THE METHODOLOGY FOR TESTING THE BOND BETWEEN FRP REINFORCEMENT AND CONCRETE UNDER THE INFLUENCE OF HIGH TEMPERATURES AND FIRE

Pavlína Zlámalová*[,1], Martin Zlámal[1], Đorđe Čairović[1], Juraj Lagiň[1], David Vašátko[1], Petr Štěpánek[1]

*176430@vutbr.cz
[1] Brno University of Technology, Faculty of Civil Engineering, Institute of Concrete and Masonry Structures

Abstract

The determination and understanding of the bond strength between FRP reinforcement and concrete, which ensures the mutual interaction of these materials, are indispensable for the proper, safe, and reliable design of concrete structures with internal reinforcement. This characteristic also serves as a fundamental parameter for designing the anchorage length of the reinforcement.

While it is one of the fundamental characteristics, there is no domestic or international standards defining the procedure for testing and determining the influence of high temperatures and fire on the bond strength between FRP reinforcement and concrete.

Keywords

Bond strength, test methods, fire, high temperatures

1 INTRODUCTION

In general, it can be observed that the failure mode and behaviour of the contact between FRP reinforcement and the surrounding concrete differs from conventional ribbed steel reinforcement [1]. The maximum stress in the bond between FRP reinforcement and the surrounding concrete depends both on the surface treatment of the reinforcement bars and the mechanical characteristics of the FRP reinforcement (modulus of elasticity, matrix type, etc.) and the concrete strength. Bond failure is typically caused by the separation of the surface treatment of the reinforcement from the core of the cross-section. However, in cases of lower concrete strengths, shear failure of the concrete may occur at the level of the reinforcement's surface treatment, regardless of the type of surface treatment used for the reinforcement, with many FRP reinforcement manufacturers predominantly employing sanding or additional groove milling for surface treatment.

An important factor affecting the bond between reinforcement and concrete is the influence of the surrounding environment, which can negatively impact the resulting bond strength, particularly with regard to temperature [2], [3], [4], [5], [6]. It can be expected that as the temperature in the surrounding environment increases, the behaviour of FRP reinforcement in terms of bond strength will be primarily influenced by the properties of the matrix, specifically reaching the glass transition temperature (T_g) at which a significant reduction in bond strength is expected to occur.

2 METHODOLOGY

The methodology for testing the bond strength between FRP reinforcement and concrete under the influence of high temperatures and fire aims to specify testing methods for assessing the bond strength between FRP reinforcement and concrete at elevated (extreme) temperatures. Simultaneously, this methodology allows for conducting tests on FRP reinforcement with variable surface treatments at a defined (fixed) bond length.

The basic concrete strength class considered for bond tests is C 30/37 according to ČSN EN 206+A2 [7]. It is possible to test different strength classes; however, this class ensures compatibility of results with available international testing procedures. When using other concrete strength classes, especially higher-strength concrete, it is not expected to have a significant influence on the achieved results, given the anticipated mode of failure (assuming there is no concrete failure).

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Destructive methods for testing the bond strength of FRP reinforcement with concrete at normal temperatures

The purpose of the methodology described below is not to establish the bond strength of FRP reinforcement with concrete at normal temperatures since standardized testing methods already exist for this purpose (see, for example, [8], [9], [10], [11], [12]). The methodology for determining the mechanical properties of FRP reinforcement, including the bond strength between FRP reinforcement and concrete, through short-term tests, is also extensively detailed in [13]. However, as these properties are further utilized as reference values, the fundamental requirements are summarized below.

For clarity, commonly used bond testing methods without temperature influence, also referred to as "pull-out tests," are presented in Tab. 1.

Tab. 1 Summary of applicable regulations for testing the bond between FRP reinforcement and concrete.

