

# DESIGN OF THE ANCHORAGE LENGTH OF FRP REINFORCEMENT WITH THE INFLUENCE OF EXTREME TEMPERATURE LOADING DUE TO THE EFFECTS OF FIRE

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## Abstract

The extremely high temperatures from fire exposure have a negative impact on the behaviour of reinforced concrete structures regardless of the type of reinforcement used. The reduced mechanical properties of the materials need to be taken into account in the design of the structure, including anchorage length, to ensure that the reinforcement does not detach from the concrete. In the case of Fibre Reinforced Polymers (FRP) reinforcement, there are limited number of codes addressing the design issues in a fire situation. This article, based on experimental findings, proposes a procedure for determining anchorage length of FRP reinforcement under elevated temperatures.

## Keywords

Fibre Reinforced Polymers (FRP), anchorage length, extremely high temperature

## 1 INTRODUCTION

To expand the practical applications of FRP reinforcement, it is necessary to determine its behaviour in extraordinary situations, such as exposure to fire. Even relatively low elevated temperatures have a negative effect on the mechanical properties of FRP reinforcement. In the safe design of a structure for an accidental load, it is therefore crucial to accurately determine the degree of reduction of tensile properties on bond strength in tensile reinforcement. To ensure the functionality of the reinforcement, it is important to proper anchor it to prevent a loss of bond strength between the concrete and the reinforcement. Anchor lengths influence the bond between the reinforcement and the concrete, and their mutual interaction, which changes with increasing temperature.

The method for designing the anchorage lengths of FRP reinforcement against the effects of fire was determined based on experimentally obtained results. Although this is one of the basic characteristics, there is no domestic or international standard defining the testing procedure and determining the impact of high temperatures and fire on the bond stress between FRP reinforcement and concrete. The testing methodology, with respect to the scope of this article, is only briefly described. The main focus of this article is to derive of relationships for determining the anchorage length of FRP reinforcement under the effects of fire.

This article builds upon another contribution in the same publication: The influence of fire and high temperatures on the bond between FRP reinforcement and concrete: an experimental study [1]. It should be noted that even though bond behaviour of FRP have been extensively investigated for example in [2], [3], to the best of the authors' knowledge, there is only a few scientific publications concerning the bond between FRP reinforcement and concrete under extreme temperatures [4], [5], [6], [7], [8].

## 2 METHODOLOGY

The aim of the experimental testing was to determine the bond strength for different types of FRP reinforcement, which would serve as a basis for determining anchorage lengths and design algorithms. The maximum bond strength between the FRP reinforcement and the concrete depends not only on the surface treatment of the reinforcement bars, but also on the mechanical characteristics of the FRP reinforcement (modulus of elasticity, type of matrix, etc.) and material characteristics of the concrete. Bond failure is typically caused by the separation of the surface treatment of the reinforcement from the core of the cross-section.

In low-strength concrete, shear failure of the concrete may occur at the location of the surface treatment of the reinforcement, regardless of the type of surface treatment of the reinforcement, which influences the bond stress at normal and higher concrete strengths. In our conditions, surface treatments of FRP reinforcements, such as sanding or additional groove milling, are commonly available. Another important factor negatively affecting bond stress is the impact of the surrounding environment and elevated temperatures.

During the anchoring of reinforcement in concrete, the transfer of tensile force from the reinforcement to the concrete occurs through the following methods [2]:

- chemical adhesion of the surface of the reinforcement to the concrete,
- frictional displacement between the reinforcement and the surrounding concrete,
- mechanical interlocking of irregularities on the surface of the reinforcement into the surrounding concrete.

Basic classification of tests for the bond stress of FRP reinforcement with concrete:

- Anchorage zone test – Pull-out test – at the reference temperature of 20 °C – determination of basic behaviour and bond strength parameter at normal temperature,
- Anchorage zone test – Pull-out test – under fire exposure – monitoring the influence of high temperature on the load-bearing capacity and behaviour of anchorage zones, or the bond strength between reinforcement and concrete.

The testing of bond strength between FRP reinforcement and concrete at normal temperatures was primarily based on relevant international standards ISO 10406-1 [9], ACI 440.3R-12 [10], CSA S806-12 [11], ASTM D7913 [12] a GOST 31938-12 [13]. There are no specific standards available for testing bond strength at elevated temperatures. The test methodology and specimens had to be designed. One of the key considerations was selecting a shape for the specimen that would allow for uniform heating. In this regard, a cylindrical shape was ideal, and reference tests were also conducted at normal temperatures of 20 °C.

