MŰEGYETEM 1782

Budapest University of Technology and Economics
Faculty of Civil Engineering
Department of Construction Materials and Technologies

NEW SCIENTIFIC RESULTS

of the PhD Thesis

Bond behaviour of FRP bars to concrete, influence of bar surface, entrained air and high temperatures

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1. INTRODUCTION AND BACKGROUND

Steel bars have been used extensively for reinforced concrete (RC) structures as internal reinforcement due to their various advantageous properties such as ductility, high tensile strength, bendability etc. However, steel is susceptible to electrolytic corrosion. One of the main advantages of Fibre Reinforced Polymer (FRP) bars is their excellent corrosion resistance [1,2].

FRP bars are composites made by embedding fibres into a polymeric resin. Fibres are the load bearing components, while the resin protects the fibres and transfers the stresses. Commonly used type of fibres are aramid (A), basalt (B), carbon (C) and glass (G), the latter is the most frequently used in structural engineering applications. The most often applied resins are thermoset (epoxy, polyester and vinyl ester) [2]. FRP bars show outstanding mechanical characteristics, such as high tensile and fatigue strength[3–5].

To facilitate the full acceptance of FRP RC structures, studies are needed to understand the influence of critical factors and thus to improve the design guidelines.

Undeniably, the bond between concrete and reinforcing bar is crucial for stress transfer from the former to the latter [6]. The bond between FRP bars and the surrounding concrete is built up from different components that are highly influenced by the mechanical and physical properties of the bars, as well as the properties of the surrounding concrete and ambient conditions, among others [7].

The surface characteristics of FRP bars can be considerably different from that of steel reinforcement. Guidelines generally claim that the surface of FRP bars influences the bond behaviour (e.g., [8]). Yet, due to the complexity of the phenomenon and the diversity of available surface profiles, there is still no agreement regarding the magnitude of this influence [9,10].

The combined use of air-entrained concrete (AEC) with FRP reinforcement could further increase the durability of RC structures. However, it must be ensured that no considerable negative effect is associated with the artificially entrained air void system. The interaction between reinforcement and AEC is one of the characteristics that might be susceptible to additional air since it can create barriers at the contact surface.

The critical temperatures of FRP bars are lower than those of steel, due to softening of the polymer matrix at temperature levels close to their glass transition temperature (T_g) [1]. Yet, there are still very little studies available on the bond behaviour of FRP bars at hot state.

2. OBJECTIVES

The main aim of the thesis is to specify the influence of significant factors on the bond behaviour of FRP bars to concrete. To reach the targeted aim, the following objectives are performed.

I. Determine the bond characteristics of FRP bars with different ***surface profiles*** *having various bar diameters and concrete strengths. Furthermore, define the significance of the interactions among the influence of parameters (NSR 1 and 2).*

II. Determine the bond characteristics of FRP bars in ***air-entrained concrete*** *having different bar diameter, surface profile, fibre type and concrete strength. Furthermore, define the significance of the interactions among the influence of parameters (NSR 3 and 4).*

III. Determine the bond characteristics of indented GFRP bars at ***high temperature*** *(NSR 5 and 6).*

3. Research methods and main parameters

Three separate research methods were applied during the PhD work: experimental, analytical and statistical analysis.

3.1 Experimental methodology

Pull-out (P-O) test [8,11,12] was chosen to investigate the bond behaviour of FRP bars in concrete. P-O test proved to be an effective method to identify and compare the influences of different factors on bond behaviour [13]. The P-O test is relatively simple to perform that makes it repeatable [14]. A schematic representation of the specimens (a cube of 150 mm) is shown in Figure 1, while the test setup is presented in Figure 2.

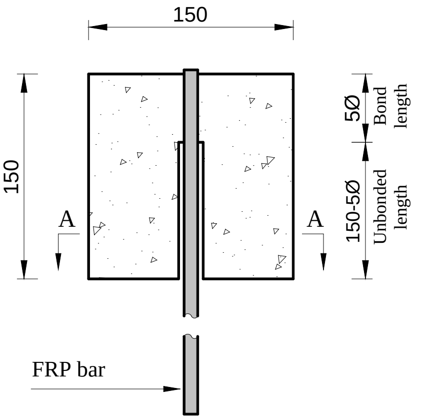

Figure 1 Schematic representation of a P-O test specimen (dimensions are in mm)

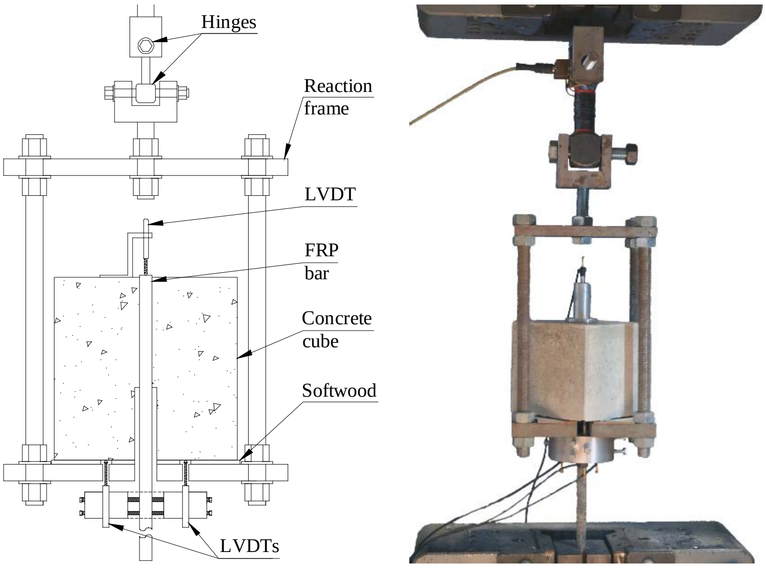

Figure 2 Pull-out (P-O) test setup: schematic representation (left) and photo (right)

Although most of the experimental work, has been done by applying the conventional P-O test (Figure 2), two alternative test methods were developed during the PhD research to overcome the given drawbacks, such as to avoid the compressive stress – due to the reaction plate – in the concrete during a pull-out test (Figure 4) and to allow the free end slip measurement during high temperature test (Figure 5).

