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Bond Behavior of GFRP Rebars in Reinforced Concrete Members under Flexure

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Abstract

A proper bond between reinforcement and concrete is key for an appropriate composite action of both materials in reinforced concrete structures. However, to-date limited studies exist on bond of fiber reinforced polymer (FRP) bars in concrete members under flexure. In this paper, the bond strength developed by FRP and steel rebars is evaluated and compared, by testing reinforced concrete beams under three point bending load. The investigation included 4 beams that were 183 cm long × 15 cm wide × 36 cm deep: two of them were reinforced with sand coated GFRP rebars, while steel was used to reinforce the other two. For each of the reinforcing systems, two different embedded lengths were tested: 30 d_b (380 mm) and 40 d_b (510 mm). The beams were tested under a 3-point-bending setup and they were monitored using several measuring devices: LVDTS, potentiometers and strain gauges. Preliminary results show that the GFRP rebars have lower bond capacity than the ones made of steel. Moreover, it was inferred that the embedded lengths suggested by actual code provisions for GFRP rebars are too conservative.

Keywords: Bond; embedded length; GFRP; composites; flexure; sustainability; resilience

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Introduction

The use of fiber-reinforced polymer (FRP) rebars in substitution of traditional steel leads to an extended service life of reinforced concrete structures, because of the corrosion resistance of these composite rebars compared to steel [1]. To ensure a proper composite action between the rebars and concrete in reinforced concrete systems, an adequate interfacial bond between both materials is crucial to allow stresses to be transferred. Even if the bond behavior between steel rebars and concrete is well understood and addressed in design codes, this approach cannot be directly applied for FRP rebars due to the difference in the physio-mechanical properties compared to steel. In fact, the surface enhancement of FRP rebars is not standardized, as it is in the case of steel rebars: the surface finishing of the different commercially available FRP rebar type is unique [2], which make the bond properties product-dependent [3].

Different research studies exist related to the bond properties between FRP rebars and concrete; however, most of them are based on the traditional 'pull-out' test [4–6]. Even if the use of this test setup gives valuable results to compare the bond behavior of different rebar types, it doesn't represent the 'real' bond behavior in one of the most commonly found structural elements, flexural members. In flexural elements, both the tensile reinforcement, as well as the concrete at that height, are in tension. In the 'pull-out' test, however, while the rebar is in tension, the concrete block is compressed during the test, which sets it aside from the actual bond behavior of a concrete member under flexure. To-date, very few studies have been carried out the bond behavior of rebars in beams under bending [7].

This paper summarizes the preliminary results of an ongoing research project that aims to define the bond performance of GFRP rebars and compare it to that of steel, by using different embedded lengths. Four beams were tested: two of them were reinforced with helically wrapped-sand coated GFRP rebars, while steel was used to reinforce the other two. For each of the reinforcing systems, two different embedded lengths were tested: 30 d_b (380 mm) and 40 d_b (510 mm).

Experimental Program

Four reinforced concrete beams with a section of 15 x 36 cm, and a length of 183 cm were tested under a 3-point-bending setup. A span length of 152 cm was used and the load was applied vertically in mid-span, as shown in Figure 1 and 2. The test was run in load control at a rate of 222 N/s up to 85% of the peak load (in 4 load-unload cycles) and it was then tested in displacement control at a rate of 0,32 mm/s up to failure, to be able to analyze the post-failure behavior.

The design of all the beams reinforced with GFRP was done according to ACI440.1R-15 [8] and for those reinforced with steel was done according to ACI318-14 [9]. The transversal reinforcement both for GFRP and steel beams was designed according to ACI318-14. The beams were designed to be tension controlled, to avoid concrete crushing and force the tensile failure or de-bonding (in case the embedded length is not sufficient) of the rebar. The beams were reinforced using Ø10 mm stirrups (7,5 cm on center), Ø10 mm top reinforcement (for constructability purposes) and Ø13 mm tensile reinforcement. The designed ensured that the top reinforcement had no tensile contribution, ensuring that the neutral axis was below the location of the top reinforcement throughout the test. The reinforcement placed on the bottom of the section had the particularity to be formed by two Ø13 mm rebars that run up to 5 cm away from mid-span on one of the halves of the beam, while a single rebar was placed on the other half, that exceeded a length denominated as embedded length over mid-span, as seen in Figure 1 and 2 (right). The beam was notched in mid-span to induce a main localized crack and ease its monitoring during testing.