The samples primarily differed in the type of reinforcement and its surface treatment. Therefore, the following reinforcements were used:

- GFRP reinforcement based on glass fibres (Prefa Rebar), diameter of 14 mm. The surface of the reinforcement is treated by sand coating. Sample designation "PF",
- GFRP reinforcement based on glass fibres (ComBar) by Schöck, diameter of 12 mm. Reinforcement with surface treated by milled grooves. The reinforcement is chosen for comparing the influence of surface treatment, using the same type of fibers. Sample designation "CF",
- BFRP reinforcement based on basalt fibres (RockBar) by Galen, diameter of 12 mm. The surface of the reinforcement is treated by sand coating. The reinforcement is chosen to compare the influence of the used fibres, using the same type of surface treatment. Sample designation "BF".

### 3 RESULTS

The main aim of the article is the experimental investigation of the effects of fire on bond strength between FRP bar and concrete is [1], including a detailed description of test setup, geometry boundary conditions, material properties and other. The authors also state that in normal conditions, the bond strength significantly affects the reinforcement from the perspective of its surface treatment. The increasing temperature has a negative impact on the bond strength between the reinforcement and the concrete, regardless of the type of reinforcement, as shown in Fig. 1. This applies even to steel reinforcement. In the case of FRP reinforcement, significant changes occur at lower temperatures compared to steel reinforcement. At temperatures above 100 °C, the bond stress starts to depend on the properties of the polymer matrix, especially at temperatures approaching the glass transition temperature  $T_g$ , when the matrix begins to lose its properties and adhesion rapidly decreases. Therefore, when designing the anchorage length of FRP reinforcement, it is necessary to consider the potential influence of elevated temperature.

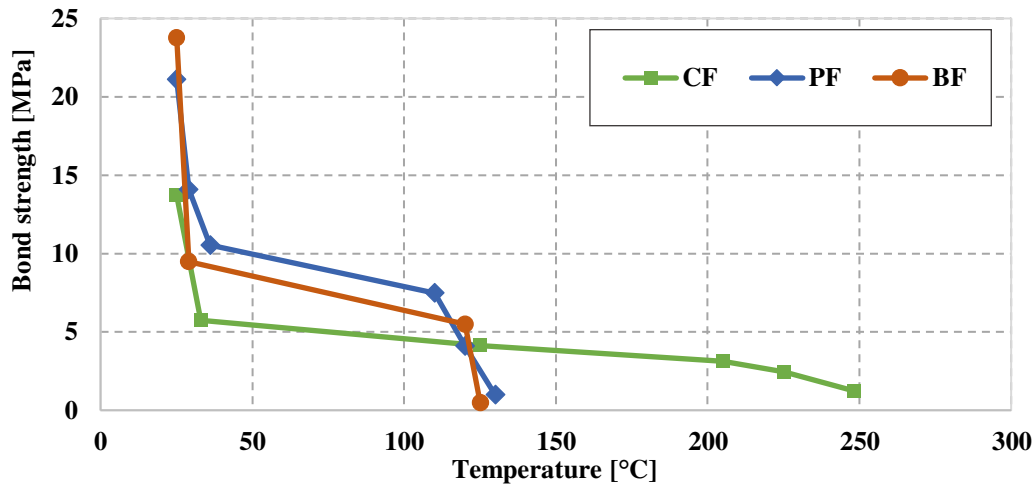


Fig. 1 The results of pull-out tests at elevated temperatures, CF is ComBar, PF is Prefa Rebar and BF is RockBar.

## 4 DISCUSSION

Concrete structures reinforced with FRP reinforcement, where mechanical resistance is required, must be designed to maintain their load-bearing function even in the event of fire exposure for the required fire resistance duration.

In relation to the design of structures reinforced with FRP reinforcements for fire effects, there is no normative regulation that comprehensively addresses this issue. Foreign normative regulations only address the issue marginally, or they provide the option to design this type of construction conservatively, for example, based on nomograms (e.g., CSA S806-12, Appendix R [11]). However, this approach is often limited to typical cases of construction, or to specific dimensions of a given type of structure.

The use of existing normative regulations for designing concrete structures for high-temperature and fire effects appears as a more suitable approach, especially ČSN EN 1992-1-2 [14], and the integration and application of knowledge and findings about the behaviour of FRP reinforcements at high temperatures to these regulations. However, none of these approaches address anchorage zones, which is the aim of this article – to provide further clarification in this regard.