I have developed the Direct Tension pull-out (DT) test (Figure 4) to study whether the test setup influences the measurable bond strength. A DT test specimen consists of a concrete prism (cross-section of 100x100 mm and length of 200 mm) with two bars embedded in the centre of the prism and protruding from opposite sides. One of those bars is the tested FRP bar with an embedded length equal to 100 mm (Figure 3). The test procedure and instrumentation were similar to that of P-O test. Gripping of the specimens is done by a steel threaded bar eliminating the compressive stresses induced by the reaction plate in case of P-O tests. Hence, the stress state in the concrete – during the DT test – is similar to that of field application (e.g., bar in the tension zone).

During a high temperature pull-out test the measurement of free end slip is not possible by traditional (e.g., LVDT) equipment. To overcome this drawback, I have developed a non-contact optical measurement system for the determination of the slip at the free end of the specimen. Steel brackets were rigidly connected to the top insulating ceramic plate as well as to the GFRP bar (Figure 5). These brackets were coated with black, heat-resistant paint except for circular markers of approximately 20 mm in diameter to create a high contrast target, suitable for image analysis. The brackets on the two sides, acting as reference, had two markers, while the central one, moving rigidly with the bar, had one. The optical system consisted of tracking the centroid of each marker in consecutive images and measuring the free end slip as the average relative vertical displacement of the central marker with respect to the others. Images were acquired with a CMOS digital camera.

The loading rate of all three types of the pull-out test was set to 1 mm/min (displacement controlled) while the bond length to 5·Ø (Ø - nominal bar diameter).

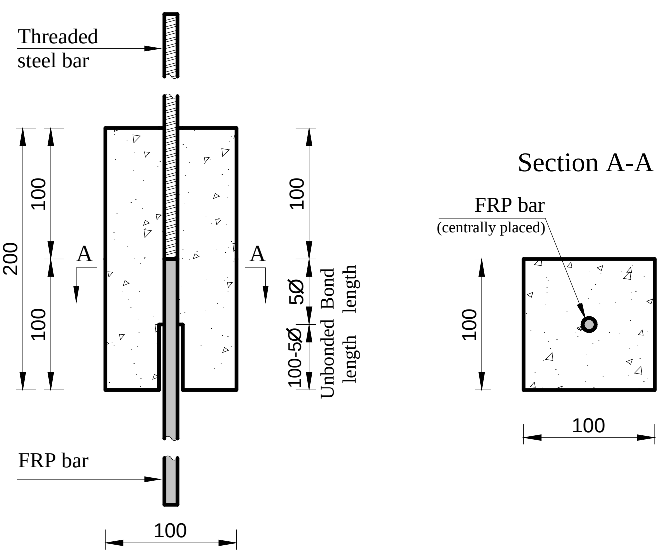

Figure 3 Schematic representation of Direct tension pull-out (DT) test specimen — dimensions are in mm

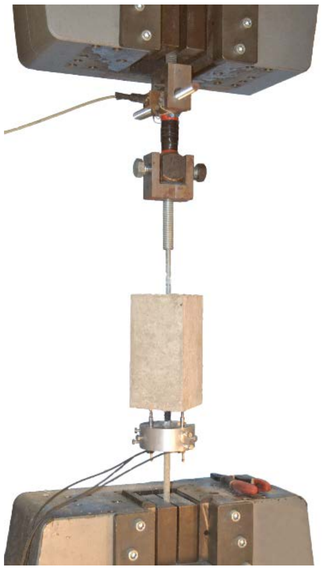

Figure 4 DT test setup

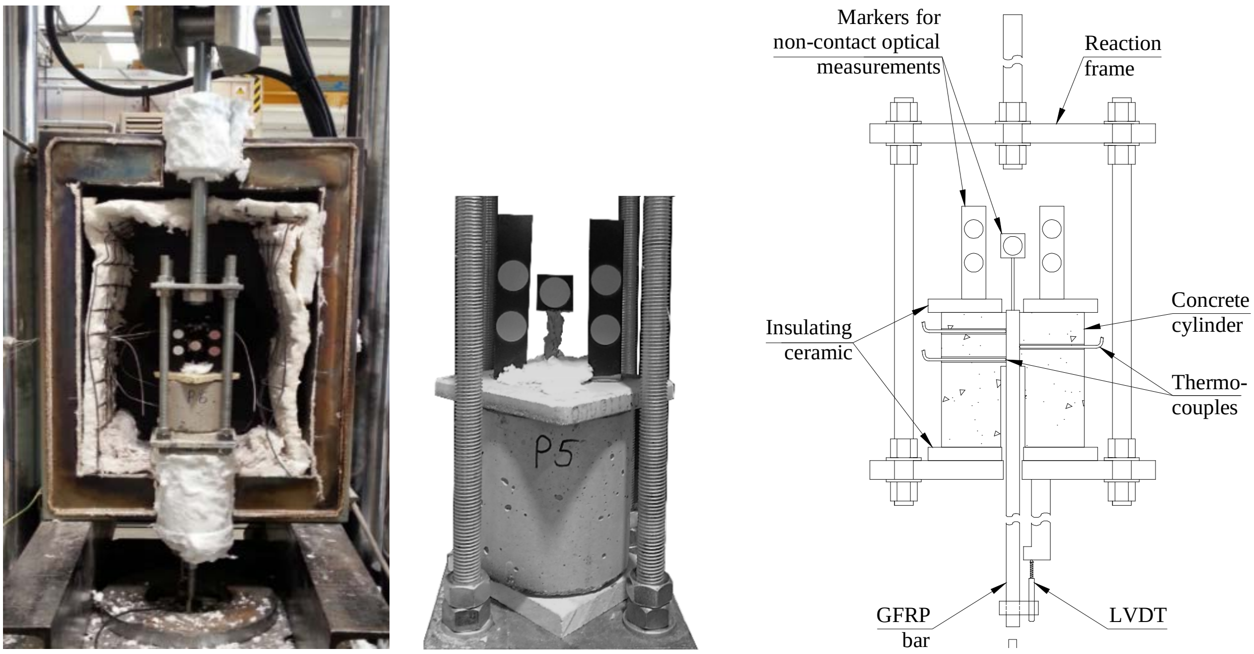

Figure 5 Photo and schematic representation of the pull-out test specimen and setup for high temperature

