THE IMPACT OF ELEVATED TEMPERATURES ON THE INTERACTION OF FRP REINFORCEMENT AND CONCRETE: AN EXPERIMENTAL STUDY

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Abstract
This research focused on determining the interaction of FRP reinforcement and concrete under normal conditions and elevated temperatures. The specimens consisted of reinforcement embedded into a concrete block and loaded with tensile force. Specimens representing extreme conditions were placed in a furnace and exposed to elevated temperatures. Three types of composite rebars with different properties were tested. The results of the experiments confirm a significant reduction in bond of composite rebars, which, at higher temperatures, can lead to a sudden loss of bond between the rebar and concrete.

Keywords
FRP reinforcement, bond stress of FRP reinforcement, impact of elevated temperature

1 INTRODUCTION

The aim of this study was to describe the issue of load-bearing capacity of bond stress of FRP reinforcement in common conditions and also extreme conditions represented by elevated temperature, i.e. the impact of fire on concrete structures. The bond between reinforcement and concrete is a crucial factor that ensures their interaction and functionality of the concrete element [1]. For the sake of safety, it is therefore important to demonstrate this functionality even in extraordinary design situations, i.e. to define the behavior of FRP reinforcement in extreme conditions. [2], [3], [4]. This article focused on the experimental part of the research, which subsequently allowed us to define the modification of the anchoring relationships for FRP reinforcement. Three types of composite reinforcement were used in the experimental part, with different material properties and surface treatment.

2 METHODOLOGY

The experimental part of the research focused on testing the properties and behavior in the anchoring area. For the purpose of this experimental study, the manufacturer´s declared diameter of the rebars was used and further referred to as a nominal. The following reinforcements were used:

- GFRP composite reinforcement based on glass fibers Prefa Rebar, nominal diameter of rebar 14 mm. The surface of the reinforcement is treated by sand coating. Sample designation "P";
- GFRP composite reinforcement based on glass fibers ComBar, nominal diameter of rebar 12 mm, manufactured by Schöck. The surface of the reinforcement is treated with milled grooves. The reinforcement was chosen for comparison of the effect of surface treatment, when using the same type of fibers. Sample designation "C";
- BFRP composite reinforcement based on basalt fibers RockBar, nominal diameter of rebar 12 mm, manufactured by Galen. The surface of the reinforcement is treated by sand coating. The reinforcement was chosen for comparison of the effect of the used fibers, when using the same type of surface treatment. Sample designation "B";

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The reinforcement was tested in two configurations of loading tests:

- Pull-out test at the reference temperature of 20 °C – the test is designed to determine the basic parameters of the bond of the reinforcement at normal temperature when loading with linearly increasing force until the failure of the anchoring area. The sample designation is "0".
- Pull-out test under the effect of fire, i.e. elevated temperature – the test is designed to determine the bond behavior of the reinforcement under the effect of fire. It is assumed that the sample is loaded with the effect of fire while maintaining a constant force throughout the experiment. The sample designation is "F", referring to the word "fire".

A total of 24 specimens were tested under normal conditions and 30 specimens under elevated temperature conditions. The specimens are summarized in Tab 1.

Tab. 1 Summary of the number of tested samples for loading states.

Specimens	**Normal conditions**			**Fire**		
	P0	**C0**	**B0**	**PF**	**CF**	**BF**
Quantity	6	6	12	12	12	6
Summary		24			30	