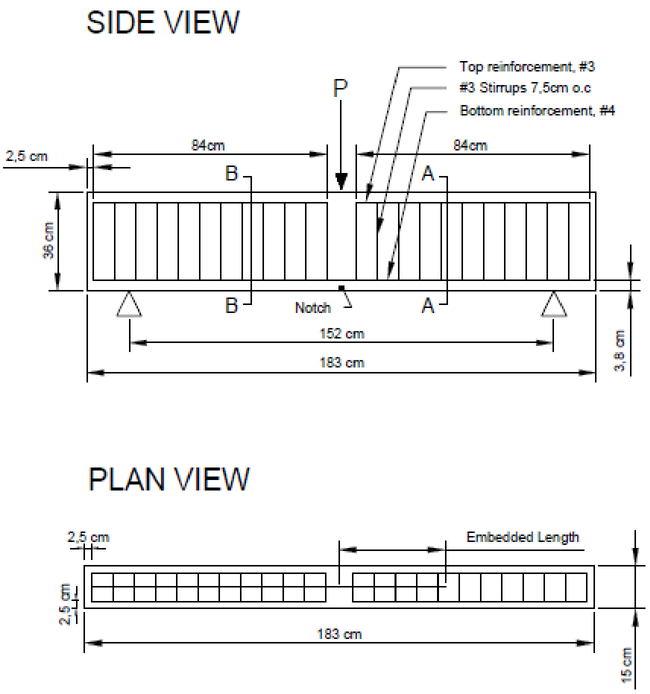

Figure 1: Reinforcement plans

Steel stirrups (Ø10 mm) with a yield strength of 415 MPa were used to reinforce the four beams. The longitudinal rebars (Ø10 mm for the top and Ø13 mm for the bottom reinforcement) were made of steel for two of the specimens and GFRP was used for the other two. The steel rebars had a yield strength of 415 MPa (ultimate strength of 720MPa) and an E-Modulus of 200GPa, while the tensile strength of the GFRP rebars was 890 MPa and the E-modulus 46 GPa (reported by the manufacturer). The GFRP rebars used for this project were sand-coated and helically wrapped. The compressive strength of the concrete after 28 days was 42.3 MPa with a coefficient of variance of 4.1%.

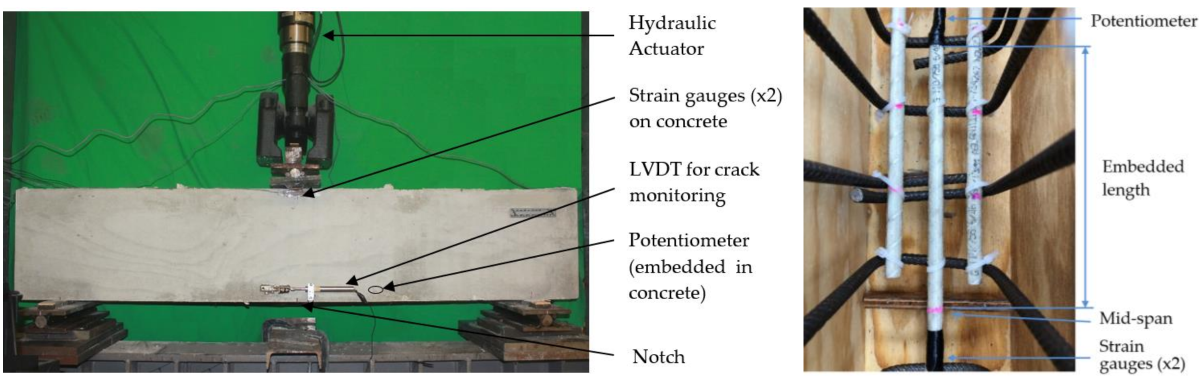

Figure 2: Test set-up (left) and plan view of the instrumented rebar in mid-span.