3.2 Analytical methodology

Bond stress-slip constitutive laws are essential for finite element analysis of FRP RC structures [15,16] as well as for the analytical definition of the required anchorage length of the bars [17,18]. Parameters of analytical models (i.e., mBPE and CMR) to predict the bond stress-slip relationship was defined. The calibrated parameters can be adopted by researchers and engineers to account for the influence of different parameters on the bond behaviour of FRP bars embedded in concrete (e.g., [19,20]). The analytical models for the ascending part of the bond stress-slip curves provide the following forms, mBPE model [21] (Eq. 1) and CMR model [22] (Eq. 2), respectively.

$$\tau_b = \tau_{b,max} \left(\frac{s}{s_m}\right)^{\alpha} \tag{1}$$

$$\tau_b = \tau_{b,max} \left[1 - e^{\left(-\frac{s}{s_r}\right)}\right]^{\beta} \tag{2}$$

where τ_b is the bond stress, s is the slip, $\tau_{b,max}$ is the maximum bond stress, s_m is the slip corresponding to $\tau_{b,max}$. α, β and s_r are experimental parameters, needed to be defined.

3.3 Statistical methodology

Mathematical statistics provide powerful tools (e.g., independent t-test, analysis of variance (ANOVA)) to analyse whether a statistically significant difference exists between the means of two or more independent groups. It allows deciding that the analysed effect is due to random errors or it is likely that the difference exists in the population as well, not just in the sample. Moreover, statistical analysis helps to observe if there are interactions among the involved factors. An interaction exists when the effect of a factor depends on the level of another factor, that is the factors are in synergy [23]. A comprehensive statistical model was built to study the combined effect of the involved parameters on the bond strength.

The statistical test results will not only provide evidence if the means of the independent variable are equal, but it can also provide "how far" they are to each other. In engineering, the magnitude of such distance is not as useful as the ratio between the two means, as the latter is better suited to generalize the results. Most of the available formulae for bond strength definition (e.g., [11,24,25]) takes into account the effect of different parameters as a multiplicative factor. To overcome this inconvenience, it is common to mathematically manipulate the database. That is, the database – built up by the experimental results and the defined parameters of the analytical models – was transformed by the natural logarithm function to perform the statistical analysis [26]. After analysis, the results of the statistical analysis were back-transformed to be interpretable on the original database. The 95% confidence intervals (CI) were defined.

Although a considerable amount of the new scientific results (NSR) are based on statistical analysis, it is important to bear in mind that statistical analysis is applied to provide strong confidence of experimental and analytical findings.

3.4 Parameters of the studies

Overall, sixteen different FRP bars have been used (Figure 6), having different surface characteristics (sand coated (SC), helically wrapped (HW), helically wrapped and sand coated (HWSC), indented (In) and ribbed (Rb)), diameters (6 to 16 mm) or fibre type (basalt, carbon, glass or hybrid). The concrete was design to have three different compressive strength levels and was prepared in laboratory (BME: Obj. I. and II.; The University of Sheffield: Obj. III.) using natural aggregate with a maximum aggregate size (MAS) of 16 mm for Obj. I. and II., whereas the MAS was 10 mm for Obj. III. The consistency of the concrete was set to flow class F4 [27]. A total of 482 specimens were prepared and tested. Detailed information about concrete mix designs and the mechanical properties of the concrete and applied FRP bars as well as the experimental matrices are presented in the PhD thesis.

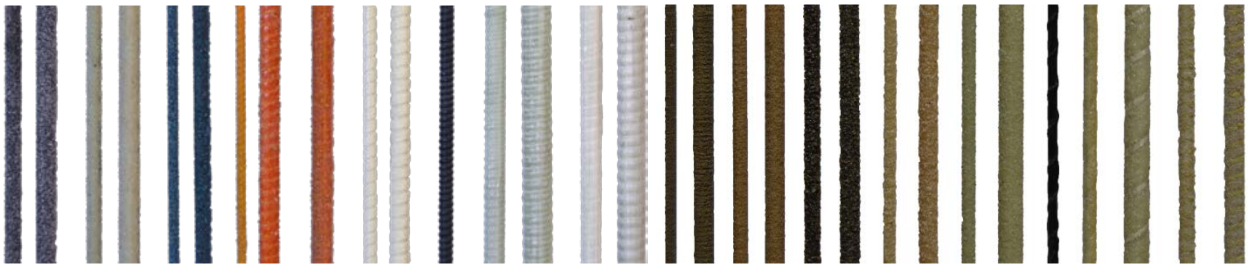

Figure 6 FRP bars applied in the study (not each diameter is represented)

3.4.1 Research methodologies and parameters for Objective I.

I have designed and performed an extensive experimental program (238 pull-out tests) to study the influence of GFRP and BFRP bar surface characteristics on the bond behaviour in concrete. FRP bars with various surface characteristics (In, HW, sand coated SC, HWSC, Rb) were applied. Additional factors include the concrete compressive strength (approximately 35 and 66 MPa) bar diameter (6 to 12 mm) and test type (P-O and DT tests). I have assessed the bond behaviour through bond failure mode, bond stress-slip relationship, bond strength and analytical models. I have defined the coefficients for mBPE and CMR analytical bond stress-slip models based on the experimental curves. I have performed statistical null hypothesis tests, on the experimental data and analytical coefficients, to study the statistical significance of the influence of FRP surface characteristics. I have performed ANOVA (analysis of variance) test to define whether there are statistically significant interactions among the influence of involved factors.