Specimen configuration

The configuration of the experiment can be based on the methodology described in ACI 440 3.R-12 [5], ISO 10406-1:2015 [6], ASTM D7913 [7], CSA S806-12 [8] or GOST 31938-12 [9]. The summary of the methodology is described in [10]. The configuration of the specimens was defined as a concrete block, with the rebar in contact with the concrete for a length equal to five times the diameter of the rebar. The remaining part of the rebar should be isolated, so that during the loading test there is no contribution to the overall load-bearing capacity of the rebar. For the experimental part, the shape of the concrete body was chosen to be a cylinder with a diameter of 150 mm, which allowed the same distribution of temperature around the reinforcement in the case of elements exposed to elevated temperature. This configuration was used for both types of environments due to the comparability of results. The concrete mix corresponded to regular concrete with an average compressive strength of the concrete of approximately 60 MPa. To prevent potential damage to the concrete layer due to applied loading and elevated temperature, the concrete blocks were reinforced with a spiral reinforcement of 6 mm diameter at a pitch of 60 mm. The configuration of the test specimen under normal conditions is depicted in Fig.1.

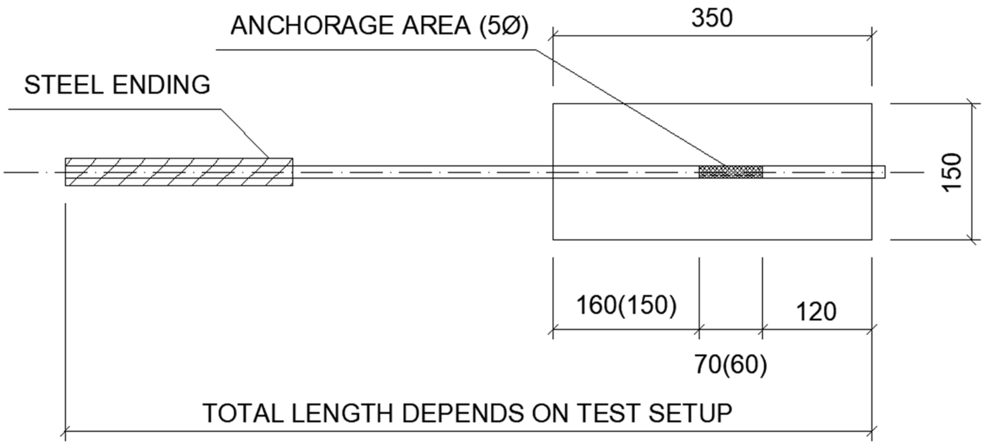

Fig. 1 Scheme of the sample tested at normal temperatures.

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A typical configuration of specimens for the fire test is depicted in Fig. 2.

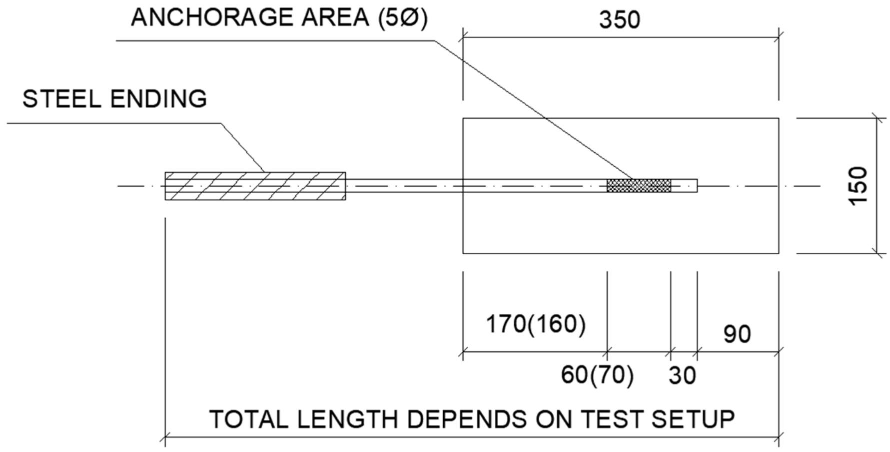

Fig. 2 Scheme of the sample tested at elevated temperatures.

The configuration of the loading test for specimens in a normal environment consists of a steel assembly, a hollow hydraulic cylinder, a load cell, and inductive (LVDT) sensors. During testing, the rebar is gradually loaded with tensile force through a steel end cap. Deformations (slip) of the rebar are measured at the free end of the rebar (bottom part) and the loaded end of the rebar (top part). The increase in force continues until complete failure. The diagram of the loading test is shown in Fig. 3.