Standard/ Regulation	Shape of specimen/ reinforcement	Reinforcement diameter	Edge length of the cube	Loading rate 1)	Length of the bond portion L_s
ACI 440.3R-12 [12]	*Cube unreinforced*	*Without differentiation*	*200 mm*	*20 kN/min* *1.3 mm/min*	*5d*
ISO 10406-1 [10]	*Cube reinforced*	*< 17 mm* *17 – 30 mm*	*100 mm* *150 mm*	*10 – 20 MPa/min*	*4d* *4d*
ASTM D7913 [13]	*Cube unreinforced*	*Without differentiation*	*200 mm*	*20 kN/min* *1.3 mm/min*	*5d*
CSA S806-12 [11]	*Cube unreinforced*	*Without differentiation*	*150 mm*	*22 kN/min* *1.27 mm/min*	*4d*
GOST 31938-12 [14]	*Cube unreinforced*	*≤ 10 mm* *12 – 18 mm* *20 – 30 mm*	*100 mm* *150 mm* *200 mm*	*20 kN/min*	*5d*

1) The loading rate is defined as:
- the increase in applied force in kN/min;
- the displacement of the loading device in mm/min;
- the increase in stress in the reinforcement in MPa/min.

Destructive methods for testing the bond strength of FRP reinforcement with concrete under the influence of fire/high temperatures

As already mentioned, testing methods for the bond strength of FRP reinforcement with concrete at high temperatures or under the influence of fire do not exist. Similar regulations for bond testing at elevated temperatures are also lack for steel reinforcements. However, defining the relationship between mechanical properties and exposure temperature is essential for robust and safe concrete structure design. Therefore, in the past 10 years, this phenomenon has been a frequent subject of experimental research (see, for example, [14].

Testing procedures and equipment

Determining the effect of high temperatures on the bond between FRP reinforcement and concrete is a complex issue that combines two different types of loading: mechanical and thermal, similar to the influence of high temperatures on the tensile strength of the FRP reinforcement.

Therefore, it is possible to define two distinct testing methods for bond testing:

- under a steady temperature state (*steady temperature state*), or
- under a transient temperature state (*transient temperature state*).

Both approaches can be used to experimentally assess the impact of high temperatures and fire on the bond between FRP reinforcement and concrete. It is evident that material properties at high temperatures can be determined under various conditions.

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Considering the configuration of the experimental specimen for bond testing, which is a concrete element with FRP reinforcement, the test under a steady temperature state, unlike the tensile strength test of FRP reinforcement, may not be suitable.

In most cases, for conducting the test under a steady temperature state, electrical heating in specialized environmental chambers is utilized. However, it is assumed that uniform heating of the concrete specimen intended for bond testing to the desired temperature would be disproportionately long, inefficient, and not reflecting real conditions.

Since fire is a relatively short, non-stationary process lasting from a few minutes to several hours, the determined properties should ideally reflect the varying thermal conditions and loading conditions (as well as the duration of heating) that can occur in reality.

From this perspective, the testing method under a transient temperature state appears to be more appropriate and descriptive, as it takes into account and encompasses the influence of microstructural damage to concrete at elevated temperatures due to the effects of fire. It is further described in this methodology.

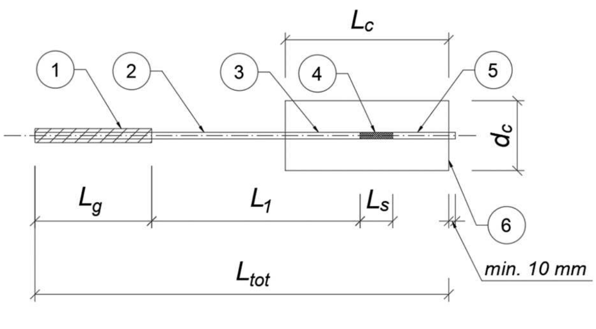
The bond between FRP reinforcement and concrete under a variable temperature condition

The purpose of this testing method is to determine the ultimate stress in the bond between non-metallic FRP reinforcement and concrete. Circular or predominantly circular cross-sectional FRP reinforcement bars are intended for use as internal load-carrying reinforcement in the concrete structures. The method assumes variable temperature conditions and a temperature range of up to 200 °C on the portion of the surface of the reinforcement in contact with the concrete. This surface temperature, present inside the concrete test specimen, corresponds to the temperature inside a fire furnace in which the fire exposure follows a predefined fire curve, up to a maximum of 1100 °C.