3.4.2 Research methodologies and parameters for Objective II.

I have designed and performed an extensive experimental series (232 pull-out tests) to study the influence of air-entrained admixture (AEA) on the bond behaviour of FRP bars in concrete. Additional factors include the concrete compressive strength (approximately 35 and 77 MPa), FRP bar surface characteristics (In, SC, HWSC and Rb) diameter (6 to 16 mm) and fibre type (glass, basalt, carbon, hybrid). I have evaluated the bond behaviour by bond failure mode, bond stress-slip relationship, bond strength and analytical models. I have defined the analytical parameters for mBPE and CMR models. I have performed statistical null hypothesis test, on the experimental data and analytical parameters to study the statistical significance of the influence of AEA. I have performed an ANOVA statistical test to define whether there are statistically significant interactions among the influence of involved factors.

3.4.3 Research methodologies and parameters for Objective III.

I have designed and performed an experimental test series to study the temperature dependence of the bond behaviour of indented, 8 mm-diameter GFRP bars to concrete at high temperature (up to 300 °C). I have performed 12 modified pull-out tests at hot state, at a steady temperature, inside an electric furnace. I have assessed the bond behaviour through bond stress-slip relationship, bond strength, bond failure mode and analytical models. The average concrete compressive strength at ambient temperature was 38.7 MPa.

4. NEW SCIENTIFIC RESULTS (NSR) OF THE PHD THESIS

The text in bold provides the NSR, while others serve as introduction or explanation.

NSR 1 [SS2], [SS3], [SS6], [SS7], [SS9]

I have determined the influence of the FRP bar surface on the bond behaviour to concrete. I have demonstrated it for GFRP and BFRP bars having indented, helically wrapped, sand coated, sand coated and helically wrapped or ribbed surfaces; diameters of 6 to 12 mm and average concrete compressive strengths of 35 and 66 MPa.

1.1

Based on the statistical analysis of variance of the experimentally measured bond strength values of GFRP and BFRP bars I have determined that the influence of bar surface on the bond strength is in statistically significant 2-way interaction with the influence of both of the bar diameter and the concrete strength (Figure 7).

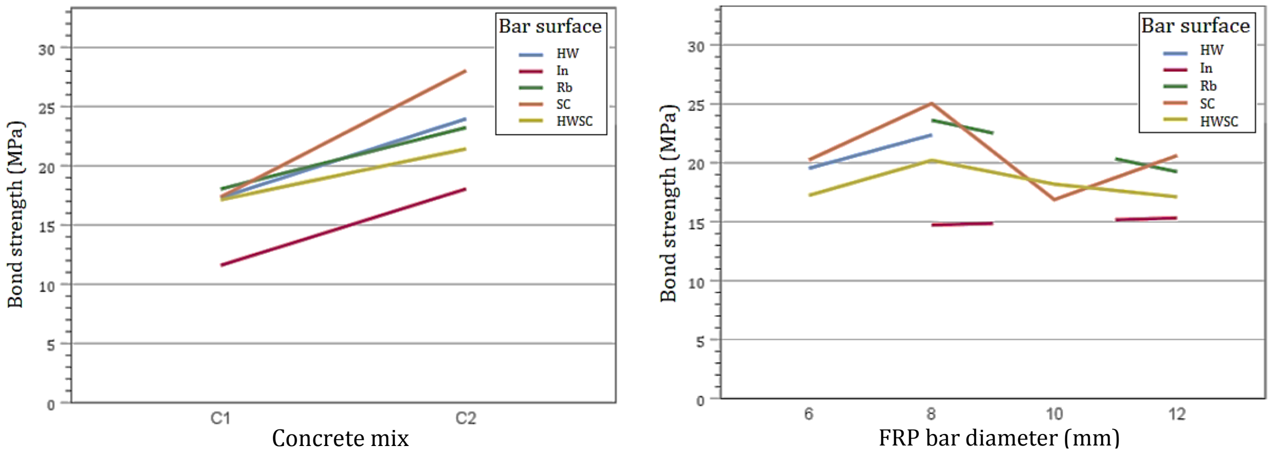

Figure 7 Interaction between parameters of the study: FRP bar surface and concrete strength (left); FRP bar surface and diameter (right). Average compressive strengths of 35 (C1) and 66 MPa (C2). Bar surfaces: HW – helically wrapped, In – indented, Rb – ribbed, SC – sand coated, HWSC – helically wrapped and sand coated

1.2

I have proved – for bars having sand coated or ribbed surfaces – that the bond strength varies statistically significantly within the same surface category.

These findings (1.1 and 1.2) prove that the influence of bar surface cannot be considered as a stand-alone parameter, defined based solely on surface category – despite the provisions of CSA S806-12 [11] – but it must be considered in synergy with the influences of other factors.

1.3

I have experimentally determined that the highest slip value corresponding to the bond strength is achieved by the helically wrapped bars (Figure 8).