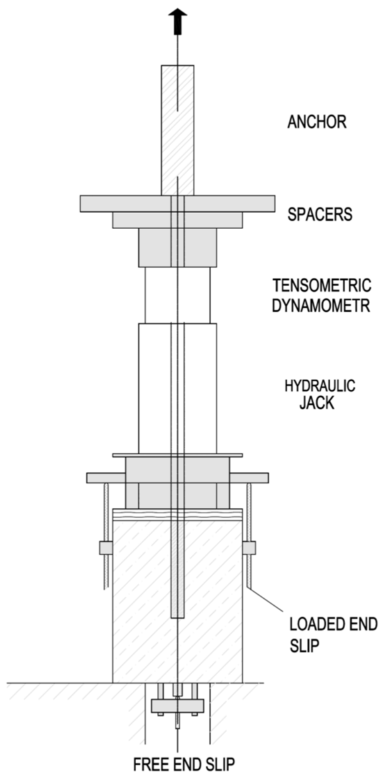

Fig. 3 Test setup for reinforcement under normal conditions.

In the case of specimens loaded with elevated temperature, the concrete block of the sample is placed horizontally into the heating furnace (see Fig. 4 left) at normal temperature. Subsequently, after applying a static force to the rebar, the fire test process begins, defined according to the standard curve ISO 834-1 [11]. Force measurement is ensured by a force meter connected through steel end cap and a joint. In this configuration,

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deformation is measured only at the loaded end of the rebar. Fig. 4 on the right shows a sample placed into the heating furnace.

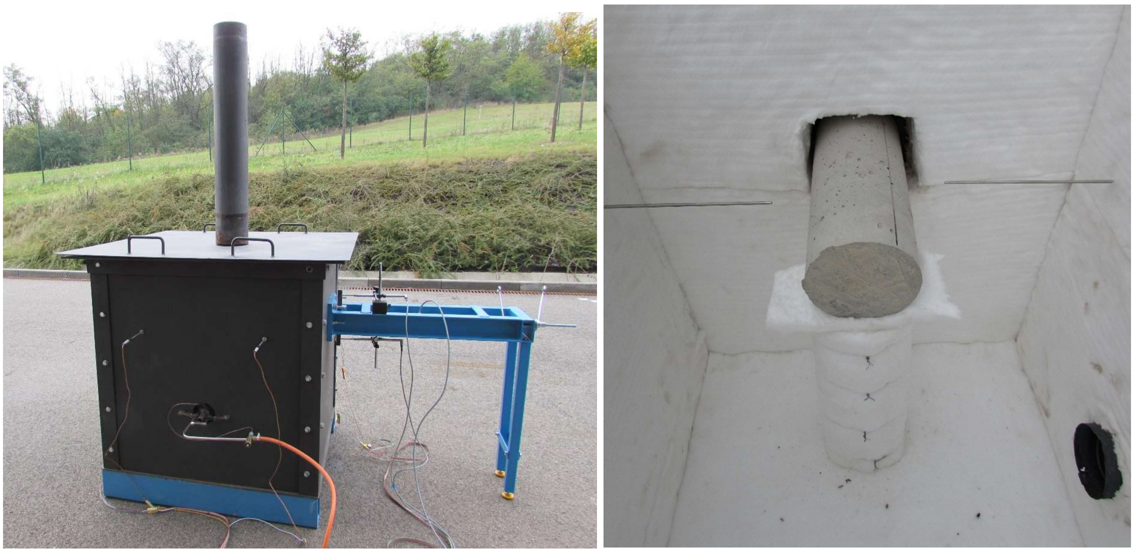

Fig. 4 Test setup for reinforcement fire conditions.

