebars (ASTM-International, 2012a,b; ASTM International, 2014). To summarize the guaranteed mechanical strength values for all rebar types evaluated in this study, the following Tables 1 and 2 list the shear and bond-to-concrete characteristics, as well as the tensile properties, respectively. Table 1 highlights the transverse shear strength, the horizontal shear strength, and the bond-to-concrete strength for the three different BFRP rebar types (A, B, C). The final results (per test group) were compared to the acceptance criteria for GFRP rebars as given in FDOT Specifications section 935, such that the prevalent value for the GFRP acceptance criteria represent 100 % and a value above 100 % indicates a performance above the minimum requirement (for GFRP rebars). According to ACI Committee 440 (2015), the guaranteed strength, f^*_{fu}, of GFRP rebars is defined as the experimentally obtained average tensile strength minus three times the measured standard deviation, as shown in equation 1, while the guaranteed elastic modulus, $E_f = E_{f,ave}$, is defined as the mean elastic modulus of a test sample (specimen group).

$$f^*_{fu} = f_{fu_{average}} - 3\sigma \tag{1}$$

Accordingly, the calculated value for f^*_{fu} corresponds to the 99^{th} percentile (Rossini et al., 2018), such that the chance for material failure (before any design factors are applied) remains below 1 %. The strength of commercially available GFRP rebars differs based on the fiber content and manufacturing techniques (Emparanza et al., 2017), and the guaranteed strength is typically exper-

Table 1: Guaranteed shear and bond-to-concrete strength of rebars

			Transverse Shear Strength			Horizontal Shear Strength			Bond-to-Concrete Strength		
	Rebar size	Lot	ksi	MPa	%[†]	ksi	MPa	%[†]	ksi	MPa	%[†]
Rebar A	# 3	1	35.20	242.7	160.0	7.00	48.31	n/a	2.33	16.09	211.8
	# 5	1	33.74	232.7	153.4	6.41	44.16	n/a	2.96	20.41	269.1
	# 3	2	37.67	259.7	171.2	6.49	44.71	n/a	1.92	13.22	174.5
	# 5	2	36.48	251.6	165.8	6.41	44.15	n/a	1.65	11.41	150.0
Rebar B	# 3	1	31.39	216.4	142.7	6.42	44.22	n/a	2.79	19.23	253.6
	# 5	1	26.51	182.8	120.5	6.53	45.00	n/a	2.88	19.85	261.8
Rebar C	# 3	1	34.48	237.7	156.7	5.56	38.38	n/a	3.77	26.00	342.7
	# 5	1	31.69	218.5	144.0	6.64	45.77	n/a	3.77	26.01	342.7

† Percentage comparison based on FDOT specifications section 932, where 100 % is GFRP rebar acceptance criteria .

imentally determined at the time of (concrete) design. If a specific rebar product strength is not defined experimentally at the time of (concrete) design, the manufacturer specified rebar strength (f'_{fu}) is to be used (ACI Committee 440, 2015; Rossini et al., 2018). This specified design strength, f'_{fu}, is always less than the guaranteed strength (c.f. equation 2) of the particular lot of rebars that is to be used for construction.

$$f'_{fu} < f^{*}_{fu} \tag{2}$$

While most strength values for the basalt FRP rebars tested in this research showed that basalt rebars have a higher performance, the general material behavior appeared to be similar to the behavior of GFRP bars, and it is reasonable to assume that Equation 2 applies and can be used to calculate the guaranteed strength of basalt rebars. Accordingly, table 2 lists the guaranteed strength values and elastic modulus for the three different BFRP rebar types (A, B, C) tested in this study and the results are compared to criteria for GFRP rebar according to FDOT specifications section 932. The results in Table 2 show that both # 3 and # 5 rebar from lot 1 of rebar C were the strongest among all tested rebar samples. But the standard deviation of # 3 type B rebars was the smallest,