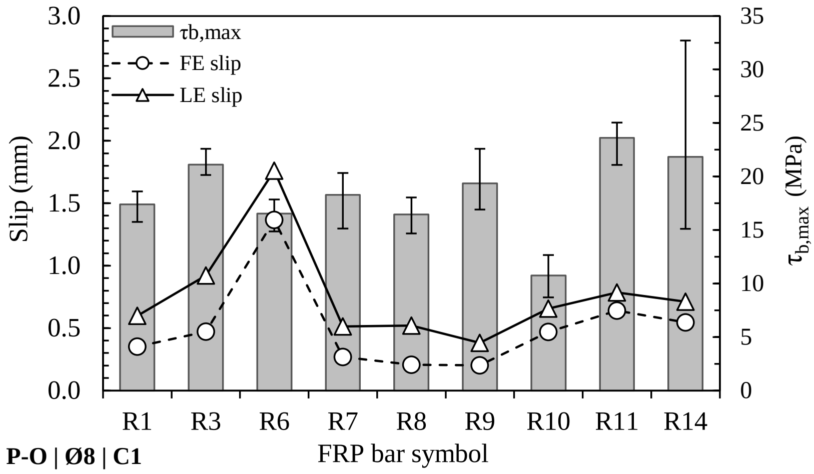

Figure 8 Slip and bond strength ($\tau_{b,max}$) results of 8 mm bars in C1 concrete mix. R6 bars have helically wrapped surfaces (R1, R3: SC; R7 to R9: HWSC; R10: In; R11: Rb; R14: deformed steel). For symbols of the surfaces, see Figure 7

1.4

I have developed a statistical model and determined the coefficient α for the mBPE analytical bond stress-slip model depending on the surface category and slip $\alpha_{fe,sanded}$ = 0.134, $\alpha_{fe,deformed}$ = 0.234, $\alpha_{le,sanded}$ = 0.493 and $\alpha_{le,deformed}$ = 0.379 (free (fe) and loaded end (le)).

I have defined the coefficient α of the mBPE analytical bond stress-slip models for each pull-out test (Figure 9). I have demonstrated that the concrete compressive strength (35 and 66 MPa) does not influence the coefficient α. Furthermore, I have determined that the bar diameter (6 to 12 mm) has a limited influence of α_{fe} (explaining only 3.9% of the variance) and no influence on α_{le}.

I have observed (Figure 9) that sanded (SC, HWSC) and non-sanded (In, Rb) bars show distinct values of the parameters of the analytical bond stress-slip models (i.e., α, Eq.1). I have completed the observations with statistical analysis of variance to demonstrate its significance.

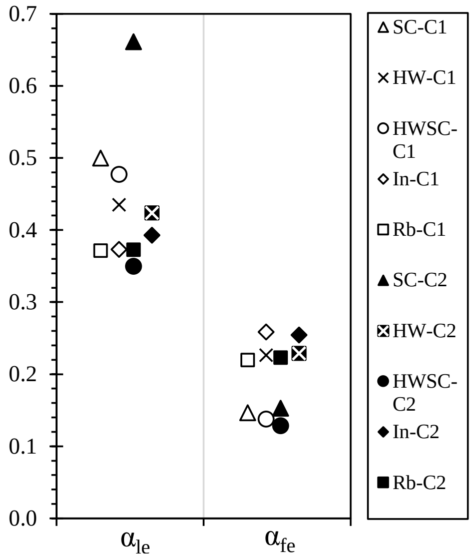

Figure 9 Influence of surface category on the coefficient α. For symbols see Figure 7.
(for better visibility symbols are spread horizontally)

NSR 2 [SS2], [SS5], [SS11], [SS14]

I have proved the influence of concrete compressive strength on the bond behaviour to concrete. I have developed a new test method. I have studied GFRP and BFRP bars having indented, helically wrapped, sand coated, sand coated and helically wrapped or ribbed surfaces and diameters of 6 to 12 mm. The average concrete compressive strengths were 35 and 66 MPa.

2.1

I have experimentally proved that the increase of concrete compressive strength from 35 to 66 MPa has an enhancing effect on the bond strength of GFRP and BFRP bars (Figure 10), despite the fact that according to available literature [14] the concrete compressive strength has no influence above approximately 30 MPa. **Moreover, I have proved that the increase in the bond strength is statistically significant**.

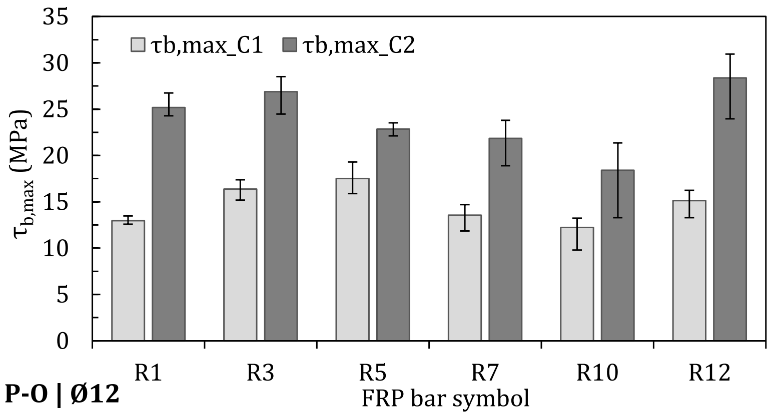

Figure 10 Effect of concrete strength (35 (C1) and 66 MPa (C2)) on the bond strength ($\tau_{b,max}$) of various FRP bars (R1, R3, R5: SC; R7: HWSC; R10: In; R12: Rb). For symbols of the surfaces, see Figure 7

2.2

I have developed – and proved its applicability – a new test method and specimen to study the bond behaviour of FRP bars, that is, the Direct Tension (DT) pull-out test, (Figure 3 and Figure 4). The stress state in the concrete – during the DT test – is similar to that of structural application (e.g., bar in the tension zone). I have experimentally proved that the measurable bond strength by DT test method is lower than that of P-O test. The difference in bond strengths is a function of the bar diameter and surface, as well as the concrete strength.