In Fig. 5, it is possible to observe the illustrative progress of the loading test of specimens exposed to elevated temperature. The graph shows the application of static force (blue color), the gradual increase of ambient temperature in the furnace measured by 4 thermocouples (green color, labeled as Furnace 1 to Furnace 4), and the increase of temperature on the surface of the rebar (brown color), measured using thermocouples placed as a pair of opposing thermocouples at the unloaded end (labeled as Rebar_F1 and Rebar_F2) and one individual thermocouple at the loaded end of rebar (labeled as Rebar_L1). The red mark indicates the moment of failure of bond stress of the rebar and concrete. The testing methodology is described in detail in study [10].

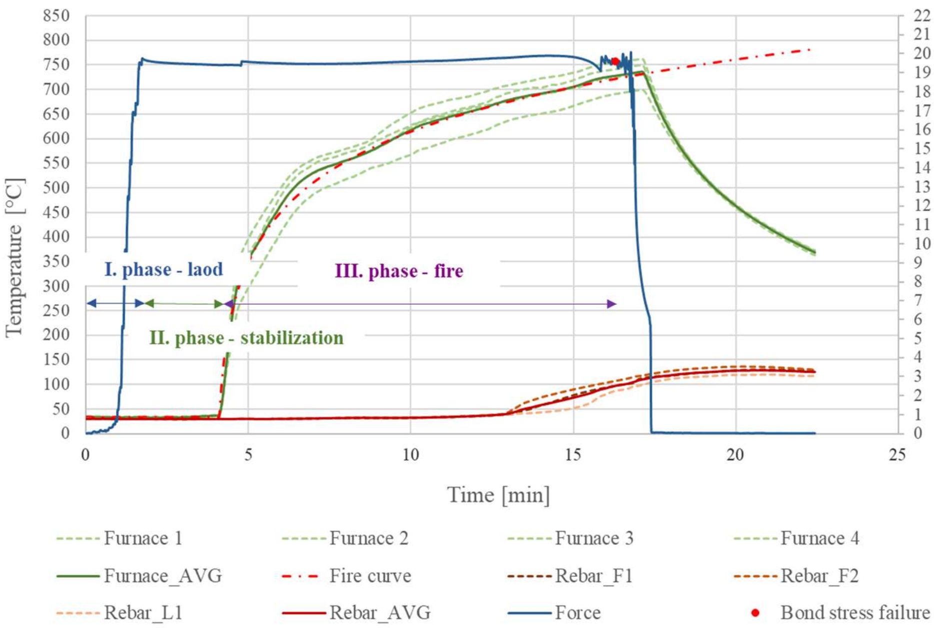

Fig. 5 Illustrative progress of the loading test of samples exposed to elevated temperature [10].

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3 RESULTS

Experimentally determined bond stress capacity of reinforcement and concrete under normal conditions

The results obtained during the pull-out test under normal conditions (temperature) can be seen in Fig. 6. This graph shows the average results achieved on individual types of rebars (designation according Tab. 1). It should be noted, that in Fig. 6, linear interpretation between chosen key points (i.e. 0.05 mm, 0.1 mm, 0.25 mm and when maximum stress was obtained) only represents the simplified approximations of the bond stress-strain curves.