Table 2: Guaranteed strength and elastic modulus of rebars

			Tensile Strength							Elastic Modulus		
			Mean μ		Standard Deviation σ		Guaranteed $\mu - 3\sigma$			E		
	Rebar size	Lot	ksi	MPa	ksi	MPa	ksi	MPa	%†	ksi	GPa	%†
Rebar A	# 3	1	183.9	1268	4.80	33.12	169.5	1168	141.2	7154	49.32	110.0
	# 5	1	161.2	1112	12.85	88.63	122.7	1074	130.7	5267	36.31	81.03
	# 3	2	169.2	1166	5.03	34.69	154.1	1062	128.4	7200	49.64	110.8
	# 5	2	147.8	1019	4.04	27.86	135.6	935	144.5	7480	51.57	115.0
Rebar B	# 3	1	121.7	839	3.82	26.36	110.2	760	91.83	5482	37.80	84.33
	# 5	1	134.2	925	4.34	29.92	121.3	836	129.2	7735	53.46	119.0
Rebar C	# 3	1	196.3	1353	4.21	29.03	183.6	1266	153.0	7808	53.83	120.1
	# 5	1	172.5	1189	9.19	63.33	145.0	999	154.5	7946	54.79	122.2

† Percentage comparison based on FDOT specifications section 932, where 100 % is GFRP rebar acceptance criteria

while the type A # 5 rebars measure the highest standard deviation. The graphs in figures 1 and 2 visualize the Gaussian distribution for the measured tensile strength results for # 3 and # 5 rebar, respectively. The mean value and guaranteed tensile strength (mean-3σ) are indicated on the curves.