NSR 3 [SS4], [SS8], [SS12]

I have determined the influence of entrained air on the bond behaviour of FRP bars to concrete. I have demonstrated it for GFRP and BFRP bars having indented, sand coated, sand coated and helically wrapped or ribbed surfaces; diameters of 6 to 12 mm and average concrete compressive strengths of 36 to 75 MPa. The amount of air-entrained admixture was 0.15% of the mass of applied cement.

3.1

I have demonstrated that there is no statistically significant interaction between the influence of entrained air and the influence of the other involved factors (concrete strength, bar surface and diameter).

3.2

I have experimentally proved that the entrained air does not influence the bond failure mode nor the shape of the bond stress-slip curves (Figure 11 and Figure 12).

B6-In-12-G-C1A B6-In-12-G-C1 B2-SC-12-G-C1A B2-SC-12-G-C1

Figure 11 Failure surfaces of representative samples of pull-out specimens (images not to scale). C1A represents the specimens with air-entrained, while C1 stands for normal (non-air-entrained) concretes.

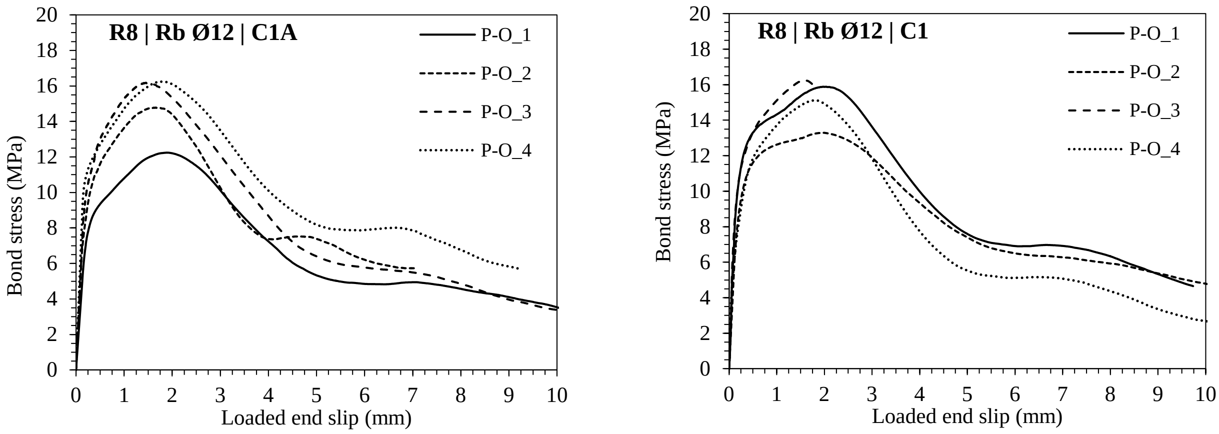

Figure 12 Representative bond stress-slip relationships for air-entrained (left) and normal concrete (right)

3.3

I have proved – based on the statistical hypothesis analysis of the experimental bond strength results (Figure 13) **– that the mean bond strength of FRP bars statistically significantly decreases due to the entrained air** (Table 1)**. I have performed hypothesis and analysis of variance tests to define the ratio of the average bond strength results in air-entrained and non-air-entrained concretes. Furthermore, based on the lower limit of the 95% confidence interval I have defined reduction factors to account for the decrease in bond strength.**

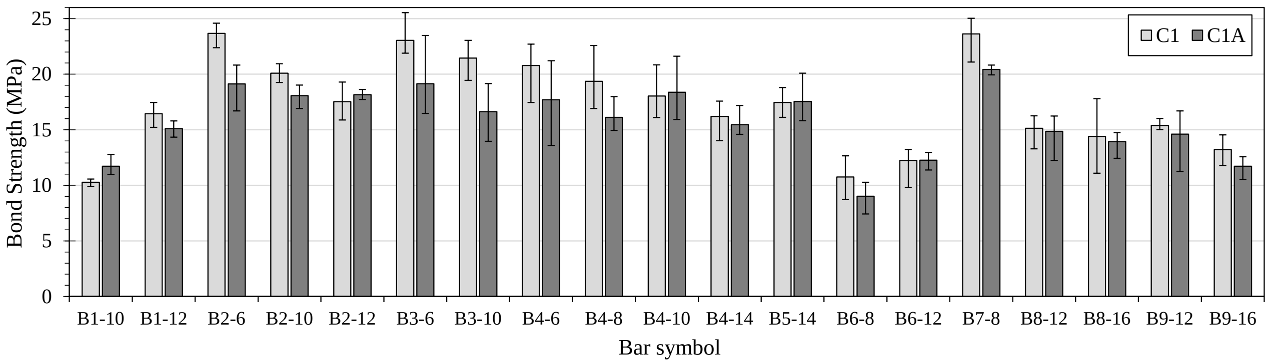

Figure 13 Effect of AEA on bond strength. C1A – air-entrained, C1 – non-air-entrained concrete. Bar symbols are described in the PhD thesis

Table 1 Welch t-test for equality of means: Effect of AEA on the bond strength. Bond strength in NC and AEC are statistically significantly different ($p<0.05$)

t	df	p	MD	SED	95% CI	
2.560	132.516	0.012	0.110	0.043	0.025	0.194

NSR 4 [SS4], [SS8], [SS12]

I have experimentally (Figure 14) **and statistically proved that the bond strength of the applied indented GFRP bars increases with the diameter.** I have demonstrated it for average concrete compressive strengths of 36 to 75 MPa, and bar diameters of 8 and 12 mm.

Literature reports (e.g., [14]) that bond strength decreases as the bar diameter increases. I have demonstrated that in the case of indented GFRP bars the converse trend is caused by the different rib geometries (e.g., CLR).