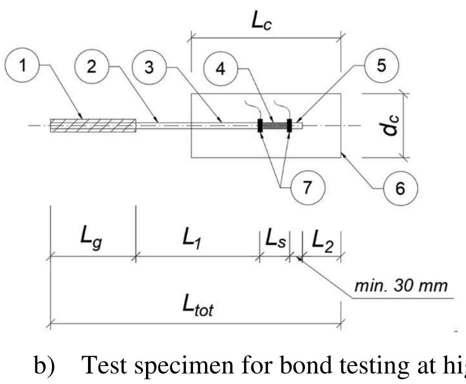
Within this method, test specimens are initially subjected to a selected level of mechanical loading and subsequently exposed to variable high temperatures until bond failure occurs. The ambient temperature must be within the range of 10 °C to 35 °C, and actual temperature and humidity values must be recorded and included in the test report.

Geometry of test specimens

As mentioned earlier, it is ideal to produce both test specimens for high-temperature testing and samples for testing at normal temperatures in an identical configuration concerning the concrete portion of the test specimen and the placement of the reinforcement (Fig. 1).



a) Test specimen for bond testing at normal temperatures.



b) Test specimen for bond testing at high temperatures.

1 - Anchorage termination of reinforcement
2 - Free length of reinforcement
3 - Disbonded reinforcement without bond
4 - Portion of reinforcement with full bond
5 - Disbonded reinforcement without bond
6 - Concrete anchorage block
7 - Thermocouples

L_{tot}… Total sample length
L_g… Anchorage termination length
L_1… Total disbonded length
L_s… Bonded length
L_2… Distance from the end of reinforcement to the surface
L_c… Concrete anchorage block length
d_c… Concrete anchorage block diameter

Fig. 1 Test cylindrical specimen for bond testing.

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Considering the performance of the high-temperature test using the transient temperature state method, it is assumed that the experiment is conducted in a fire furnace. The optimal shape for the concrete anchorage block is cylindrical to ensure the uniform heating of the specimen and the heat flow around it.

Determination of initial diameter, cross-sectional area, and active bond length

To calculate bond stress and evaluate the results of bond tests between FRP reinforcement and concrete at both normal and elevated temperatures, as described in this document, it is necessary to establish the nominal diameter of the reinforcement, denoted as d, the nominal cross-sectional area of the reinforcement A_f (typically specified by the manufacturer or determined in accordance with [10]), the length of the bond portion of the reinforcement denoted as L_s and the free length of the reinforcement between the anchorage termination and the bonded portion, denoted as L_l (with a precision of 0.5 mm).

The actual diameter of the reinforcement (in millimetres), which includes the surface treatment of the reinforcement (e.g., sanding, ribbing, etc.), and the length of the bonded portion of the reinforcement must be measured at least six times using a vernier calliper in accordance with ISO 13385-1 [15] and be in compliance with ISO 10406-1 [10], in two mutually perpendicular directions. The measurement record is a mandatory component of the test report.

Testing equipment

An sample testing equipment for conducting bond tests between FRP reinforcement and concrete under variable temperature conditions consists of:

- a specially designed fire furnace for subjecting the specimen to test conditions;
- a temperature control system;
- a loading frame for anchoring and mechanically loading the specimens designed to create suitable conditions for supporting and loading;
- equipment for applying loads to the test specimen, including a control and monitoring system;
- instruments for measuring the temperature inside the fire furnace and on the heated surface of the bonded FRP reinforcement;
- devices for measuring the deformation of the test specimen;
- devices for continuous time measurement and recording.

3 RESULTS

Conducting the test

Following the testing equipment assembling and securely fastening the test specimen, the load values must be set to zero before commencing the test. Once the values were zeroed, adjustments to the load measurements are not permitted during the test.

The test specimen must be clamped using suitable means, ensuring that the axial loading of the sample is maximized to minimize bending and torsion. If it is necessary to pre-load the test specimen before the start of the test, to ensure proper alignment of the sample and to establish its concentricity with the measurement and loading system, as well as for the installation of deformation sensors and recording their positions relative to the test specimen, it is permitted to tension the sample to a pre-load force denoted as F^*, which does not exceed 1 kN or 5% of the prescribed value to which the sample is subjected during the test (1). A similar method of clamping and test conditions is also specified in standards such as ISO 6892-1 [9]. It is recommended to adjust the applied load and specimen elongation measured using an extensometer to eliminate the influence of pre-stressing.

$$F^* \leq \begin{cases} 1\,kN \\ 5\,\%\,z\,F_{b,T} \end{cases} \tag{1}$$

The test specimen can be supported within the fire furnace to ensure its optimal position concerning the applied tensile force. The method of support must not adversely affect the distribution of the temperature field within the test specimen.