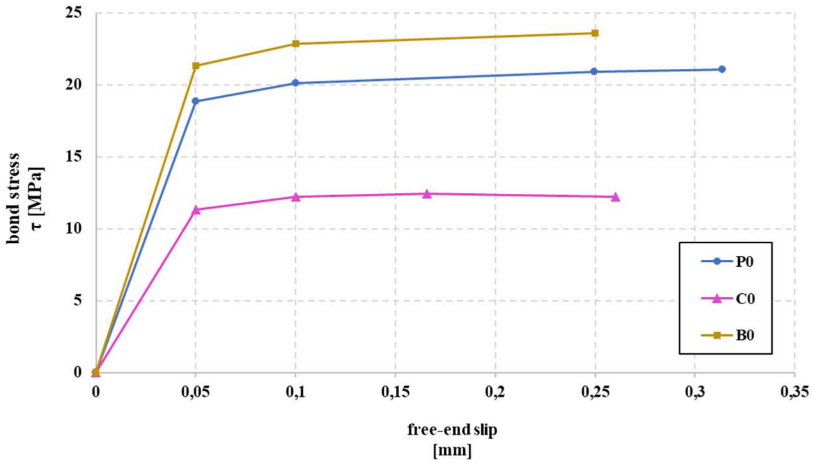

Fig. 6 Graphic representation of the results of pull-out tests under normal conditions.

Concrete with mean compressive strength determined on cubes 58,8 ± 1,2 MPa, tensile strength 4,1 ± 0,2 MPa and modulus of elasticity 28,1 ± 0,6 GPa was used in this experimental study. All types of tested rebar, namely Prefa ReBar, ComBar, and RockBar, show the first bond failure at a deformation of approximately 0.05 mm (Fig. 5). This is followed by softening of the contact stiffness and a rapid increase in deformations; however, at the same time, the bond stress continues to increase until the sample fails gradually.

Experimentally determined bond stress capacity of reinforcement and concrete at elevated temperatures

The results obtained during the pull-out test under the effect of elevated temperature cause by fire can be compared graphically (Fig. 7). This graph shows the approximations of the results achieved for individual types of rebar.

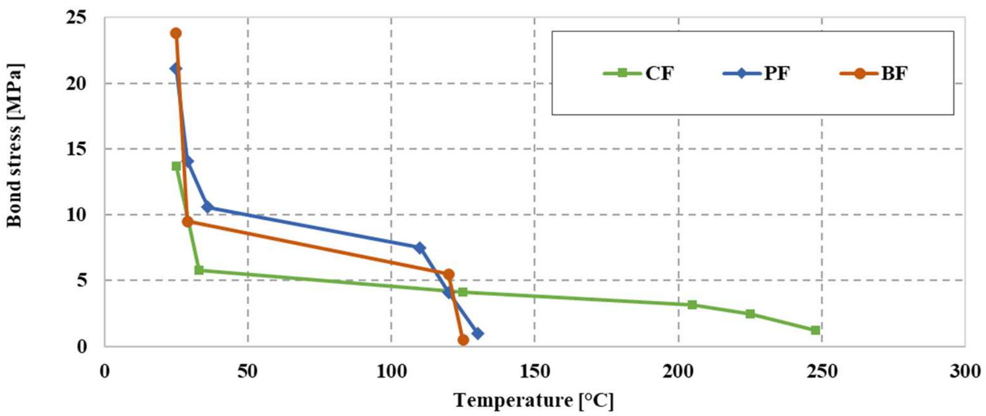

Fig. 7 The results of pull-out tests at elevated temperatures.

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4 DISCUSSION

Bond stress behavior of reinforcement under normal conditions

Fig. 8 Typical failure of the reinforcement in pull-out tests under normal conditions a) RockBar "BN", b) ReBar "PN", c) ComBAR "CN" (left to right).

Surface modification of FRP reinforcement by sand coating seems to be more suitable in terms of bond stress of concrete at normal temperature. Considering the differences in the quality of concrete in individual series, i.e. approximately 15% lower tensile strength of concrete for samples with ComBar reinforcement compared to samples with sand coated rebars ReBar (Fig. 8 a)) and RockBar (Fig. 8 b)), the comparison of the test results from the graph in Fig. 6 shows a significantly better bond stress capacity value of sand coated rebars with concrete compared to ComBar rebarswhich is modified with milled grooves and the bond is mainly provided by the anchor effect between the rebar and the concrete. In this case, the failure is accompanied by the shearing of concrete at the location of the ribs (Fig. 8 c)).