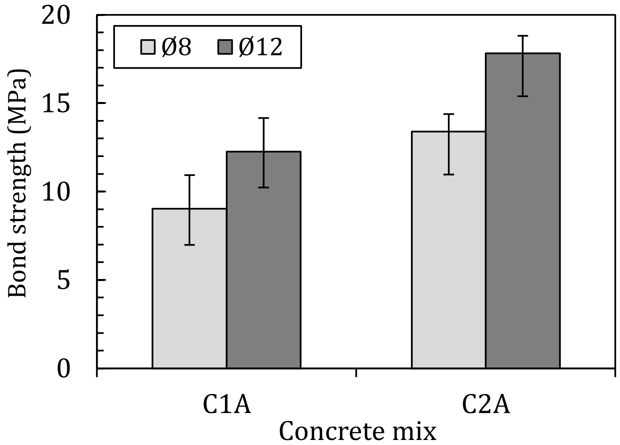

Figure 14 Bond strength of indented GFRP bars

NSR 5 [SS1], [SS10], [SS13]

I have developed – and proved its applicability – a new test method (Figure 5) **to study the bond behaviour of FRP reinforcement at hot state. It includes a contactless optical measurement technique (sensitivity of 1 µm) to evaluate the free end slip during the test.**

The appropriateness of the test setup is proved through the defined bond stress-slip relationships (Figure 15). Loaded and free end slips show good agreement (e.g., [28–30]), thus confirming the reliability of the optical measurement technique implemented to measure the free end slip.

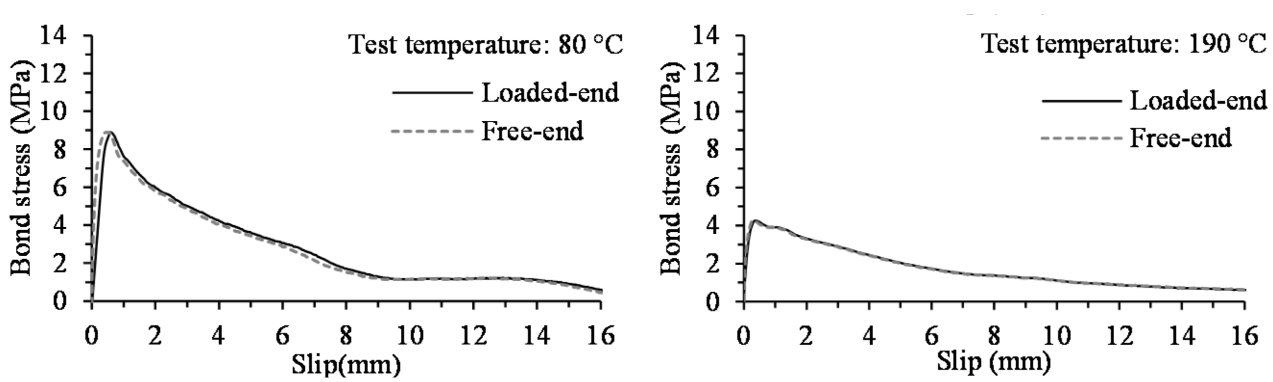

Figure 15 Comparison of bond stress-slip relationships — loaded versus free end

NSR 6 [SS1], [SS10], [SS13]

I have determined the influence of high temperature on the bond behaviour of indented GFRP bars to concrete. The concrete had an average compressive strength of 38.7 MPa at ambient temperature.

6.1

I have experimentally demonstrated that the bond failure mode of the indented 8 mm GFRP bars changes at the glass transition temperature (T_g). Failure occurs through shearing off of the concrete lugs for specimens tested at temperature levels lower than T_g, whilst failure developed within the GFRP bar surface at higher temperatures (Figure 16).

6.2

I have determined that the bond strength reduction at 80 °C is caused by the decrease of concrete mechanical properties at the same temperature (Figure 17).

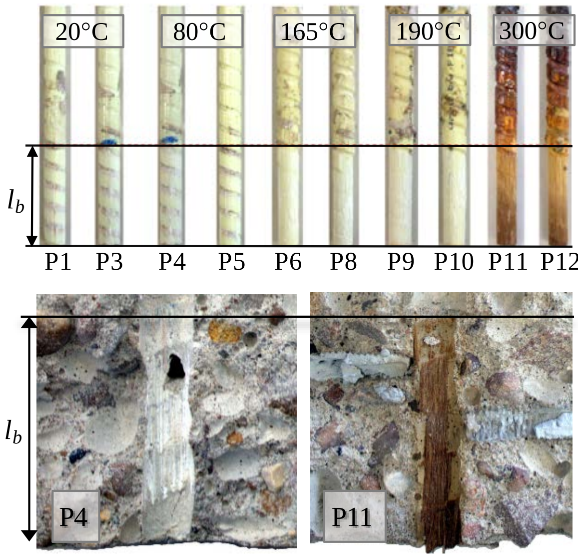

Figure 16 Surface of the GFRP bars (top) and concrete (bottom) after failure

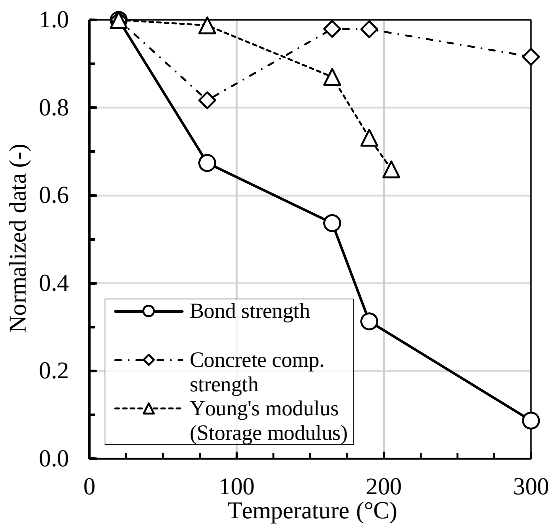

Figure 17 Effect of temperature on bond strength, concrete compressive strength and FRP bar modulus

6.3

Based on the experimental results, I developed adjustments to mBPE and CMR analytical models to account for the temperature dependence of bond stress-slip relationships up to 300 °C (Table 2).