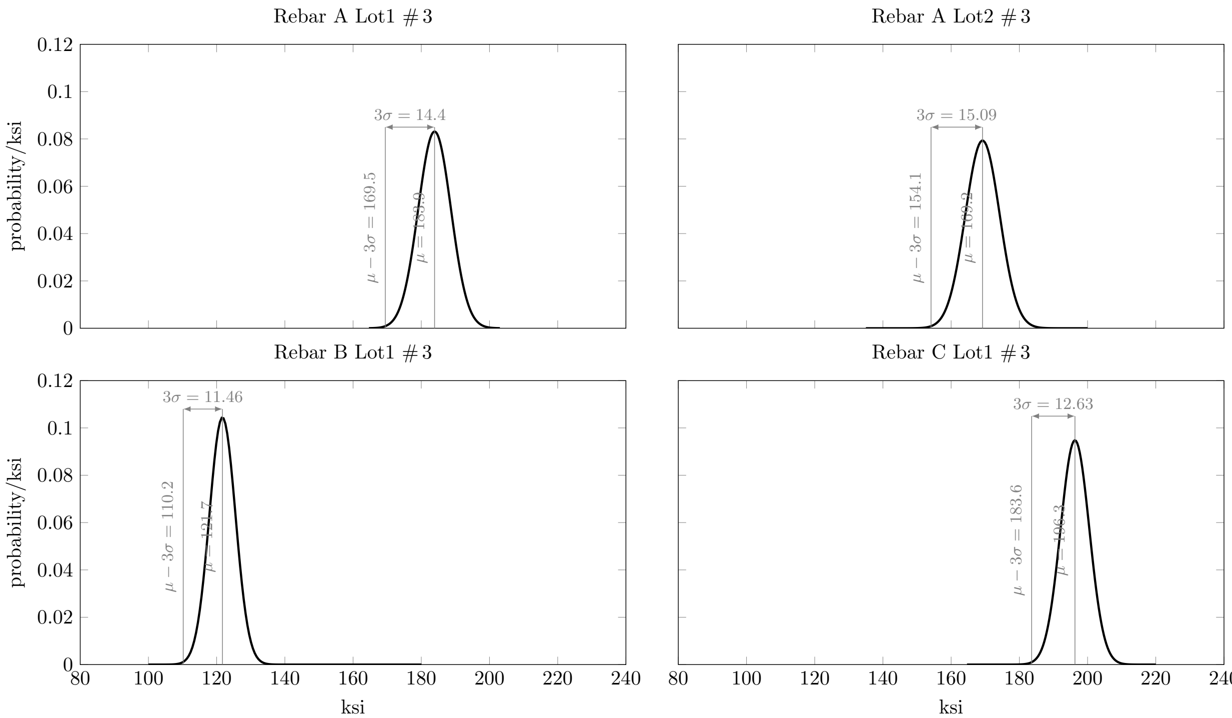

Figure 1: Gaussian distribution for tensile strength of # 3 rebars

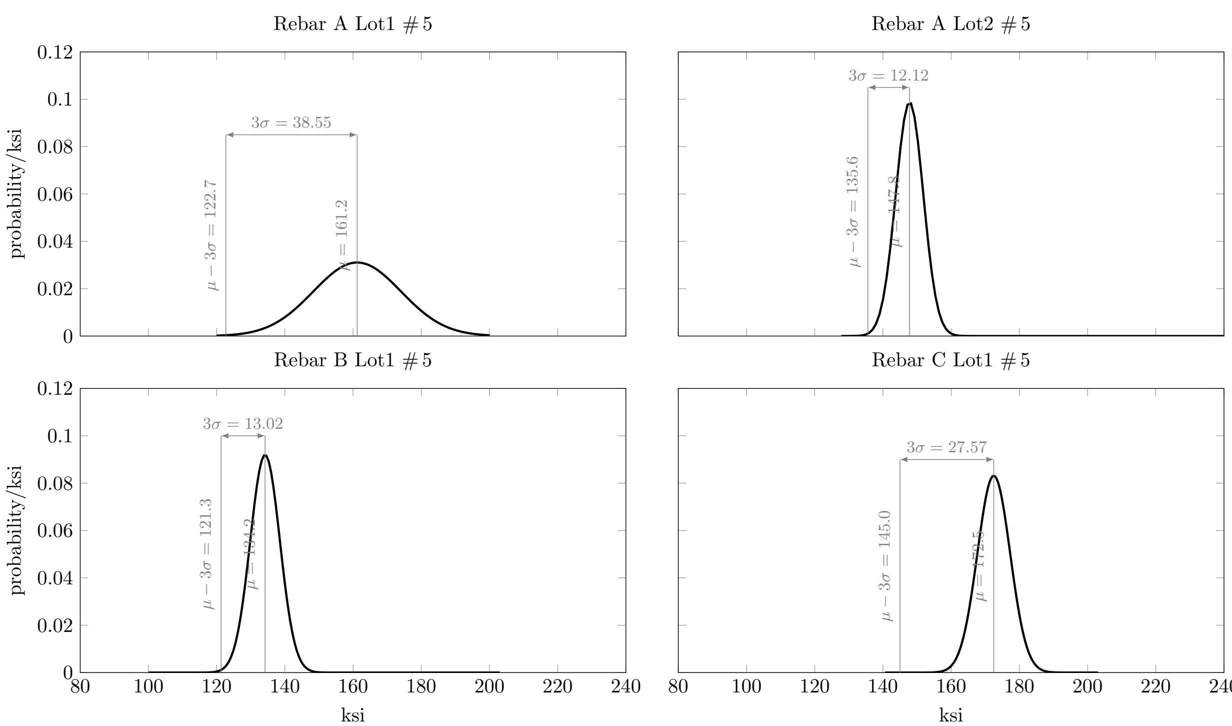

Figure 2: Gaussian distribution for tensile strength of # 5 rebars

Recommendations

Because FRP rebars are desirable for use in harsh environments and material properties generally degrade in aggressive media (ACI Committee 440, 2015; du Béton, 2007), the long-term chemical durability performance of BFRP rebars, including their raw material components, have to be studied and evaluated in various alkaline and saline environments, before minimum material and design criteria can be ultimately defined. According to AASHTO-LRFD Bridge Design Guide Specifications for GFRP Reinforced Concrete which deals with specifications for GFRP rebars as reinforcement for concrete bridges and ACI 440.1R Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer (FRP) Bars which deals with FRP reinforcement for concrete structures, strength reduction factors must be applied to decrease the design strength of FRP to overcome strength degradations. The guaranteed strength of FRP rebars must be reduced by applying the environmental factor (C_E) (ACI Committee 440, 2015). Likewise, the design strength for FRP rebars under sustained load must be reduced via the creep rupture factor (C_c) to avoid premature failure due to creep (ACI Committee 440, 2015; du Béton, 2007). The fatigue reduction factor (C_f) must be applied to properly define the strength of FRP rebars under cyclic loading.