After securing the specimen, all deformation sensors must be installed, and thermocouples (TCs), placed in advance on the surface of the reinforcement in the bond area for temperature measurement, must be connected.

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Subsequently, the area around the test specimen's transition through the fire furnace insulation layer should be sealed.

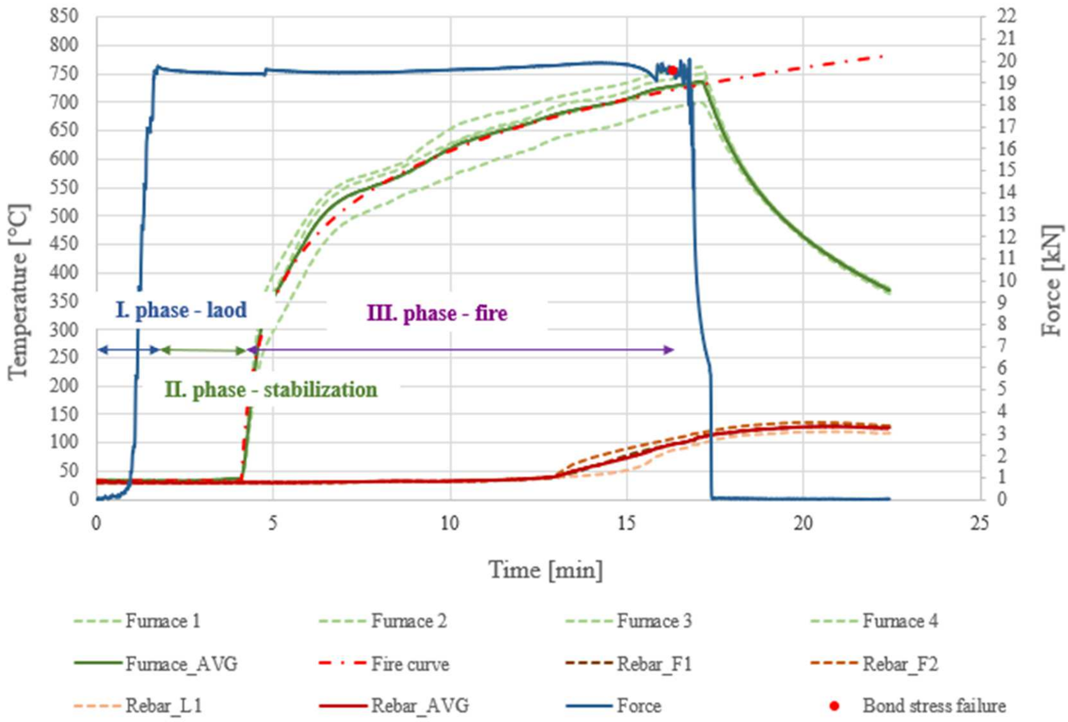

Fig. 2 Variable temperature state – typical test record.

Similarly to the testing of the tensile properties of FRP reinforcement under a variable temperature state, three distinct phases of the test procedure can be defined, with the loading sequence corresponding to a real fire scenario:

- Mechanical loading of the sample to the target level of tensile stress (phase I) - to minimize differences between testing methods according to the various standards, all conditions for testing at normal temperatures, including loading rate, must be maintained during the mechanical loading. The application of static force can be seen in the graph (blue colour).
- Deformation/stress stabilization (Phase II) - during the deformation stabilization, the force value should not exceed the prescribed value within the specified tolerances.
- Heating the sample until failure (Phase III) - the last phase of the test (heating the sample) should begin only after the measured deformation on both sides of the fire furnace was stabilized. The test sample should be heated until failure of bond stress of the rebar and concrete (red mark in the diagram). The temperature in the fire furnace must be controlled to closely match the nominal standard fire curve according to ISO 834-1 [17] considering the maximum tolerances. The gradual increase of temperature in the furnace is measured by 4 thermocouples (green colour, labelled as Furnace 1–4). The heating rate on the surface of the area with bond FRP reinforcement depends directly on the size of the concrete part of the test specimen. The increase of temperature on the surface of the rebar (brown colour) is measured by thermocouples placed as a pair of opposing thermocouples at the unloaded end (labelled as Rebar_F1 and Rebar_F2) and one individual thermocouple at the loaded end of rebar (labelled as Rebar_L1).