Table 2 Summary of the parameters of the constitutive analytical bond stress-slip models

Parameter	Ambient temperature		High temperature	
	Loaded end	Free end	Loaded end	Free end
α	0.322	0.253	0.676	0.367
β	0.999	0.530	0.999	0.613
s_r	0.114	0.114	0.086	0.067

Graphical comparisons of the experimental and analytical bond stress-slip relationships are presented in Figure 18.

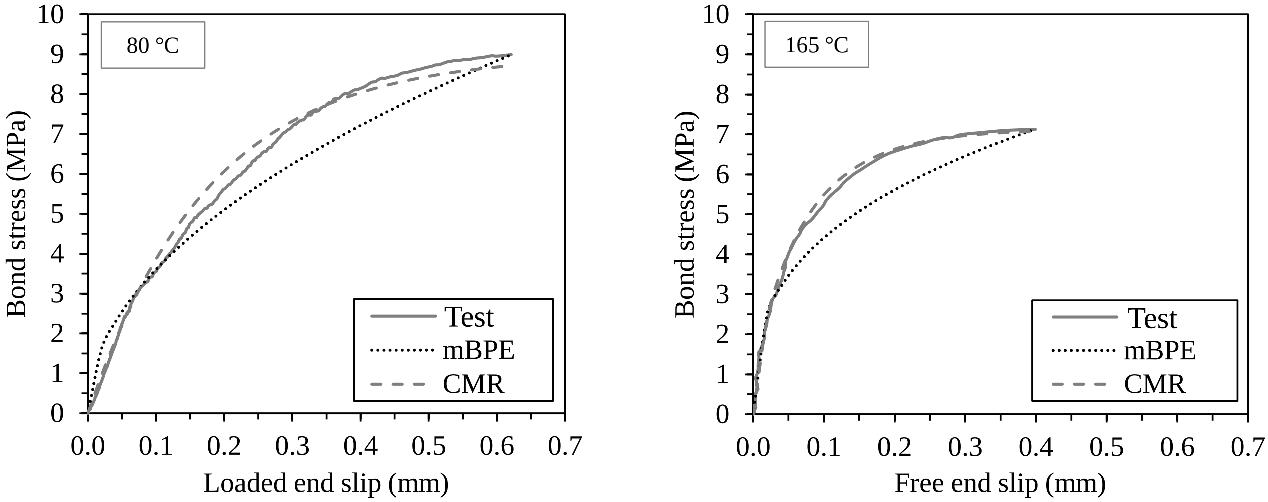

Figure 18 Comparison of the mBPE and CMR models with the experimental bond stress-slip relationship

5. APPLICATION OF NEW SCIENTIFIC RESULTS

The experimental data presented in this thesis completes the available data (Obj. I.) or provides data (Obj. II. and III.) stimulating a better understanding of the complex bond behaviour of FRP bars. Adjusted analytical models can be used to define characteristics such as anchorage length, transfer and development length as well as crack width and spacing. Whereas, the statistical hypothesis analysis allows locating the significant bond influencing factors and disclosing possible interactions among the influence of these factors.

Results presented for the influence of surface characteristics on the bond strength (e.g., statistically significant difference within the same surface category; statistically significant interaction between the effect of bar surface and diameter) can be used to take into consideration more accurately the effect of the surface.

The limit for the concrete compressive strength – to which extent it influences the bond strength – could be adjusted based on the presented results.

The research carried out can encourage the applications of FRP reinforced AEC, that diminishes the two most significant degradation types. However, the research should be completed with different AEAs and dosages.

The provided statistical methodology can be applied on the available database or it can help to design a new test series and to improve the available formulae for bond strength estimation.

The robust framework developed allows running repeatable pull-out tests at high temperatures. A contactless measurement system has been developed and integrated within a well-established pull-out test methodology to reliably monitor the behaviour of specimens exposed to simultaneous mechanical and thermal loading. The calibrated parameters can be adopted by researchers and engineers to account for the effect of temperature on the bond behaviour of GFRP bars embedded in concrete. However, further experimental results are necessary for FRP bars with other surface characteristics.

The calibrated parameters of the analytical models can be adopted by researchers and engineers to account for the effect of surface characteristics on the bond behaviour of FRP bars embedded in concrete.

In addition to the above, the results of this thesis can be used for the standardization process of FRPs.

6. References

6.1 List of publication related to the new scientific results

Journal papers

[SS1] Sólyom, Sándor, Di Benedetti, Matteo, Guadagnini, Maurizio, Balázs, György L. Effect of temperature on the bond behaviour of GFRP bars in concrete. Compos Part B Eng 2020; 183. doi:10.1016/j.compositesb.2019.107602. IF 7.635, Q1.

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[SS3] Sólyom, Sándor, Balázs, György L. Analytical and statistical study of the bond of FRP bars with different surface characteristics. Submitted for publ.

[SS4] Sólyom, Sándor, Di Benedetti, Matteo, Balázs, György L. Bond of FRP bars in air-entrained concrete: experimental and statistical study. Submitted for publ.

[SS5] Sólyom, Sándor, Di Benedetti, Matteo, Balázs, György L. Effect of surface characteristics of FRP bars on bond behavior in concrete. ACI SP 2018; 327:41.1-41.20. Scopus.

[SS6] Sólyom, Sándor, Di Benedetti, Matteo, Szijártó, Anna, Balázs, György L. Non-metallic reinforcements with different moduli of elasticity and surfaces for concrete structures. J of ACEE 2018; 11:79–88. doi:10.21307/ACEE-2018-025. WoS.

[SS7] Sólyom, Sándor, Balázs, György L. Sand coated CFRP rebars – Modelling of bond. J Concr Struct 2016; 17:29–36.

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