### Design of anchorage length – the theoretical approach

When determining the anchorage length of reinforcement at normal temperatures, as seen in the equation (2), we can rely on a generally accepted assumption, which is also adopted by most of the normative regulations, including ČSN EN 1992-1-1 [15], that the force in the reinforcement is the same as the force required to pull the reinforcement out of the concrete, as seen in the equation (1).

Based on this assumption, we can derive the basic equation for determining the anchorage length of reinforcement  $l_b$ :

$$A_f \cdot \sigma_f = \pi \cdot d \cdot l_b \cdot f_b \quad (1)$$

$$l_b = \frac{d \cdot \sigma_f}{4 \cdot f_b} \quad (2)$$

where  $A_f$  is the cross-sectional area of the reinforcement in  $\text{mm}^2$ ,  $\sigma_f$  is the stress in the reinforcement for determining the corresponding anchorage length in MPa,  $d$  is the diameter of the reinforcement in mm,  $l_b$  is the anchorage length (general value) in mm, and  $f_b$  is the bond strength in MPa.

The determination of the anchorage length is primarily influenced by the diameter of the reinforcement, denoted as  $d$ , and the bond strength, denoted as  $f_b$  (general value). The bond strength between FRP reinforcement and concrete  $f_b$ , can be determined experimentally or conservatively based on normative regulations (e.g., ČSN EN 1992-1-1 [15]), with appropriate considerations for the bond strength values in relation to the strength characteristics of concrete (compressive or tensile strength). However, it should be noted that the condition mentioned above (1) may not always apply. Especially in the case of high-strength reinforcement, there may be

instances where exceeding a certain critical anchorage length no longer leads to an increase in transferred tensile force<sup>1</sup>.

### Experimental determination of bond strength under effects of fire

Assuming that bond strength values are determined experimentally based on standard regulations (see, for example, [9], [10], [11]), it is necessary to take into account that these values represent short-term bond stress under optimal conditions. The mean value of bond strength under normal temperatures  $\tau_{fb,m,0}$  must be further statistically evaluated (e.g. according to [16]) to determine the design value of bond stress  $\tau_{fb,d,0}$ .

In the case of structures loaded by high temperatures or fire, it is necessary to reduce the bond strength considering all negative impact that can affect the interaction between the reinforcement and concrete. In the case of high temperatures or fire, the intensity and speed of temperature changes in concrete due to fire are enormous and have a significant impact on the behaviour of the reinforcement in bond strength, regardless of the type of reinforcement used. Similarly, the behaviour of concrete is affected, as the extreme temperature increase leads to rapid changes in the structure of concrete and its accelerated degradation. This degradation is due to the development of microcracks, caused by volumetric changes in concrete due to temperature, and chemical changes caused by the degradation of cement paste and the release and transformation of free water, resulting in a loss of bond stress between the reinforcement and concrete. In a construction subjected to the effect of fire or high temperatures, rapid heating of the concrete leads to degradation and a decrease in bond stress to 40% of the value at normal temperatures (parameter  $D$ ), already at the initial temperature rise on the surface of the reinforcement [1].