Bond stress behavior of reinforcement at elevated temperatures

Generally, we can state that the bond stress on the interface of rebar and concrete decreases very rapidly with the increasing temperature in the structure, regardless of the type of rebar. At temperatures of up to 100 °C on the surface of the rebar, there is a gradual loss of capillary water and a reduction in bond stress capacity due to the expansion of moisture and dehydration of ettringite and the bond stress capacity of the rebar is reduced to an average of 40% (Fig. 7). The loss of bond stress capacity is obviously due to the degradation of the concrete layer at the interface with the rebar (Fig. 9 a)). It should be noted that the temperature on the surface of the sample is already above 600 °C at this moment, and the gradual degradation of concrete due to elevated temperatures has an impact on the overall behaviour of the sample and the bond effect at elevated temperature caused bythe fire. The reduction in bond stress increases until the critical temperature of approximately 125 °C on the surface of the reinforcement is reached.

Therefore, there is a significant change in FRP rebar at lower temperatures. At temperatures above 100 °C on the surface of the rebar, the bond of FRP rebar becomes strongly dependent on the properties of the polymeric matrix, especially the glass transition temperature T_g, and the surface layer of sand coating begins to fail (Fig. 9 b)). When the matrix softening temperature range is reached, the bond stress capacity of the FRP rebar decreases very rapidly (Fig. 7), and at temperatures of around 150 °C, it is practically zero due to changes in the polymeric matrix (Fig. 9 c)) with a visible change in color before the ignition of the matrix. This behavior applies to both types of sand coated rebar.

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Fig. 9 Typical failure of the rebar in pull-out tests at elevated temperatures (left to right)
a) Rebar "PF" at a temperature below 100 °C, b) Rebar "PF" at a temperature above 100 °C, c) Rebar "PF" at a temperature above 150 °C, d) ignition of the Combar "CF" rebar at a temperature of 200 °C.

The behavior of FRP rebar ComBar with milled grooves is different. There is also a drop in bond stress capacity up to about half its value at slightly elevated temperatures, and with increasing temperature, bond stress continues to decrease. However, at temperatures of around 125 °C on the surface of the rebar, there is a different type of failure, namely the failure of concrete in the area of the grooves. With a further increase in temperature and exceeding 200 °C on the surface of the rebar, there is self-ignition of the matrix, disintegration of the FRP reinforcement ribs, and loss the bond is lost without failure of the concrete (Fig. 9 d)).

5 CONCLUSION

Based on the results of the experimental study aimed to determine the bond stress capacity of rebar and concrete for various surface modifications of the reinforcement, it can be concluded:

- the best variant of surface treatment of reinforcement out of the tested samples appears to be sand coating in normal environments;
- ribbed reinforcement achieves approximately 50% lower maximum stresses on the surface of the reinforcement.

Based on the results of the experimental study aimed to determine the effect of elevated temperature on the bond stress capacity of FRP reinforcement and concrete, it can be concluded:

- bond stress capacity generally decreases very rapidly in all types of reinforcement with increasing temperature, with a reduction to an average of 40% of the original bond stress capacity already at 100 °C;
- the behavior of FRP reinforcement is dependent on the value of the glass transition temperature of the reinforcement matrix T_g. Above 100 °C, the matrix softens and the surface layer of the reinforcement is damaged. After reaching the critical temperature, which was 150 °C for the tested reinforcement, the load-bearing capacity of the reinforcement is practically zero due to the changes in the polymeric matrix;
- in the case of ribbed surface of reinforcement, the drop in load-bearing capacity was more rapid at slightly elevated temperatures, up to T_g (i.e. 125 °C) which is when rib shearing begins. Nevertheless, it should be noted that even after reaching T_g, ribbed rebars have a capacity to carry the bond stress, and overall behavior can be described as more ductile;
- it is possible to define the dependence of the bond stress of FRP reinforcement and concrete at elevated temperatures.

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