A typical testing procedure, including its individual phases, can be seen in Fig. 2.

4 DISCUSSION

It is necessary to determine the mean values of the stress in the bond between FRP reinforcement and concrete $\tau_{fb,T,m}$ (including standard deviation or coefficient of variation), or characteristic values $\tau_{fb,T,k}$ based on the obtained results. Additionally, it is recommended to establish so-called normalized values (indicating the ratio between the

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value determined at high temperatures and the reference value, i.e., the value determined at normal temperatures) and their dependence on the acting temperature.

The decisive parameter for evaluation is the average temperature reached on the surface of the part of the FRP reinforcement bonded to the concrete at the moment of failure of the test specimen. The temperature difference measured on individual thermocouples (TCs) from the average temperature on the surface ot the reinforcement should not exceed 10%. If a greater difference is reached on any TEC, this sample should be excluded from the evaluation and replaced with a new one if necessary.

The bond stress in the bond between FRP reinforcement and concrete with temperature influence $\tau_{fb,T}$ (2), at the measured critical temperature T, is determined as the ratio of the target force $F_{b,T}$ o the product of the reinforcement's circumference u assumed in the case of an idealized circular cross-section) determined from the average value of the reinforcement diameter d and the length of the part of the FRP reinforcement with bond L_s:

$$\tau_{fb,T} = \frac{F_{b,T}}{u \cdot L_s} \tag{2}$$

where $\tau_{fb,T}$ is the bond stress between the FRP reinforcement and concrete with temperature influence, $F_{b,T}$ is the selected level of loading of the test specimen, u is the circumference of the reinforcement, L_s is the length of the part of the reinforcement with the bond.

In addition to the maximum bond stress value, it is also necessary to determine the bond stress values when the reinforcement is displaced in the bond region s_f (3) o 0.05; 0.1 a 0.25 mm, where the displacement of the reinforcement in the bond region must be defined as the total deformation value obtained from the deformation measuring device $s_{f,tot}$ located at the loaded end of the reinforcement, reduced by the elastic elongation of the reinforcement $s_{f,el}$ (4). The effect of temperature on rebar displacement was neglected since the free length of the rebar exposed to the effects of fire in a furnace is minimal. Moreover, this measurement is practically impossible with regard to the configuration of the experiment.

$$s_f = s_{f,tot} - s_{f,el} \tag{3}$$

where s_f is the displacement of the reinforcement in the bond-slip region (*bond-slip*), $s_{f,tot}$ is the total displacement at the loaded end of the reinforcement at the location of the measuring device, $s_{f,el}$ is the elastic elongation of the reinforcement over the length L_e.

The elastic deformation of the reinforcement is determined using Hooke's law and the assumption of elastic behaviour of the reinforcement over the length L_e which corresponds to the distance between the region of bond with the FRP reinforcement and the position of the measuring device at the loaded end of the reinforcement:

$$s_{f,el} = \frac{F_{b,T} \cdot L_e}{E_{f,0} \cdot A_f} \tag{4}$$

where $F_{b,T}$ is the selected load level of the test specimen, L_e is the distance between the region of the bond with the FRP reinforcement and the position of the measuring device at the loaded end of the reinforcement, $E_{f,0}$ is the modulus of elasticity of the reinforcement without the influence of high temperatures, A_f is the cross-sectional area of the reinforcement.

5 CONCLUSIONS

The presented methods and recommendations to testing the mechanical properties of non-metallic internal structural reinforcements under the influence of high temperatures and fire, specifically tensile strength and modulus of elasticity of composite reinforcement and their compatibility with concrete, have been experimentally verified and can be considered valid within the scope defined by this methodology.

The acquired knowledge is applicable for the design and assessment of fire resistance in concrete structures reinforced with internal non-metallic reinforcement, significantly expanding and complementing existing regulatory provisions in this design domain.

The methodology allows for the expansion of application areas for concrete structures reinforced with internal non-metallic reinforcement and may represent a significant step towards innovating existing normative regulations for designing concrete structures subjected to the effects of fire.

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