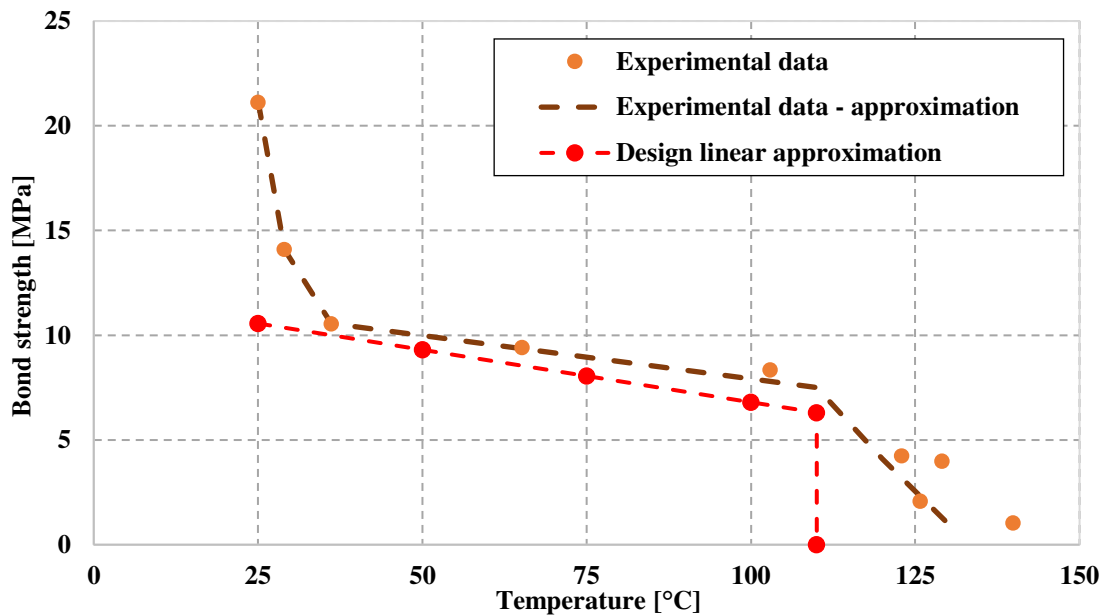


Fig. 2 An example of experimentally determining the bond strength between FRP reinforcement and concrete.

With increasing temperature due to fire, or high temperatures, there is a further decrease in the bond strength between the reinforcement and concrete. This decrease can be approximated by a linear relationship (equation (3)) depending on the temperature increase, taking into account the differences in behaviour with respect to the initial strength of concrete. This approximation is valid for the temperature range of 20 °C to  $T_g$ , where the glass transition temperature  $T_g$  is limiting regardless of the surface treatment of the reinforcement. It can be assumed that when this value is exceeded, the bond stress will approach zero limiting (Fig. 2).

$$\tau_{fb,d,T} = D \cdot \tau_{fb,d,0} - E \cdot (T - T_0), \quad \text{pro } T \in (20 \text{ } ^\circ\text{C}; T_g) \quad (3)$$

where  $\tau_{fb,d,T}$  is the design value of the bond strength between FRP reinforcement and concrete at high temperatures, or in the case of fire in MPa,  $\tau_{fb,d,0}$  is the design value of the bond strength between FRP reinforcement and concrete

<sup>1</sup> Similar behaviour is described, for example, in the anchoring of high-strength helical reinforcement or in the anchoring of carbon laminates. The value of the critical anchorage length has not been experimentally determined for internal FRP reinforcement under the impact of temperature.

at normal temperatures in MPa,  $T$  is the temperature at the surface of the reinforcement at the time of assessment in °C,  $T_0$  is the base temperature in °C,  $D$  and  $E$  are experimentally determined parameters without units.

The basic, or design, anchorage length of FRP reinforcement with concrete at high temperatures, or in the case of fire, is then determined based on the same assumptions as the bond strength of FRP reinforcement with concrete at normal temperatures. In the provided equations, the design value of bond strength at normal temperatures  $\tau_{fd,0}$  is replaced with the design value of bond strength at elevated temperatures  $\tau_{fd,T}$ .

## Determination of bond strength based on normative regulations

A normative approach for determining the anchorage length and bond strength between FRP reinforcement and concrete is to use methods based on valid normative regulations (ČSN EN 1992-1-1 [15]) as seen in the equation (4) and (5). When using these values specified in the valid norms [15], it is necessary to consider that these values express the long-term bond strength, including long-term negative effects. The design value of the ultimate bond strength can then be determined based on the design tensile strength of concrete  $f_{ctd}$ :

$$f_{bd} = 2,25 \cdot \eta_1 \cdot \eta_2 \cdot f_{ctd} \quad (4)$$

where  $f_{bd}$  is the design value of the bond strength between FRP reinforcement and concrete in MPa,  $f_{ctd}$  is the design value of concrete tensile strength in MPa, and  $\eta_i$  are coefficients according to [15] without unit.

From the determined bond strength value, the basic anchorage length of the reinforcement  $l_{b,req}$  can be determined:

$$l_{b,req} = \frac{d \cdot f_{fu}}{4 \cdot f_{bd}} \quad (5)$$

where  $f_{fu}$  is the strength of the reinforcement (generally the strength of the reinforcement is assumed) in MPa,  $d$  is the diameter of the reinforcement in mm,  $l_{b,req}$  is the basic required anchorage length in mm, and  $f_{bd}$  is the design value of the bond stress of FRP reinforcement with concrete according to ČSN EN 1992-1-1 [15] in MPa.