The brittle nature of FRPs implies a possibility of over-reinforced flexural members, which leads to concrete failure in the compression zone or to under-reinforced compression members, which may cause reinforcement rupture in the tension zone (ACI Committee 440, 2015; Rossini et al., 2018). The two failure modes — failure in the compression zone and rupture in the tension zone — are characterized by two different strength factors ϕ_c and ϕ_t respectively (ACI Committee 440, 2015; Rossini et al., 2018). As flexural member can sometimes undergo shear failure, the strength reduction factor ϕ_s is incorporated in the design, in other words nominal shear resistance of the designed member shall be reduced to factored shear resistance (Rossini et al., 2018). These factors are applied during the design phase to reduce the estimated nominal moment of a reinforced concrete member. For the design of FRP rebar reinforced concrete structures, a reduction factor has to be applied for the bond strength (C_b) of the rebars listed in table 1 to account for the different surface enhancement properties, which may differ significantly in comparison to steel rebars (ACI Committee 440, 2015). ACI Committee 440 (2015) defines the bond reduction factor as the inverse of the bond coefficient (k_b), which is larger than 1.0 for FRP rebars with a bond strength that is inferior to the bond strengt for traditional steel rebars and less than 1.0 for FRP rebars with superior bond strength. Table 3 provides an overview of these factors and exemplifies how each factors is applied in the design procedures according to ACI Committee 440 (2015); AASHTO (2018).

Table 3: Reduction factors

Reduction factor	Equation used in design
Environmental factor (C_E)	$f_{fd} = C_E f'_{fu}$
Creep rupture factor (C_c)	$f_{f,c} = C_c f_{fd} = C_E C_c f'_{fu}$
Fatigue rupture factor (C_f)	$f_{f,f} = C_f f_{fd} = C_E C_f f'_{fu}$
Bond reduction factor (C_b)	$(C_b) = 1/k_b$
Factor for compression-controlled failures (ϕ_c)	$M_r = \phi_c M_n$
Factor for tension-controlled failures (ϕ_t)	$M_r = \phi_t M_n$
Factor for shear-controlled failures (ϕ_s)	$V_r = \phi_s V_n$

The Bond strength results obtained through this research project can be used in the development of a bond factor (C_b) for BFRP rebars, and this factor can be implemented in ACI 440 and AASHTO-bridge design guide specifications. Additional studies with a focus on bond-to-concrete properties of BFRP rebars and the bond degradation over time in harsh environments is recommended to fully develop a suitable bond reduction factor (C_b) that is specific to BFRP rebars. Because BFRP rebars are thought of as a preferable alternative in harsh environments, it is important to study the long-term chemical durability properties of such rebars before the environmental reduction factor (C_E) for BFRP rebars can be developed.

References

AASHTO (2018). *AASHTO LRFD Bridge Design Guide specifications for GFRP-Reinforced Concrete*. American Association of State Highway and Transportations Officials.

ACI Committee 440 (2015). *"Guide for the design and construction of structural concrete reinforced with fiber-reinforced polymer (frp) bars."* Report No. ACI 440.1R-15, American Concrete Institute.

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 (2014). "Standard test method for bond strength of fiber-reinforced polymer matrix composite bars to concrete by pullout testing." ASTM International.

du Béton, F. I. (2007). "Frp reinforcement in rc structures." *Task Group*, *9*, 151.

Emparanza, A. R., Kampmann, R., and y Basalo, F. D. C. (2017). "State-of-the-practice of global manufacturing of frp rebar and specifications." *The 13th International Symposium on Fiber-Reinforced Polymer Reinforcement for Concrete Structures (FRPRCS-13)*, American Concrete Institute Anaheim, CA.

Rossini, M., Matta, F., Nolan, S., Potter, W., and Nanni, A. (2018). "Aashto design specifications for gfrp-rc bridges." *Italian Concrete Days*, Associazione Italiana Calcestruzzo Armato e Precompresso (AICAP) & Collegio .

y de Caso, B. F. J., Matta, F., and Nanni, A. (2012). "Fiber reinforced cement-based composite system for concrete confinement." *Construction and Building Materials*, *32*, 55–65.