Results

The experimental results are summarized in Table 1. Out of the four beams, the two reinforced with steel and the one reinforced with GFRP with the longer embedment length (L_d = 510 mm) reached the failure of the reinforcement; the GFRP reinforced beam with shorter embedded length (L_d = 380 mm), however, showed a bond failure of the embedded rebar. This was proven not only visually but was also quantified by the potentiometer placed at the end of the embedded rebar, which recorded a slippage at peak load of 1,67 mm. Figure 3 shows the 3-point-bending-load development with respect to the slippage of the end of the embedded rebar relative to the concrete.

Table 1: Experimental results at ultimate

Rebar type	L_d	P_{max}	Deflection at P_{max}	Crack width at P_{max}	Slippage at P_{max}	Failure mode
	mm	kN	mm	mm	mm	
GFRP	380	85,85	16,70	5,10	1,67	Bond slip
	510	95,91	21,35	6,14	0	Rebar rupture
Steel	380	76,11	28,14	15,03	0	Rebar rupture
	510	76,59	23,04	21,65	0	Rebar rupture

In general, the ultimate capacity of the GFRP reinforced beams was higher than the ones reinforced with conventional steel, as expected, since the beams were designed to be tension controlled; therefore, the ultimate capacity of the beam was directly dependent of the tensile capacity of the reinforcement, which was higher for GFRP. In the case of the GFRP reinforced beam with a shorter embedded length, the peak load was lower than the one with the longer one because of the failure mode: the shorter one failed in bond before reaching the failure of the rebar, whereas the longer embedment provided enough anchorage to break the rebar. The deflection and crack width at peak load were higher for the steel reinforced beams than for GFRP, due to the higher ultimate strain of steel compared to GFRP.

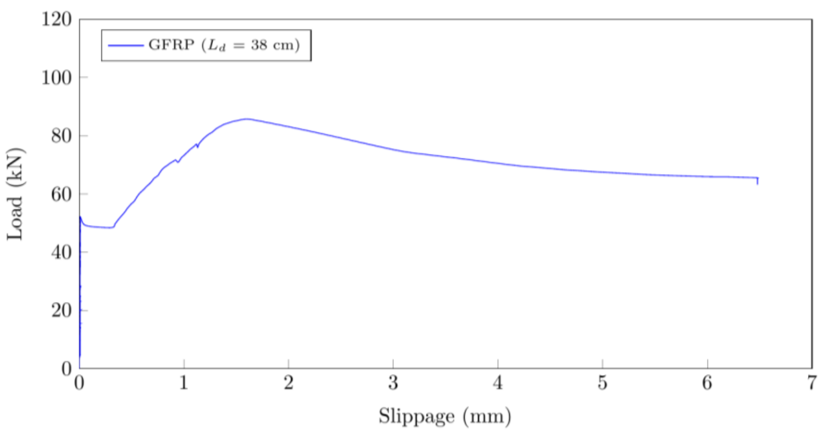

Figure 3: Flexural load – slippage relationship

In addition, the serviceability state was analyzed, considering it as 35% of the ultimate load. In this case, for GFRP reinforced beams a higher deflection and crack width was recorded compared to steel. The reason behind it was the lower stiffness (lower E-Modulus) of GFRP in comparison with steel.

Table 2: Experimental results at service

Rebar type	L_d	Service load	Deflection at service	Crack width at service
	mm	kN	mm	mm
GFRP	380	30,05	6,04	1,34
	510	33,57	7,83	1,80
Steel	380	26,64	3,59	0,25
	510	26,81	3,10	0,29

Conclusions

From the preliminary results obtained, it can be concluded that the type of GFRP rebar tested in this project, showed a lower bond capacity than steel, being 38 cm of embedded length not enough anchorage. This means that in the case of these GFRP rebars, the required embedded length for a complete stress transfer would lie between 38 and 51 cm, way below the required development length for sand coated GFRP rebars according to ACI 440.1R-15 (94 cm), which appears to be very conservative.
In terms of capacity, due to the higher tensile capacity of GFRP, the two beams reinforced with this type of reinforcement failed at a higher peak load than the steel reinforced ones (since all of them were designed to be tension-controlled). At service loads (35% of ultimate), however, GFRP reinforced beams showed higher mid-span deflection and crack-width compared to the steel reinforced beams, because of the lower stiffness of GFRP rebars in comparison to steel.
To confirm these preliminary findings additional tests should be done, including more repetitions for statistical relevance, as well as, a higher number of embedment lengths and ideally, different types of GFRP rebars.

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