The design value of the anchorage length (equation (6)) can then be determined based on the standard ČSN EN 1992-1-1 [15], taking into account all necessary parameters:

$$l_{bd} = \alpha_1 \cdot \alpha_2 \cdot \alpha_3 \cdot \alpha_4 \cdot \alpha_5 \cdot l_{b,req} \quad (6)$$

where  $\alpha_i$  are parameters expressing the interaction effect according to ČSN EN 1992-1-1 [15] without unit,  $l_{bd}$  is the design anchorage length in mm, and  $l_{b,req}$  is the basic required anchorage length in mm.

In the case of structures loaded to extreme high-temperature or fire, it is necessary to reduce the bond strength once again, considering all negative influences that may affect the behaviour of the bond strength between the FRP reinforcement and concrete. In the case of using a normative approach to determine the design value of the ultimate bond strength between FRP reinforcement and concrete  $f_{bd}$ , it is necessary to take into account that the standard ČSN EN 1992-1-1 [15] already considers long-term loading, the size of the reinforcement cover etc., which affect the bond strength between FRP reinforcement and concrete. Furthermore, it is again necessary to consider short-term loading due to high temperature or fire, by reducing the initial ultimate bond strength  $f_{bd,0}$  with the parameter  $D$ .

The impact of high temperature, or fire, on the bond strength between the reinforcement and concrete can be determined based on the following relationship (7). This approximation is valid for a temperature range of 20 °C to  $T_g$ , where the glass transition temperature  $T_g$  is limiting regardless of the surface treatment of the reinforcement, and it can be assumed that when this value is exceeded, the bond stress will approach zero limit.

$$f_{bd,T} = D \cdot f_{bd,0} - E \cdot (T - T_0) \quad (7)$$

where  $f_{bd,T}$  is the design value of the bond strength between FRP reinforcement and concrete at high temperatures, or fire in MPa,  $f_{bd,0}$  is the design value of the bond strength between FRP reinforcement and concrete at normal temperatures in MPa,  $T$  is the temperature at the surface of the reinforcement at the time of assessment in °C,  $T_0$  is the reference temperature in °C, and  $D$ ,  $E$  are experimentally determined parameters in without unit.

To prove design approach presented above, extensive experimental study has been performed and was presented in [1]. The recommended values for experimentally determined parameters are  $D = 0.4$ ;  $E = 0.02$  for  $f_{cm} < 35$  MPa;  $E = 0.05$  for  $f_{cm} > 35$  MPa in without unit. These parameters were determined from tests on FRP reinforcement based on glass and basalt fibres, with both sand-coated and milled surfaces. It should be noted that those parameters were obtained using the data from centric pull-out tests [9]. For this study, it was assumed, that the same values of parameters  $D$  and  $E$  will be obtained, regardless of the test type (centric pull-out, excentric pull-out, beam test or or other). Although further tests need to be performed to allow implementation and practical use of the presented approach, it presents a rather simple and effective way of including the reducing effects of fire and extreme temperatures on bond strength.

The basic, or design, anchorage length of FRP reinforcement with concrete under high temperatures, or fire, is then determined based on the same assumptions as the bond strength of FRP reinforcement with concrete under normal temperatures. In the provided equations, the bond strength at normal temperatures  $f_{bd,0}$  is replaced by the bond strength at elevated temperatures  $f_{bd,T}$ .

## 5 CONCLUSION

This article focused on the bond between FRP reinforcement and concrete under both normal and elevated temperatures. For the safe design of structures under fire conditions, there is a limited number of approaches to address this issue [11], [14]. Each of these approaches typically deals with commonly used constructions and none addresses anchorage lengths of FRP reinforcement under the influence of fire.

Through experiments on the bond strength between concrete and FRP reinforcement, the following key points were determined:

- The bond between FRP reinforcement and concrete is significantly influenced by the surface treatment of the reinforcement and the size of the reinforcement cover, even at normal temperatures.
- Elevated temperature reduces the bond strength for all types of reinforcement.
- In FRP reinforcement, the temperature approaching the glass transition temperature  $T_g$  is problematic, as the polymer matrix loses its properties, leading to a complete loss of bond strength.
- The determination and application of the  $D$  and  $E$  parameters is a practical and easy way to include the effects of fire and extreme temperatures on bond strength. However, for realistic and practical application, the findings need to be verified by other experiments.

Based on experimentally obtained results, the equations for determining anchorage length have been modified, serving for the safe design of concrete structures with FRP reinforcement against the effects of fire. They can be generally applied to any experimentally determined data.

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